



European Union Network for the Implementation
and Enforcement of Environmental Law



In-situ Thermal Desorption (ISTD) report

Draft Report

Date of report: June 2024

Report number: 2022/11 ISTD EN

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Introduction to IMPEL

The European Union Network for the Implementation and Enforcement of Environmental Law (IMPEL) is an international non-profit association of the environmental authorities of the EU Member States, acceding and candidate countries of the European Union and EEA countries. The association is registered in Belgium and its legal seat is in Brussels, Belgium.

IMPEL was set up in 1992 as an informal Network of European regulators and authorities concerned with the implementation and enforcement of environmental law. The Network's objective is to create the necessary impetus in the European Community to make progress on ensuring a more effective application of environmental legislation. The core of the IMPEL activities concerns awareness raising, capacity building and exchange of information and experiences on implementation, enforcement and international enforcement collaboration as well as promoting and supporting the practicability and enforceability of European environmental legislation.

During the previous years, IMPEL has developed into a considerable, widely known organisation, being mentioned in a number of EU legislative and policy documents, e.g. the 7th Environment Action Programme and the Recommendation on Minimum Criteria for Environmental Inspections.

The expertise and experience of the participants within IMPEL make the network uniquely qualified to work on both technical and regulatory aspects of EU environmental legislation.

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Title of the report: In-situ Thermal Desorption (ISTD) report	Number report: 2022/11 ISTD EN																																																																																					
Report adopted at IMPEL General Assembly Meeting: -	Total number of pages: 156 Report: 56 pages Annexes: 100 pages																																																																																					
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Executive Summary

Keywords

In Situ Thermal Desorption, Sustainable Remediation, Soil, Groundwater, Soil Policy, Remediation, Environment, Pollution, Polluted sites, Contamination, Contaminated sites, Monitoring, In field test.

Target groups

Competent authorities for remediation technology approval/application/monitoring, industrial operators, environmental protection agencies, nature protection bodies, environmental inspectorates, environmental monitoring, and research institutions, technical universities, environmental associations, NGOs, insurance companies and associations, environmental consultants.

As part of its 2020 Work Programme, the IMPEL Network set up this project Water and Land Remediation (2020/09), concerning the criteria for evaluating the applicability of remediation technologies.

The Water and Land Remediation project takes guidance on definitions and key steps of remediation technology application as a springboard and focuses on the technical procedures connected with the remediation technologies. The ultimate goal of the project is to produce a document proving criteria for the assessment of the proposal of remediation technology application, to understand the applicability, what to do in the field tests, and in the full-scale application. Annex 1 covers a number of case studies, that may help the reader to anticipate any problems they may encounter and see if the provided solution applies to their site, knowing that every contaminated site differs from others and it is ever needed a site-specific approach.

The Water and Land Remediation project for 2022-2024 has the objective was to concentrate on two remediation technologies, for 2023 the technologies are Phytoremediation and In Situ Thermal Desorption.

Finally, Water and Land Remediation project intends to contribute to promoting the application of in situ and on-site remediation technologies for soil and groundwater, and less application of Dig & Dump and Pump & Treat that are techniques widely used in Europe but not sustainable in the middle-long term. Soil and water are natural resources and, when it is technically feasible, should be recovered not wasted.

Acknowledgements

This report has been peer reviewed by a wider IMPEL project team and by the IMPEL Water and Land Expert Group, Common Forum network, NICOLE network, EIONET WG Contamination and a group of external reviewers.



Disclaimer

This publication has been prepared within the IMPEL Water & Land Remediation project with the support of partner networks interested in Contaminated Land Management. Written and reviewed by a team of authors the document on hand intends to serve as primary information source to bridge and broaden knowledge among European countries and regions. In aiming support for a joint understanding the potentials of the specific remediation technology it seeks to facilitate.

The content reported here are on the basis of relevant bibliography, the authors' experience, and case studies collected. The document may not be extensive in all situations in which this technology has been or will be applied. Case studies (see annex) are acknowledged voluntary contributions. The team of authors had no task like evaluating or verifying case study reports.

As well some countries, regions, or local authorities may have launched particular legislation, rules, or guidelines to frame technology application and its applicability.

This document is NOT intended as a guideline or BAT Reference Document for this technology. The pedological, geological and hydrogeological settings of contaminated sites across Europe show a broad variability. Therefore, tailor-made site-specific design and implementation is key for success in remediating contaminated sites. So, the any recommendation reported could be applied, partially applied, or not applied. In any case, the authors, the contributors, the networks involved, cannot be deemed responsible.

The opinions expressed in this document are not necessarily those of the individual members of the undersigned networks. IMPEL and its partner networks strongly recommend that individuals/organisations interested in applying the technology in practice retain the services of experienced environmental professionals.

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Glossary

TERM	DEFINITION	SOURCE	PARAGR.
'compliance point'	location (for example, soil or groundwater) where the assessment criteria shall be measured and shall not be exceeded	ISO EN 11074	3.4.5
'compliance or performance control'	investigation or program of on-going inspection, testing or monitoring to confirm that a remediation strategy has been properly implemented (for example, all contaminated have been removed) and/or when a containment approach has been adopted, that this continues to perform to the specified level	ISO EN 11074	6.1.5
'contaminant' ¹	substance(s) or agent(s) present in the soil as a result of human activity	ISO EN 11074	3.4.6
'contaminated site' ²	site where contamination is present	ISO EN 11074	2.3.5
'contamination'	substance(s) or agent(s) present in the soil as a result of human activity	ISO EN 11074	2.3.6
'effectiveness' ³	<remediation method> measure of the ability of a remediation method to achieve a required performance	ISO EN 11074	6.1.6
'emission'	the direct or indirect release of substances, vibrations, heat or noise from individual or diffuse sources in the installation into air, water or land;	IED	Art. 3 (4)
'environmental quality standard'	the set of requirements which must be fulfilled at a given time by a given environment or particular part thereof, as set out in Union law;	IED	Art. 3 (6)
'Henry's coefficient'	partition coefficient between soil air and soil water	ISO EN 11074	3.3.12
' <i>in-situ</i> treatment method' ⁴	treatment method applied directly to the environmental medium treated (e.g. soil, groundwater) without extraction of the contaminated matrix from the ground	ISO EN 11074	6.2.3
'leaching'	dissolution and movement of dissolved substances by water	ISO EN 11074	3.3.15

¹ There is no assumption in this definition that harms results from the presence of contamination

² There is no assumption in this definition that harms results from the presence of contamination.]

³ In the case of a process-based method, effectiveness can be expressed in terms of the achieved residual contaminant concentrations.

⁴ Note: ISO CD 241212 suggests as synonym: 'in-situ (remediation) technique' [Note 1 to entry: Such remediation installation is set on site and the action of treating the contaminant is aimed at being directly applied on the subsurface.] ISO CD 24212 3.1



'pollutant'	substance(s) or agent(s) present in the soil (or groundwater) which, due to its properties, amount or concentration, causes adverse impacts on soil functions	ISO EN 11074	3.4.18
'pollution'	the direct or indirect introduction, as a result of human activity, of substances, vibrations, heat or noise into air, water or land which may be harmful to human health or the quality of the environment, result in damage to material property, or impair or interfere with amenities and other legitimate uses of the environment;	IED	Art. 3 (2)
'remediation objective'	generic term for any objective, including those related to technical (e.g. residual contamination concentrations, engineering performance), administrative, and legal requirements	ISO EN 11074	6.1.19
'remediation strategy' ⁵	combination of remediation methods and associated works that will meet specified contamination-related objectives (e.g. residual contaminant concentrations) and other objectives (e.g. engineering-related) and overcome site-specific constraints	ISO EN 11074	6.1.20
'remediation target value'	indication of the performance to be achieved by remediation, usually defined as contamination-related objective in term of a residual concentration	ISO EN 11074	6.1.21
'saturated zone'	zone of the ground in which the pore space is filled completely with liquid at the time of consideration	ISO EN 11074	3.2.6
'soil'	the top layer of the Earth's crust situated between the bedrock and the surface. Soil is composed of mineral particles, organic matter, water, air and living organisms;	IED	Art. 3 (21)
'soil gas'	gas and vapour in the pore spaces of soils	ISO EN 11074	2.1.13
'unsaturated zone'	zone of the ground in which the pore space is not filled completely with liquid at the time of consideration	ISO EN 11074	3.2.8

⁵ The choice of methods might be constrained by a variety of site-specific factors such as topography, geology, hydrogeology, propensity to flood, and climate



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1 INTRODUCTION

IMPEL, the European Union Network for the Implementation and Enforcement of Environmental Law, developed, under the Water and Land Remediation (WLR) project, a series of guidelines focusing on the most common and most used soil and groundwater remediation technologies. These guidelines summarise the latest and most updated information on these remediation technologies that could help the stakeholders such as site owners, surrounding community, project managers, contractors, regulators, and other practitioners understand all the information emanating from each remediation project. It uses information from the involved contributors from peer-reviewed scientific sources and official reports.

This guideline compiles the most recent knowledge on in situ thermal desorption (ISTD).

1.1 ISTD background

Selecting a specific remediation strategy depends on various environmental, social, and economic factors. In practice, the choice of technology is often influenced by constraints inherent to the site, the characteristics and classification of contaminants, the available timeframe for remediation, and the envisioned future land use. Effective planning, precise system design, and the seamless execution of operations are critical facets in formulating diverse remediation strategies.

Thermal desorption is a process involving the application of heat, either directly or indirectly, to elevate the temperature sufficiently to vaporise and separate contaminants from a solid medium. Thermal desorption can be applied either in situ or ex situ [1], see Table 1.1. The effective design and execution of a thermal desorption system hinge on several pivotal technical factors, encompassing physical and chemical attributes of the target medium for treatment, the groundwater conditions (for in-situ applications), and the chemical composition and concentration levels of the contaminants under consideration. Moreover, the assessment of key parameters, such as contaminant mass distribution, moisture content, soil type, grain size and heterogeneity, plays a critical role in determining the potential efficacy of thermal desorption [1].

Table 1.1 – Comparison of in-situ and ex-situ TD (based on [1]).

	In-situ TD	Ex-situ TD
Advantages	Gas treatment and monitoring systems occupy a small area	Processing on the ground, easy to control entire process
	Less secondary contamination	Easy to specify whether the soil reach the standards
	Saving cost due to the lack of need of soil excavation, transportation and backfilling procedures	Easy pre-treatment
	Small amount of produced exhaust gas with high concentration of pollutants in the gas, so the collection method is often used and other pollutants will not be produced	More contaminants can be treated e.g. PHCs, SVOCs – more versatile
	No need for excavation as it can be used under existing infrastructure	Higher heating temperatures feasible and easier to be implemented
Dis	Difficult to predict and control underground processes	An ex-situ restoration site is needed, that may occupy a large land area



Difficult to determine the treatment endpoint	Excavation and transport of contaminated soil is needed. Thus, contaminants may diffuse. Noise and dust may arise
More vulnerable to site conditions, imperfect predictions and unforeseen events	Increase of cost due to soil excavation, transportation and backfilling procedures
Higher risks in larger scales	When direct TD is used, it may produce harmful pollutants due to the combustion of exhaust gas. Improper operation may produce carcinogens and dioxins
Difficult to achieve higher heating temperatures	Cannot be used under existing building and structures

In situ thermal desorption is a remediation process in which heat and soil vapour extraction are applied simultaneously to subsurface soils [2]. ISTD implementation necessitates the use of a network of heaters. The Thermal Conductive Heating (TCH) process entails the controlled application of heat to the soil via a high-temperature surface⁶ in direct contact with the soil. Heat transfer occurs through a combination of radiation from the heater and heat transfer by thermal conduction and convection in the soil that is not in immediate proximity to the heater [2]. The most commonly used technologies are Steam Enhanced Extraction (SEE), Electric Resistance Heating (ERH), and Thermal Conductive Heating (TCH) [17]. Depending on the boiling points of the contaminants (< 200 °C) these technologies can also be operated at lower temperatures, reaching as low as 100 °C [2].

The low-temperature ISTD is suitable for the treatment of a wide range of contaminants in soils, including both volatile and semi-volatile contaminants, while TCH high-temperature applications may also get implemented for a wider spectrum of contaminants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), total petroleum hydrocarbon (TPH), hexachlorocyclohexanes (HCHs), polychloride dibenzo -p-dioxins/dibenzo-furans (PCDD/Fs), dichlorodiphenyltrichloroethane (DDT), organochloride pesticides [3], and volatile inorganic substances as the Hg [4]. Based on the US Environmental Protection Agency (EPA) and the established guidelines of "Effectiveness of thermal desorption on general contaminant groups for soil, sludge, sediments, and filter cakes" published in 1991, the method is unsuitable for the treatment of soil when organic corrosives, inorganic substances, and reactive substances (e.g. reactive oxidisers and reducers) are present [5]. ISTD is commonly applied in sites with high concentrations of contaminants covering a small area and with an urgent requirement for treatment [4].

In practice, regardless of the nature of the contaminants of concern, for high-temperature applications a significant portion (e.g., >95-99% or more) of the contaminants may undergo destruction while traversing the superheated soil zone proximate to the heater-vacuum wells prior to reaching the extraction wells [6]. Contaminants that persist in the soil after this treatment stage can be extracted from the produced vapour stream using aboveground air quality control systems [6]. As the soil undergoes heating, the resulting vaporized water, contaminants, and some volatilised inorganic compounds are directed in a counter-current manner to the heat flow into vacuum extraction wells, referred to as "heater-vacuum" wells [6]. For the purposes of this document, only in-situ methods will be presented.

⁶ Operational temperatures for heaters may range up to 800 and 900 °C, when establishing a high-temperature zone (>500 °C) near the heater. At temperatures ~ 120 °C also destruction of numerous contaminants starts before getting released from the soil [2].



1.2 ISTD applicability

ISTD may involve destroying or removing contaminants present in the (conductively) heated soil. The mechanisms responsible for the vaporisation or destruction of contaminants encompass several processes, including but not limited to evaporation into the air stream, steam distillation into the water vapour stream, boiling, oxidation, and pyrolysis [2]. This is attainable because, if required, the coolest locations within the treatment zone can be heated to the boiling points of the target compounds of concern and maintained at these elevated temperatures (e.g., exceeding 500°C for high-boiling compounds) for extended periods [6].

During the thermal conductive heating process, the transportation of vaporized contaminants is enhanced due to an increase in bulk permeability. This increase results from the drying and contraction of the superheated soil, which occurs above the boiling point of water. This phenomenon develops in a progressively expanding radius around each thermal well. Consequently, closely spaced vapour flow pathways can be established, even in impermeable silt and clay layers, facilitating the capture of vaporized contaminants and steam by nearby heater-vacuum wells [6]. ISTD demonstrates versatility in treating a diverse array of materials and soil types, offering a distinctive advantage in its ability to efficiently remediate clay-rich soils. At temperatures approximately reaching 80 °C, clay particles undergo micro fracturing, resulting in increased permeability to gas, allowing mobilisation of volatilised contaminants [2].

ISTD technologies are potentially applicable for the treatment of a wide range of contaminants, including but not limited to benzene, toluene, ethylbenzene, and xylene (BTEX); naphthalene and phenanthrene; petroleum hydrocarbons (PHC) from a broad range of from gasoline to jet fuel passing by diesel fuel; PAHs, chlorinated solvents like trichloroethylene (TCE) and perchloroethylene (PCE) and PCBs.

Extensive laboratory treatability studies and field projects have consistently demonstrated that high temperatures and prolonged residence times yield exceptional removal efficiency, even for high-boiling contaminants like PCBs [6]. In fact, contaminants and cleanup goals determine the target temperatures to apply. Contaminants and remediation objectives are pivotal in determining the specific target temperatures required. Generally, lower temperatures are suitable for addressing gasoline, benzene, TCE, and PCE contaminants, while higher temperatures are necessary for effectively treating diesel, naphthalene, and certain PAH compounds. Furthermore, even higher temperatures are mandated when dealing with PCB, dioxin, and other PAH compounds.

1.3 ISTD implementation

The implementation of ISTD involves the deployment of heating elements. These heaters are strategically distributed within the contaminated subsurface, either in a vertical or horizontal configuration. Integral to the process is continuously monitoring operating temperatures to ensure precise control. Operating in conjunction with the heating process is a vacuum extraction system, working simultaneously to remove vaporized contaminants.

Contaminants must be exposed to target temperatures sufficiently long to guarantee their effective vaporization or destruction. Rigorous contaminant monitoring is conducted throughout the process, and operational parameters are adjusted based on monitoring data and site-specific conditions. This adaptive approach ensures that the treatment remains effective and responsive to changing circumstances.



In broad terms, the equipment required for the successful implementation of ISTD typically encompasses electric resistance heaters, generating the necessary heat for the process; thermocouples and control panels for temperature monitoring and control; vacuum pumps and extraction wells for the extraction of vaporized contaminants; monitoring probes and data loggers to assess heat distribution/monitor, thermal blankets to trap heat and enhance the heating process efficiency, barrier systems around the treatment zone to contain and control the flow of vapour.

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2 Description of the technique

The ISTD is a method based on soil heating (in some cases, it can reach up to 600 °C when Hg is also considered) with simultaneous application of heat and vacuum to the subsurface. As the subsurface is heated by, e.g., electrical current passing through heating elements suspended in wells (see Figure 2.1), the contaminants vacuum pressure increases allowing the mass transfer to the gas phase and the contaminants' withdrawal by vacuum wells [7]. Besides the thermal well, other heating equipment used in the ISTD technology are the thermal blanket and the enhanced soil vapour extraction.

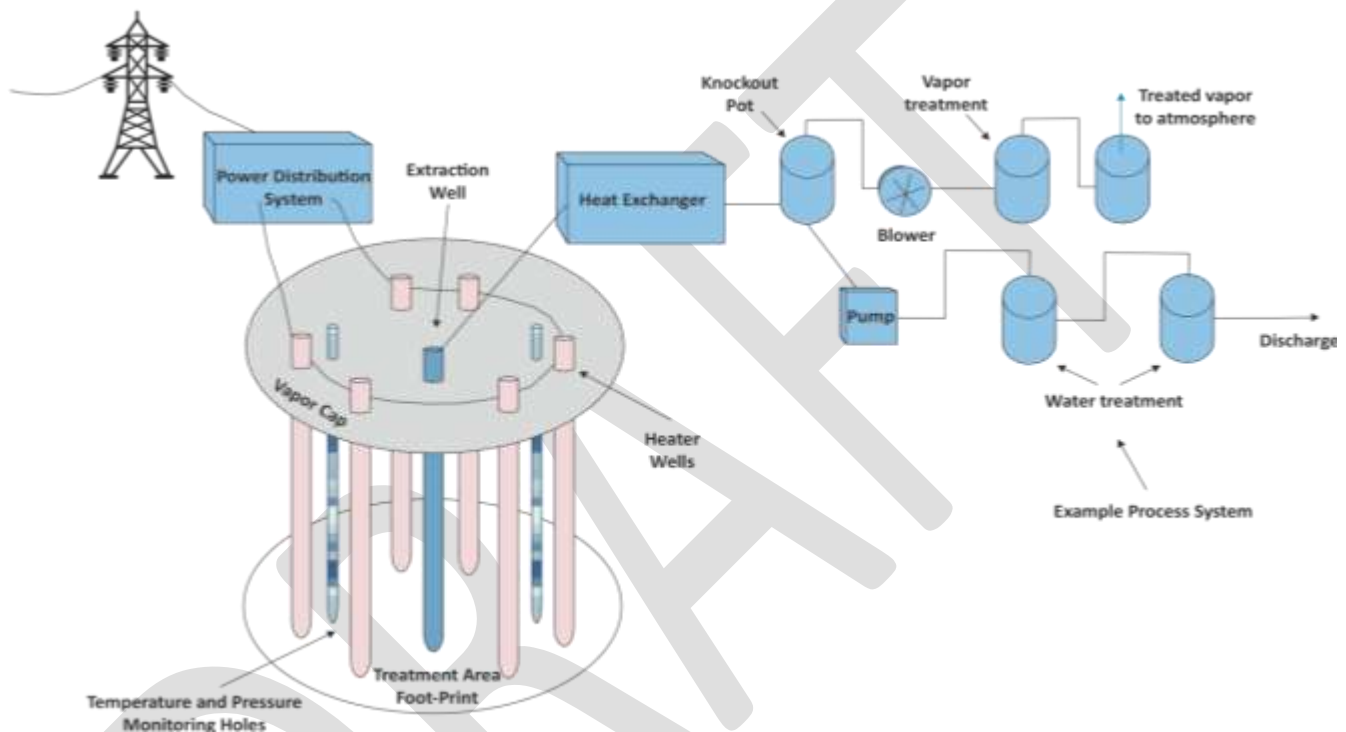


Figure 2.1 – In situ thermal desorption by thermal well utilising the thermal conduction heating (Based on [8]).

When the thermal wells are utilised for the ISTD, the main design includes (Figure 2.1)[9]:

1. A power distribution system utilising containers is able to supply and regulate power from the grid to the heater circuits. It may be multiple power containers.
2. A vapour cap can collect the vaporized contaminants, eliminating the heat loss to the atmosphere and protecting cooling rainwater from passing the heated zone. It is made of lightweight concrete.
3. Heater wells can transfer the energy, which is typically 1kW pr. m well.
4. The treatment area refers to the volume that must be heated at a target temperature. Numerous heating wells penetrate this area, while venting screens are placed horizontally, vertically, or both. The vaporisation and withdrawal of contaminants take place in this part.
5. Vapour treatment is able to collect the produced vapours and prevent pressure build-up. The condensed, collected vapours are separated into water and free-phase products. The water is normally treated before recharging (e.g. by activated carbon). At the same time, the extracted non-condensable



vapours are also treated by several techniques depending on the mass load, e.g. filtration or thermal oxidation.

While in theory, the ISTD method is based on volatilisation and desorption as the primary mechanisms for removing contaminants, in the actual process, reactions such as pyrolysis, degradation, and oxidation may take place due to the heating temperature and the atmosphere's oxygen content. When the temperature and oxygen content increase, such reactions become more intense [2, 8].

Two generic types of classification can be identified for the ISTD based on the following:

1. the theoretical temperature
2. the heat transfer methods and energy conversion

2.1 Classification of ISTD based on the theoretical temperature

Based on the temperature needed to remove the contaminants, the ISTD is separated into low-temperature thermal desorption (LTTD) and high-temperature thermal desorption (HTTD). The boundary value of temperature for the categorisation is unclear, whereas the upper limit for LTTD gets referenced at temperatures where desorption is the crucial process ($< 120\text{ }^{\circ}\text{C}$), the lower boundary line for HTTD is usually within 300 to $350\text{ }^{\circ}\text{C}$ [4, 10]. In lower temperatures, where the LTTD takes place, treating VOCs with low boiling points ($< 200\text{ }^{\circ}\text{C}$), such as benzene and gasoline, is feasible. In higher temperatures, the HTTD process is suitable for treating SVOCs characterised by high boiling points or inorganic matter, such as mercury (Hg).

Errore. L'origine riferimento non è stata trovata. gives a general range of temperatures for selecting appropriate system equipment for a specific contaminant [4].

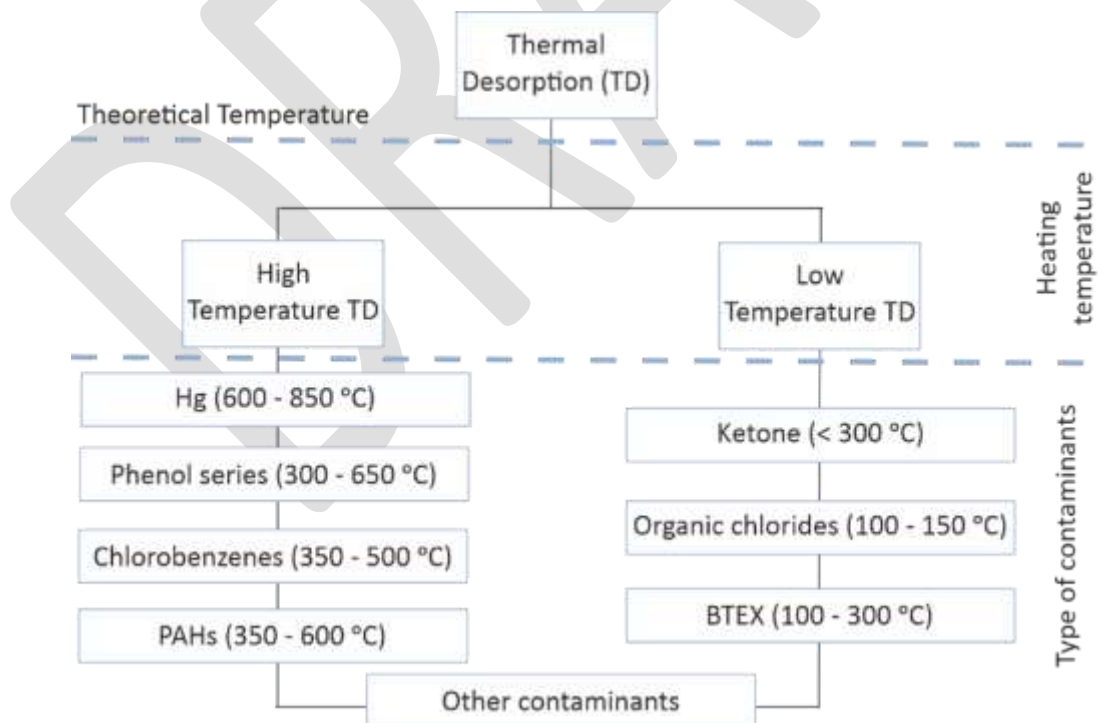


Figure 2.2 – Theoretical temperatures for the decontamination of specific components via Thermal Desorption (based on [4]).



2.2 Classification of ISTD based on the heat transfer methods and energy conversion

Regarding the heat transfer methods and energy conversion, the ISTD thermal technologies can be further divided into the following types [11, 12]:

1. Steam Enhanced Extraction (SEE) transfers heat through convection by the water vapour or hot air injection into the contaminated area. This technology is preferred in areas with good homogeneity and high hydraulic conductivity.
2. Thermal conductive heating (TCH) transfers the heat to the contaminated area by heat conductivity after its production by the heating source. TCH is preferred for areas with poor homogeneity or poor permeability. This technology comes in combination with soil gas phase extraction technology for completely remediation of the contaminated area.
3. Electrical resistance heating (ERH), based on Joule's law, takes advantage of converting electrical energy into heat, aiming to increase temperature. This technology requires specific facilities, including power control, electrodes, steam recovery, and recycling processes.
4. Radiofrequency heating (RFH), which uses electromagnetic waves to heat contaminated soils, is generated by high-frequency voltages. Despite the fact that low-frequency electromagnetic waves have higher penetration ability, they are often used for in-situ recovery.

2.3 Factors Influencing the ISTD

Eight critical factors may influence the efficiency of ISTD and must be examined based on soil characteristics and contaminant type [4]:

1. Heating temperature depends on the contaminants' type and affects the efficiency of ISTD. Generally, when the heating temperature increases, the removal efficiency gradually increases. However, no changes will occur under further increase when the heating temperature reaches a sufficiently high temperature. Thus, this critical temperature must be selected to avoid higher temperatures that will increase the cost and may damage the soil.
2. Heating time is correlated to the heating temperature. Usually, low heating temperature requires a long heating time, while it is proposed to replace high temperature to avoid soil structure damage.
3. The heating rate has a positive linear correlation with the removal efficiency as it controls the heat transfer rate between the soil and the carrier gas while affecting the desorption and degradation rates.
4. Carrier gas, as the nature of the gas, influences the efficiency of the TD. The volatilisation rate of the volatile compounds can be increased when the carrier gas flow rate increases, improving the efficiency of ISTD.
5. The initial concentration of contaminants, as the removal efficiency, is usually increased when the initial concentration is higher. The type of contaminant is critical.
6. An ideal optimal moisture content of the contaminated soil ranges between 10 – 20 %.
7. Soil particle size must be correlated with other soil characteristics, such as soil moisture or soil aggregation. Some studies proved that coarse particles are difficult to aggregate. Thus, their surface could be in full contact with the heat source, providing a good thermal conductivity and thus a satisfactory ISTD treatment, in contrast with the viscous and moist fine particles that can easily aggregate. However, other studies supported that fine particles provided higher removal efficiency than coarse particles, probably related to their higher specific surface area.
8. Additives can be added to the soil before the ISTD to effectively increase the removal efficiency by changing the soil's physical or chemical properties.



The factors need to be examined in three aspects: the operating parameters, the physical and chemical properties of soil, and the additives.

2.4 Advantages of ISTD

Compared with other techniques, the ISTD exhibits the following advantages [9]:

1. It can treat different types of contaminants, including volatile and semi-volatile compounds.
2. It has high remediation efficiency with a concentration reduction of up to 99.9 %.
3. It has a short operation time with an average of three to four months.
4. It is characterised as a relatively stable process.
5. No excavation is needed.
6. The damage to the soil is limited and can be recycled.
7. It is insensitive to geological inhomogeneities.
8. It is sufficient for the treatment of low-permeable sediments and bedrock.
9. It decreases the production of highly toxic secondary pollutants (PCDD/Fs) produced by the treatment of halogenated organic compounds, e.g. PCBs [16].
10. It is suitable for solving sudden organic pollution environmental accidents, e.g. emergency soil pollution occurring by accidental leakage.
11. It remediates residential areas with the potential to be underneath buildings.
12. It is applicable below water table.
13. It is unlimited with regard to the contamination depth.

2.5 Bibliography of Chapters 1 & 2

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3 FEASIBILITY STUDY

Knowledge management and technical innovations are one of the keys to achieve sustainable remediation especially subsurface is getting busier.

In urban environments a lot of contaminations such as chlorinated solvents are often mixed with each other and spread underneath buildings. This not only leads to technical problems for remediation, but also to liability and financial discussions and hence has an impact on society. An integrated approach, and area-oriented approach is needed to tackle the contamination problems. In situ thermal desorption (ISTD) may or can be one of the most- cost effective remediation method for many sites if it is feasibility session studied perfectly [1].

In situ thermal remediation (ISTR) refers to the application of heat to the subsurface by various methods. Independent of the heating method the general aim of temperature rising in the treatment zones is to increase mobility and/or destruction of contaminants [1].

In more details, volatile, semi-volatile and non-volatile organic contaminants in the soil are mainly vaporized or in some very special situations even destroyed. The main physical mechanisms are evaporation and steam distillation, but even oxidation and pyrolysis (chemical decomposition in the absence of oxygen) can occur. In most cases contaminants are vaporised (as it is with chlorinated solvents) and extracted via the soil gas by a soil vapour extraction system (SVE) [1].

Feasibility techniques that base solely on the transport of fluids to deliver reagents or to remove dissolved contaminants are dependent on (amongst other factors) the permeability of soil and their distribution in or around the contaminated soil volume. As the permeability of the natural subsurface (subsoil and aquifers) varies over some orders of magnitude the emission of contaminants from low permeable zones into high(er) permeability zones, where the air and groundwater flow takes place, is limited by the diffusion. Moreover, the ability to deliver reagents and/or additives to transform or to remove contaminants is only possible in the high permeable zones, whereas the contaminants unfortunately are mainly accumulated in the low permeable zones. The effectiveness of heat to remove contaminants depends mostly on the more uniform conduction of the “reagent” heat. In most soil materials, thermal conductivities range over less than one order of magnitude. Hence, the relatively small range of thermal conductivities leads to a uniform heating and subsequent treatment within a contaminated zone [1].

Thermal desorption is potentially applicable for the treatment of a wide range of volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and even high-boiling-point contaminants - including chlorinated compounds such as polychlorinated biphenyls (PCBs), dioxins, and furans [1].

Thermal desorption technology can be applied in-situ and has been shown to be able to reduce soil contaminant concentrations by over 99%. The technology can treat many different types of contaminants over a wide range of boiling points (e.g. petroleum hydrocarbons, PCBs, dioxins, and tars) [1].

In situ thermal remediation (ISTR) is a technique for source remediation of organic compounds. It refers to the application of heat to the subsurface by various methods. Independent of the heating method the focus of ISTR is to mitigate source zone contamination by vaporising the contaminants due to sub-surface heating and extraction of the gas mixture from the sub-surface by soil vapour extraction (SVE). For the typical organic contaminations (density smaller and higher than water (LNAPL, DNAPL) it is necessary to heat the sub-surface

to 50°C to 100°C. For some contaminants like PCB – the contaminant destruction can be achieved at higher temperatures. The extracted contaminated and partial hot soil gas mixture has to be subsequently cooled and treated by air treatment systems like activated carbon filters or catalytic oxidation (CatOx). In situ thermal remediation techniques have their advantages which make them ideally suited for the application in build-up urban areas

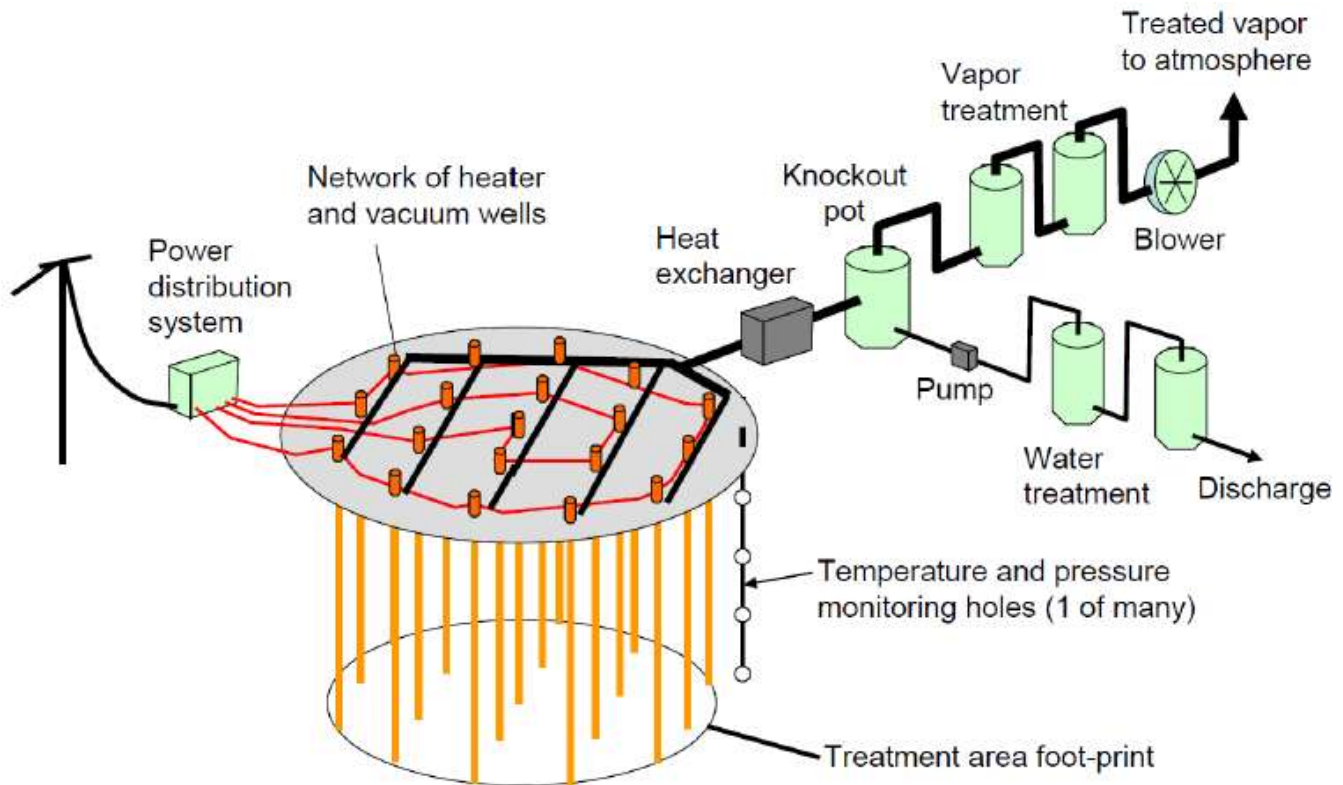


Figure 3.1. Conceptual design of a thermal conduction heating application [2].

As with other remediation technologies there are many names and methods, as different technology vendors are in this market and offer their techniques under specific names. Despite the differences between the techniques and the offering companies three general heating methods can be distinguished.

Three general heating methods can be distinguished for in situ thermal desorption:

1. Thermal conductive heating (TCH): heat is transferred by conduction from so-called thermal wells into the subsoil. Heater wells are either heated by electricity or circulating hot gas.
2. Steam air injection (SAI) or steam enhanced extraction (SEE): heat is transferred convective via steam and hot air into the subsoil
3. Electric resistance heating (ERH) and Radio frequency heating (RFH): heat is created directly in the soil.

Whereas for 1.) and 3.) the structure of the soil matrix is less important, for 2.) a good or medium permeability of the soil is necessary (gravel, sand, or coarse silt) to inject the steam air mixture and to achieve an effective “steam flow” to heat up the source zone. On the other hand, for 2) the specific energy input is much higher than for 1.) and 3.). As illustrated in Figure 4 small layers or lenses of dense soil material can be heated by a steam injection underneath [3].

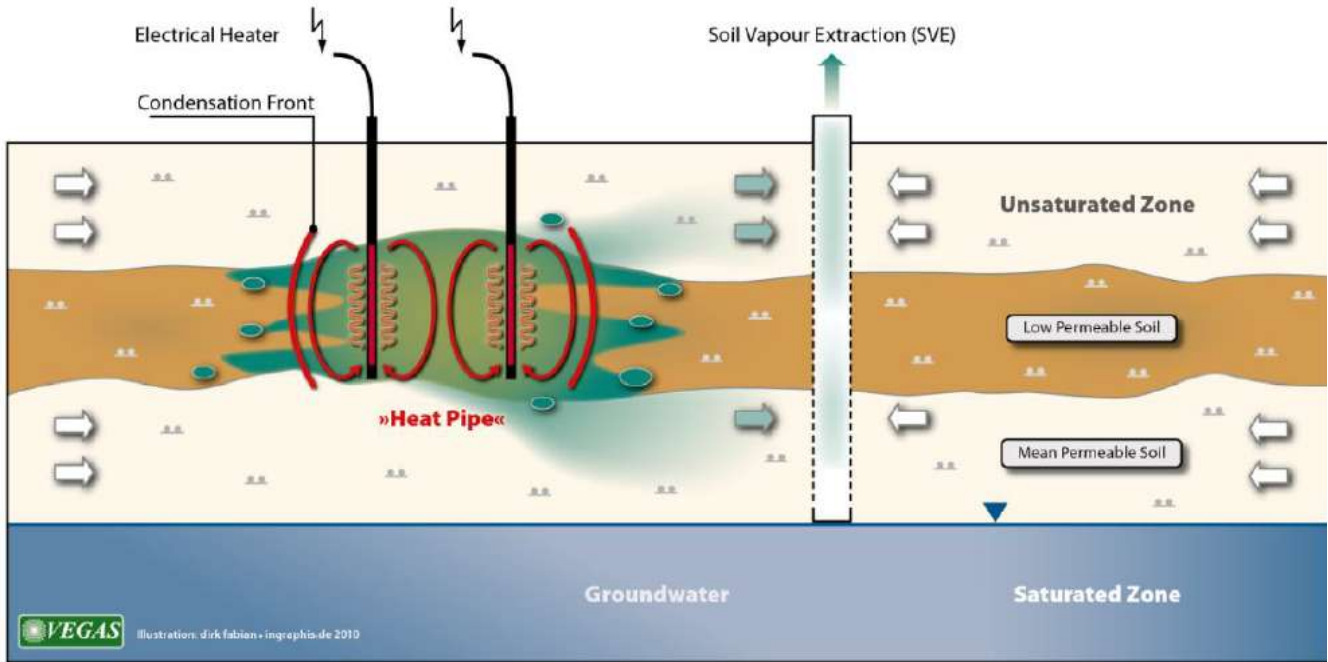


Figure 3.2. Principle of thermal conductive heating (TCH) [4].

For the preliminary design of a SAI application a software tool was developed by VEGAS (2012) and is available as free download. Key data about the site, the contamination, hydrogeology, and remediation specifications are compiled with the help of input masks (see Figure 3. The tool enables quick pre-planning of the remediation process, the field equipment (injection- and monitoring wells) and the installation engineering.

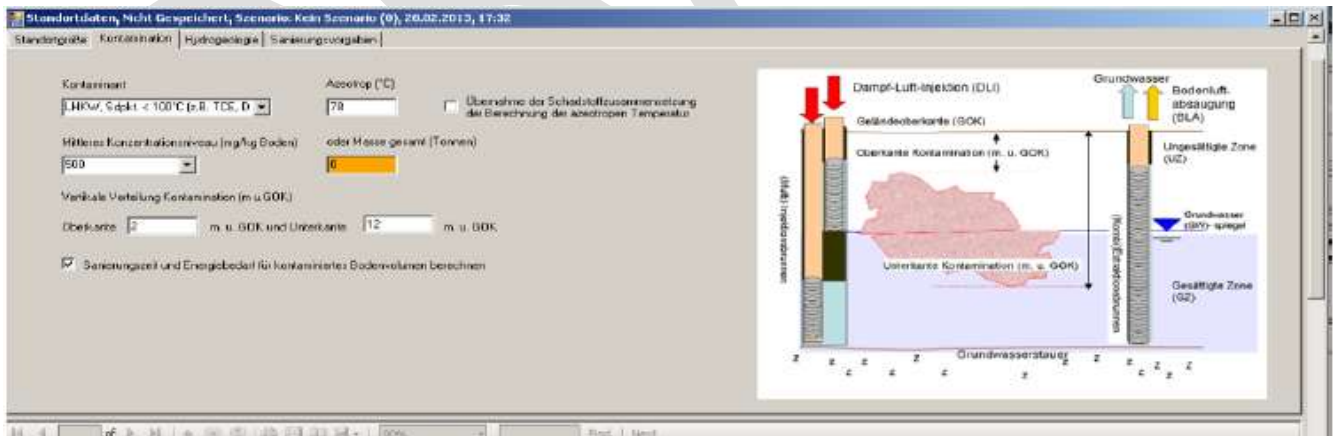
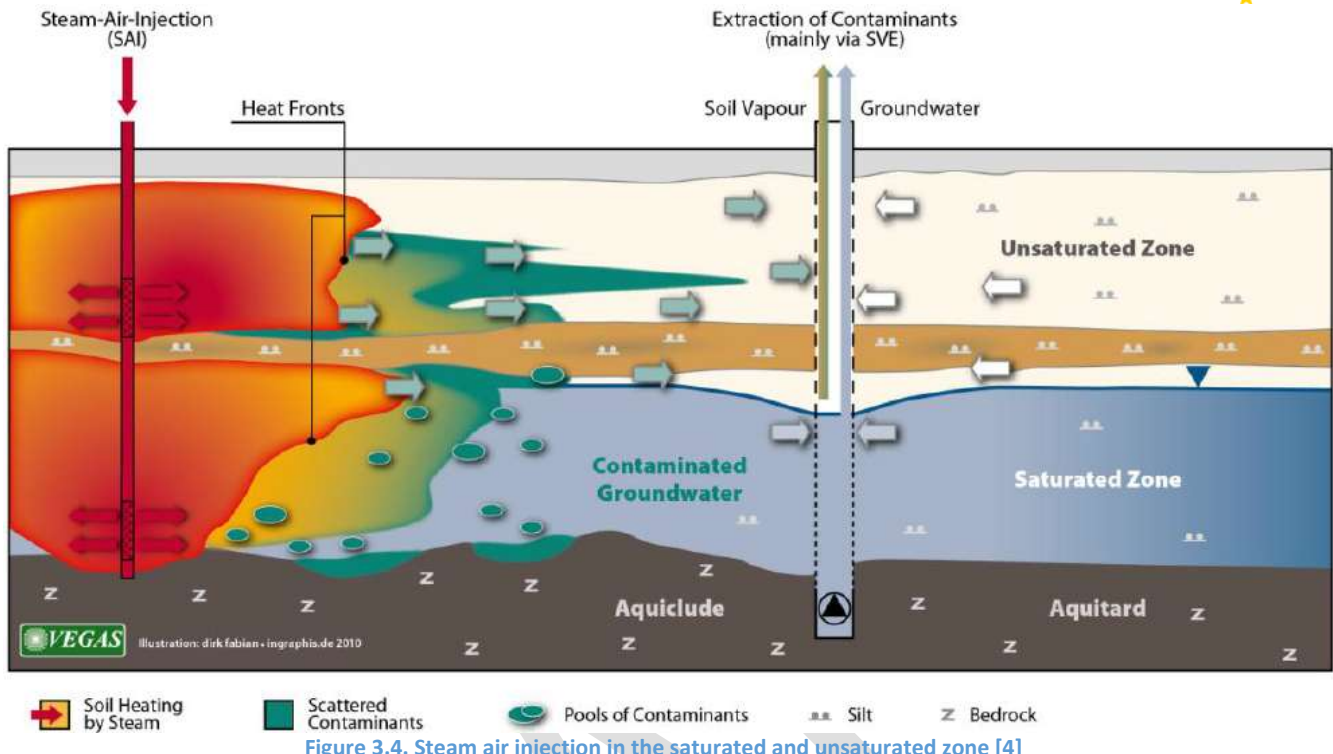


Figure 3.3. Software Tool for design of a steam air injection [4].



Especially for complex hydrogeological conditions with different layers (e.g., clay and gravel or sand layers, saturated zone) a combination of different techniques may be necessary to reach the remediation targets in an efficient way. The economical and effective delivery of heat into the subsurface is the main success factor for a thermal treatment. Each technique has a different maximum temperature level. For the remediation of chlorinated solvents all techniques can reach the necessary temperature level according to site properties and facility design. Only some of the CHCs have a boiling point below 100°C, but even the compounds with a boiling point above 100°C can be easily vaporised together with water. The reason is, that the boiling point of a mixture of NAPL and water is lower than each of the boiling points of its compounds. This so-called co-distillation (azeotropic) point for all CHCs is below 100°C and can, therefore, be reached by all the ISTR methods [5].

Thermal desorption is a term applied to many different types of soil remediation technologies. All these technologies consist fundamentally of a two-step process, as illustrated in Figure 1. In Step 1, heat is applied to a contaminated material, such as soil, sediment, sludge, or filter cake, to vaporize the contaminants into a gas stream that, in Step 2, is treated to meet regulatory requirements prior to discharge. A variety of gas treatment technologies are used to collect, condense, or destroy these volatilized gases [6].

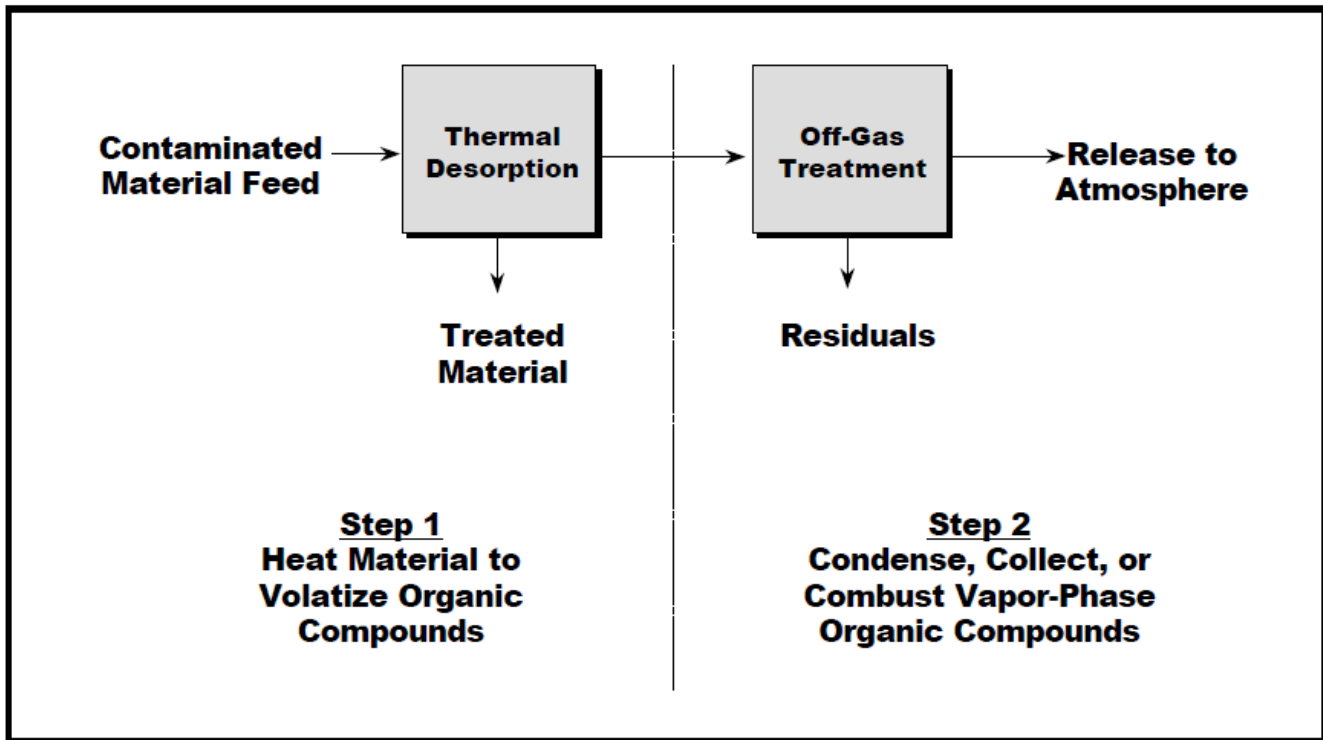


Figure 3.5. Generic Thermal Desorption Process [6]

Thermal desorption is fundamentally a thermally induced physical separation process. Contaminants are vaporized from a solid matrix and are transferred into a gas stream where they can be more easily managed in Step 2. Options used to manage or treat the contaminant-laden gas stream may consist of condensation, collection, or combustion. For the first of these two options, the condensed or collected contaminants usually are treated off-site at some time subsequent to Step 1. For the third option, combustion, treatment occurs on-site, immediately after the gases exit Step 1 of the process. In addition to volatilizing organic contaminants contained in the waste feed, moisture is volatilized and leaves with the off-gas. As a result, the thermal desorption system also functions as a dryer. In fact, many vendors refer to the primary treatment chamber of their system as a “rotary dryer,” highlighting its effect on the material, although the principal purpose is to evaporate and separate out the contaminants [6].

In the basic thermal desorption process, the application is limited to non-chlorinated contaminants with relatively low boiling points (i.e., below 315°C). The contaminated material typically is heated to between 150°C and 315°C, and the process is sometimes referred to as “low-temperature thermal desorption” (LTTD). Thermal desorption was eventually applied to contaminants having boiling points higher than 315°C. As a result, these systems have evolved so they are able to heat materials to temperatures in the range of 315°C to 1650°C. In this case, the system is sometimes called “high-temperature thermal desorption” (HTTD). In either case, the treated material essentially retains its physical properties, although it may be modified somewhat when heated to higher temperatures. Thermal desorption technologies have not only been modified to treat high-boiling-point contaminants but are also capable of treating a variety of chlorinated compounds [6].



Many factors should be considered in the selection of Thermal Desorption as a remedy for contaminated soil. If there is reasonable confidence that thermal desorption will achieve the required treatment outcome, then other issues will need to be considered to determine if it is likely to be an appropriate technology for the site. Key considerations that will often determine the feasibility of applying thermal desorption as a potential remediation option include:

- Whether stakeholders are strongly against thermal treatment (for example, stakeholders may consider that thermal desorption has unacceptable risks, particularly whether there are concerns regarding emissions).
- Whether the material to be treated contains substances such as halogens or volatile metals at concentrations that exceed regulatory limits, or may require treatment conditions, additional pollution control systems or operational controls that make the process uneconomic.
- Whether the water content of the material to be treated requires additional treatment (e.g. drying) that makes the process uneconomic.
- Whether the composition of the material can be made sufficiently uniform (e.g. through blending if necessary) to provide for safe and reliable treatment (e.g. avoid forming an explosive atmosphere, or to reliably meet the target concentrations).
- Whether the required temperature and residence time for treatment of the contaminant can be achieved by the available thermal treatment system, which should be fit for purpose [1].

If there is reasonable confidence that thermal desorption will achieve the required treatment outcome, then other issues will need to be considered to determine if thermal desorption is likely to be an appropriate technology for the site. These include:

- Will the relevant regulatory agencies accept thermal desorption as a viable means of remediation?
- For on-site treatment, can the treated material be used, or disposed of economically? Will the concentrations of inorganics and residual organics allow the treated material to be reused as backfill on the site or as clean fill elsewhere, or will subsequent treatment (e.g. stabilisation) or landfill disposal be required?

Section 3.1 presents a summary of some advantages and limitations of Thermal Desorption technology. This is not a complete listing of all pertinent technology factors but is meant to provide a capsule overview of some of the key factors to be considered. Section 3.2 continues the stages of feasibility such as data requirement, physical properties and chemical composition of soil.

3.1 Advantages, Disadvantages and Limitations of Thermal Desorption

Thermal technologies are attractive because of potentially shorter treatment times (weeks or months, rather than years for many other technologies) and in some cases lower total operations and maintenance costs. Only energy, and in some cases water and air, are added to the subsurface, rather than chemicals or bio-amendments.

In situ thermal technologies are thought to have advantages relative to other remedial options, including: (1) shorter operation times, (2) many chemicals can be treated at once, and (3) some thermal technologies, ERH and conductive heating, are less sensitive to subsurface heterogeneities across a site.

The potential drawbacks of use of in-situ thermal technologies include the following: (1) they are difficult to apply near occupied/active sites; (2) they require more sophisticated design and operation; (3) they may



enhance the potential for contaminant to migrate to previously no impacted areas; and (4) post-treatment soil temperatures may remain elevated for prolonged periods of time (months to years).

In addition, poor documentation and a lack of quantitative post-treatment performance data has made it difficult to confidently define, in some case, practicable performance expectations for thermal technologies.

There are not many cases which are well documented to make the efficiency and cost effectiveness of ISTR proof. Nevertheless, ISTR may solve remediation problems that cannot be solved in an adequate and quick manner with any other technique. Especially the short timeframe of the remediation and the possibility to remediate under existing buildings can be crucial for the use of ISTR. This can support the development off of urban areas. If ISTR is a cost-effective technique, can hardly be proven. For ISTR high costs for drilling and energy are depending on the size of the site and the (hydro-)geology. Costs for planning and monitoring are high, regardless of the size of the sites. The adoption of the technique to the site-specific conditions can be expensive and time consuming, in particular in urban environments. As ISTR generates high costs for energy consumption in a short timeframe, a thorough planning and supervision are necessary. In urban environments the costs for the supervision of neighboured buildings must be taken into account [1].

3.2 The Feasibility Stages/Sections of Thermal Desorption

3.2.1 Data Requirement

Successful implementation and design of a thermal desorption system, whichever approach is used, is dependent upon the following key technical considerations:

- The physical properties of the soil to be treated,
- The chemical composition of the soil to be treated,
- Groundwater conditions,
- The chemistry and concentrations of contaminants [1].

3.1.1.1 Physical Properties of Soil

The physical composition of the material to be treated needs to be well characterised. Important factors (some of which relate to soil type) include:

- Soil particle size and its variability needs to be characterised: coarse material (gravel or sand) is likely to be most amenable to with the extracted/ separated during the process and likely to require additional treatment.
- Moisture content – this is a primary cost factor because most of the applied heat is used to vaporise water.
- Density – this is also a critical factor because mass and energy balances and cost estimates are based on the mass and not volume of material to be treated.
- Soil heterogeneity – differing grain sizes and the presence of larger lumps of material (such as masonry in fill, scrap metal) can affect the uniformity of heat distribution through the material and the level of treatment achieved.
- Permeability and plasticity of the material – which can lead to feed problems, accelerate, or impede the distribution of heat and migration of vapour through the soil medium.



- Calorific properties of soils which are important to determine the radius of influence. Resistivity of the subsurface material – which is important in the case where electrical resistive in-situ heating is involved. Resistivity will be affected by moisture content and there may need to be sophisticated localised water injection to control resistivity and heat generation.

3.1.1.2 Chemical Composition of Soil

The composition of the material to be treated needs to be well characterised. Important factors include:

- The distribution concentrations and mass of contaminants in soils at the site, and the requirement to locate and treat contamination that exceeds certain concentrations, noting that contamination may be irregular in extent and location.
- The range of contaminants, their concentrations, and their ability to degrade or volatilise (perhaps aided by steam stripping) as the material is heated. The boiling temperature and the vapor pressure of pollutants are important parameters. Generally, contaminants with higher boiling points will require higher temperatures.
- The suitability of the air pollution control systems for removing chemicals such as dioxins and furans. This will depend on the extent to which conditions favour de novo synthesis of dioxins and furans, and the ability of the air pollution control systems to remove these substances. Regulatory agencies can impose best practice requirements and stringent limits on the emission of such chemicals for combustion and air pollution control systems and it may be necessary to demonstrate that the proposed systems will conform to these requirements.
- Limitation on humic acids and natural organic material, particularly for indirectly heated plants which will capture their distillation products, including dissolved phase in water.

3.1.1.3 Maximum allowable concentrations

- The maximum allowable concentration and variation in concentration of the contaminants in the treated soil. If very stringent remediation criteria are applicable, then higher temperatures, longer treatment times and smaller maximum soil particle sizes may be required for in-situ treatment, impacting on costs.
- Allowable concentrations of volatile metals such as mercury. The maximum concentrations will depend on the ability of the air pollution control systems to capture such metals. Note that some metals, such as mercury, may accumulate within the treatment unit and be released at higher concentrations, placing a more stringent limit on the allowable soil concentration and control of emissions.
- Maximum allowable concentrations of metals that will remain in the treated soil; this depends on the intended use or disposal of the treated soil and whether subsequent treatment (such as stabilisation) may be required, making the treatment by thermal desorption uneconomic or perhaps unnecessary.
- Concentrations and forms of compounds containing chlorine, sulphur, nitrogen, or fluorine that are present in the soil and resulting combusted gases, and the suitability and effectiveness of the air pollution control systems for removing such substances. Such substances can also give rise to corrosive conditions requiring more expensive construction materials or additional maintenance and downtime and can also give rise to greater concentrations and volumes of wastewater from air pollution control systems that may be difficult or expensive to dispose of.



3.1.1.4 Calorific value and water content

- Variations in the calorific value of the materials being treated and the maximum concentrations of volatile combustible contaminants that could give rise to rapid temperature rise and gas release that would result in explosion or uncontrolled releases of gas. Blending of material may be necessary to achieve a uniform composition and reliable and safe operation. For example, there could be a limit of 4% of total available organic carbon at the proposed treatment temperature for directly heated plants (including non-contaminants and contaminants), which could be exceeded if NAPL or saturated soil is encountered in some locations.
- Water content (high water content can greatly increase the energy cost), rate of desorption and size of the accompanying combustion system. Typically, the rate of fuel consumption rises by approximately 3 to 5% for each percent of moisture, and fuel costs could make the technology not viable.

3.1.1.5 Groundwater Conditions

In the case of in-situ treatment, hydrogeological conditions such as depth to groundwater, flow paths, flow rate and seasonal variations can be very important. For example:

- the distribution of contamination with respect to the saturated zone and whether it is necessary to treat contamination under water.
- what contaminant concentrations will remain in the groundwater after treatment and whether these will meet the remediation criteria.
- whether dewatering is necessary to effect treatment
- understanding water table variations and migration pathways to assess the potential for vertical or horizontal migration into the unsaturated treatment zone, and
- groundwater flow velocity, because high velocities can remove heat faster than it is supplied, such that a cut off wall is necessary to effectively remediate.

3.1.1.6 Waste Streams

The operation of a thermal desorption unit can create different waste streams, including for example:

- condensed contaminants and water
- thermal oxidiser residues
- clean off-gas
- spent carbon,

Clean off-gas is released into the atmosphere as part of the thermal desorption process. The air emissions from the thermal desorption system must comply with regulatory standards. Because of the potential for the production of toxic products of incomplete combustion such as dioxins and furans, the ability to show compliance with stringent can include demonstration that the air pollution control system complies with best practices, including a rapid quench system to reduce the production of dioxins and furans, scrubbing to remove acid gases, high-efficiency particulate removal (such as a bag house), and possibly additional polishing such as modified activated carbon, particularly if a volatile metal such as mercury is present[1].

3.1.2 Treatable Contaminants

Thermal desorption is potentially applicable for the treatment of a wide range of

- Volatile organic compounds (VOCs)



- semi-volatile organic compounds (SVOCs),
- and even higher-boiling-point, chlorinated compounds such as polychlorinated biphenyls (PCBs),
- dioxins, and furans [1]

Generally, in situ thermal desorption is used for compounds with a boiling temperature lower than 550°C and a vapor pressure higher than 0.5 mm Hg [7].

However, the technology is not effective at treating soils or other materials contaminated solely with inorganics such as metals (except mercury) or asbestos. It may also not be effective for the treatment of organic corrosives and reactive oxidizers and reducers, depending on the chemical composition of these contaminants. Table 1 summarises the contaminant types for which thermal desorption may be suitable.

Table 3.1: Effectiveness of thermal desorption on general contaminant groups for soil [1, table adapted]

Affect	Contaminant groups		Potential
			Soil
Contaminant groups likely to be affected:	Organic	Halogenated volatiles (e.g. TCE)	1
		Halogenated semi volatiles	1
		Non-halogenated volatiles (e.g. hydrocarbons, low molecular weight PAHs)	1
		Non-halogenated semi volatiles (e.g. oils, high molecular weight PAHs)	1
		PCBs	1
		Pesticides and herbicides (non-metallic)	1
		Dioxins/furans	1
		Organic cyanides	2
	Inorganic	Volatile metals	2
Contaminant groups unlikely to be affected:	Organic	Organic corrosives	3
		Non-volatile metals	3
		Asbestos	3
	Inorganic	Radioactive materials	3
		Inorganic corrosives	3
		Inorganic cyanides	3
	Reactive	Oxidisers	3
		Reducers	3

3.2.2 Treatable Matrices

In situ thermal treatment (ISTT) enables a fast, reliable, and economically viable remediation of source zones. Organic contaminants can be removed from highly permeable, non-cohesive soils, cohesive soils with low permeability and fractured bedrock within a few months.

ISTD can treat a wide range of material and soil types and is particularly suited to treating interbedded fine-grained soils. Clay micro fractures at around 80°C, becoming permeable to gas, thus allowing volatilised contaminants to mobilise under an applied vacuum. Both TCH and TRH have limitations in terms of the thermal and electrical conductivity of the matrix. Basaltic rock is a problem for both methods and TRH has limitations for application to soil containing fresh water, which may not conduct electricity well.

3.1.2.1 Laboratory Screening

The data from each stage of treatability testing should be reviewed and interpreted jointly by the consultant and remediation contractor, with a projection being made of the results that will be achieved under full-scale



operation and requirements established for implementation. Desktop assessment aims to broadly assess the applicability of Thermal Desorption to the general site conditions. In many cases, this stage may be preceded by some testing of discrete soil samples at the site assessment stage as a preliminary options screening, and as part of determining suitable materials for the treatability tests.

Screening tests are usually conducted in a laboratory (in a small oven) and can test a wide range of performance and soil chemical composition and physical factors. Remediation screening is relatively fast to undertake (usually a few weeks or months to obtain results) and the cost is small in relation to the overall remedial program. The tests are usually staged with conditions varied depending on the results of each stage of testing. Setting the data quality objectives for the screening treatability testing at the outset is vital to obtain the desired results. Usually, the main goal of this preliminary treatability testing is to establish the minimum temperature and residence time required to meet the remediation criteria (i.e. remediation yields). Initial screening testing can be undertaken relatively simply by placing a tray of contaminated soil into a laboratory oven capable of reaching the anticipated maximum treatment temperature in a short time frame, to obtain data to assist with establishing the required treatment time and temperature for the thermal desorption unit. Differential bed reactors can also be used where the contaminated medium is placed into an oven in a thin layer and pre heated gas is passed through the medium. Both these tests should generate data that indicate the treatment time required at temperatures to achieve the remediation criteria. The results of this initial testing can be used to indicate the parameters for the next stage of treatability testing. However, they are indicative rather than definitive of the required treatment conditions, involve little quality control and should not be used to derive cost or design data as the chemical composition and physical properties of the soil may vary from that used in the test and therefore, the degree of volatilisation and level of treatment achieved in practice may vary significantly.

TRH is applicable to both the unsaturated and saturated zones providing groundwater flow is not less than 1 ml per day. In this case heat would be removed faster than it was applied, and a cut-off wall would be required. TCH methods may also be applicable to the saturated zone but are usually applied to the unsaturated zone. Some soil types may shrink and swell in the ISTD process, which may be an issue depending on the location **[1]**.

In situ thermal remediation techniques have their advantages which make them ideally suited for the application in build-up urban areas. Nevertheless, soil shrinking should be considered under certain geological conditions, for example with clay soils and soils with high content of organic matter (lab tests necessary). Clay soils may shrink due to desiccation. Organic materials degrade due to heat and are causing a loss in volume and settlement. Risk of soil shrinking, and settlement is not an issue in non-built-up areas, but in urban areas it can be a criterion for exclusion of ISTR. Table 3.2 shows the field of application for the different thermal techniques. In general, the field of application for steam-air-injection are non-cohesive soil types, whereas conductive heating (thermal wells) has its field in dense soils like silt, loam and clay. Radiofrequency has the widest field of application related to the soil types. However, an individual appraisal for each site is necessary. Especially for complex hydrogeological conditions with different layers (e.g., clay and gravel or sand layers) a combination of different techniques may be necessary **[5]**.



Table 3.2: Fields of application of in situ thermal remediation [8]

Espesial field of application		Steam-air-injection (TUBA)	Thermal wells (THERIS)	Radio-frequency-energy (RF)
Unsaturated Zone				
Soil type				
NON-COHESIVE	Gravel	++	o	+
	Sand	++	o	++
	silty sand, sandy silt	+	++	++
COHESIVE	Silt	o	++	++
	loam, marl	-	++	+
	Clay	-	++ to +	+
Contaminants				
CHC		++	++	++
BTEX		++	++	++
Petroleum Range Organics		o	+ to o	+ to o
PAH		-	o to -	o
Saturated Zone				
Soil type				
AQUIFER	Gravel	+ to o	-	o to -
	Sand	++	-	o to -
	silty sand, sandy silt	+	+ to o	+
AQUITARD	Silt	-	+	++ to +
	loam, marl	-	++ to +	+
	Clay	-	++ to +	+
Contaminant				
CHC		++ to +	++ to +	++ to +
BTEX		++ to +	++ to +	++ to +
Petroleum Range Organics		o	+ to o	+ to o
PAH		o	o	o
++ very good + good o partly possible / individual examination - inappropriate boundary conditions due to an economic application. Individual examina. necessary				

3.1.2.2 Feasibility test in static conditions (Tier I)

The feasibility test in static conditions consists of placing a soil sample in an oven brought to a precise temperature and for a well-determined residence time, and this under oxidizing or reducing conditions. Several tests must therefore be carried out in order to carry out a parametric study, following in particular the temperature and the residence time. By varying these two parameters in a well-defined study area (several temperatures and several residence times), we can observe the behaviour of pollutants, in particular their desorption rate.”

It would also be necessary to integrate the monitoring parameters and the following elements:



- a few grams of soil; a few minutes
- Different temperatures and different residence times
- Measurements of pollutant concentrations before and after treatment, measurements of pollutant concentrations in soil gases
- Energy expenditure measures

The cost of first-tier testing can range from \$8,000 to \$30,000, according to the U.S. EPA [4].

3.1.2.3 Feasibility test in dynamic conditions (Tier II)

This test is a continuation of the tests in static conditions. It makes it possible to characterize the nature of the gases generated by the application of the previously selected conditions of temperature and residence time. It has the particularity of placing the soil sample under a sweep of air leading the vapours extracted at the set temperature to a device suitable for their capture and analysis. The analysis concerns the products (solid, liquid, gas) of desorption and possible decomposition which can be recovered by condensation or solubilization in appropriate solvents.”

Feasibility test in dynamic conditions: characterize the vapors extracted under temperature and residence time conditions conducive to desorption: test carried out under the effect of a gas flow imposed by means of a column oven, a tubular furnace or an equivalent device.

It would also be necessary to integrate the monitoring parameters and the following elements:

- A few kg; a few minutes
- Different temperatures and different residence times
- Measurements of pollutant concentrations before and after treatment, measurements of pollutant concentrations in soil gases
- Measurements of gas flow rates and vapor production flows
- Energy expenditure measurements

Second-tier treatability testing may cost in the range of \$10,000 to \$100,000. The second tier of treatability testing might be best left to prospective bidders to perform themselves. [9].

To gain access to the test results, the Navy would require that the results be included with the offerors' proposals. This course of action has the following advantages:

- The thermal desorption system vendors would design and implement the testing according to their own equipment, so the results would be more meaningful.
- The cost of testing could be reduced if vendors already have test facilities and laboratory arrangements.
- The bidders may absorb much or all the cost of conducting the second-tier treatability testing.
- Allowing multiple vendors to run tests simultaneously would be more expedient, and different types of thermal desorption systems could be tested.
- By conducting the testing, themselves, the vendors should have a higher confidence level in the results and be in a better position to interpret them based on their own thermal desorption system.
- Full-scale remediation probably would cost less, because some of the contingency that the bidders would have included for uncertain operational performance could be eliminated.
- There would be a reduced likelihood for change orders later due to claims for unexpected soil behaviour during processing [9].

The test are conclusive for determining the feasibility and to go forward with the field tests.



3.2.3 Regulatory Requirements

The regulatory agencies (particularly the agencies responsible for the protection of the environment, town planning, and licensing treatment facilities) should be consulted to determine the specific requirements relating to obtaining the necessary approvals and licences, and controls that can be expected. The application of thermal desorption is often a matter of concern for the community, and it can be expected that regulatory agencies will be careful in applying their processes for permitting and approval. For more detailed information on regulatory requirements and stakeholder engagement, readers are directed to the NRF Guideline on regulatory considerations and Guideline on stakeholder engagement, respectively [9].

3.3 Bibliography of Chapter 3

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4 IN FIELD TEST

Thermal desorption is a process that directly or indirectly heats contaminants to a temperature high enough to volatilise and separate them from a contaminated solid medium. Thermal desorption is potentially applicable for the treatment of a wide range of volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and even high-boiling-point contaminants - including chlorinated compounds such as polychlorinated biphenyls (PCBs), dioxins, and furans.

Successful design and implementation of a thermal desorption system is dependent on the following key technical considerations:

- physical properties of the medium (e.g., oil) to be treated
- chemical composition of the medium (e.g., soil) to be treated
- groundwater conditions (for in-situ applications), and
- chemistry and concentrations of contaminants [1].

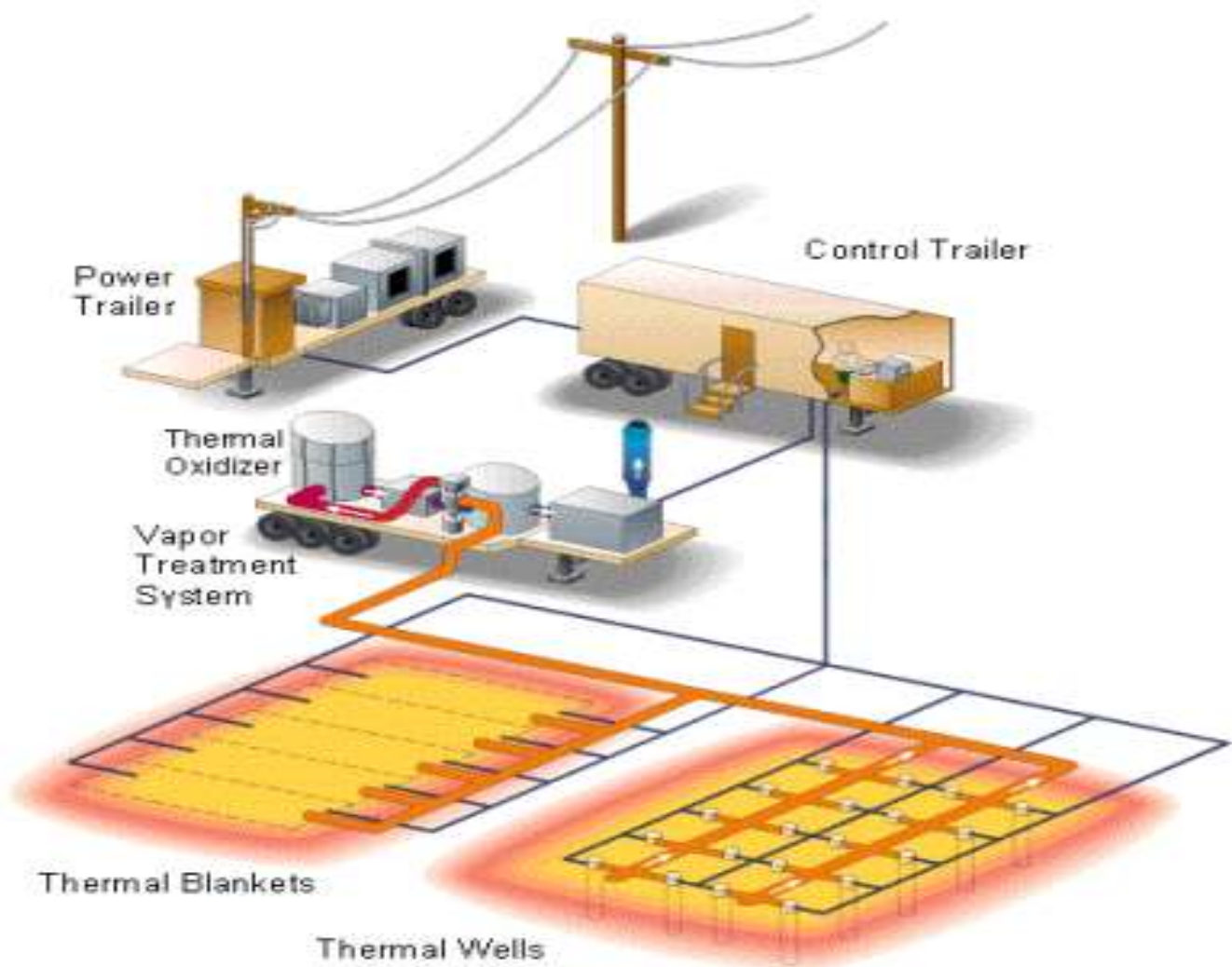


Figure 4.1 Typical elements of an in-situ thermal desorption system - Thermal Desorption process diagram [2]



Type of contaminant, moisture content, contaminant mass and distribution, soil type, grain size and heterogeneity are key factors to consider in assessing whether thermal desorption will be effective. Thermal desorption technology can be applied in-situ, on-site or ex-situ and has been shown to be able to reduce soil contaminant concentrations by over 99%.

Figure 4.1 provides typical elements of an in-situ thermal desorption system.

4.1 Treatability Studies

Thermal Desorption is a volume reduction/waste minimisation treatment technology based on physical and/or chemical processes.

If there is uncertainty as to whether thermal desorption will achieve the desired outcome in terms of treated soil, or if there are other issues that make it uncertain as to whether thermal desorption will prove to be applicable, it may be necessary to conduct treatability tests to resolve the issues. Treatability studies also allow remedial costs and technology efficiency to be better determined.

Designing the treatability study may require input from several technical specialists including environmental specialists, chemical engineers, mechanical engineers, thermal engineers and air quality specialists to ensure that the study is targeted to obtain the data required to enable the most appropriate implementation strategy to be developed.

The type of additional information required can be decided upon by undertaking additional research into the available information on the application of the type of thermal desorption process being evaluated. If the technology has been widely applied and the results are readily available, it may be possible to extrapolate the information from these previous case studies and avoid carrying out a treatability study to assess the technology performance.

The additional information required may be determined by reviewing the published literature and information on case studies on the application of Thermal Desorption [1].

There are generally the following stages of testing that can be undertaken:

- **Bench Tests:** to determine whether Thermal Desorption is a viable treatment solution for the specific site and assess its effectiveness for the site specific conditions and contaminant concentrations. In general, the Remediation Action Plan (RAP) can be designed and written upon completion of this stage.
- **Pilot trial:** to determine specific operating parameters and performance criteria and provide sufficient information to enable completion of the RAP.
- **Process of Treatability Testing in Evaluating a Remedy:** Treatability studies should be performed in a systematic approach.

The data from each stage of treatability testing should be reviewed and interpreted jointly by the consultant and remediation contractor, with a projection being made of the results that will be achieved under full-scale operation and requirements established for implementation. If it has been established that treatability testing is required to adequately assess the application of thermal desorption or to assist in cost appraisals, then there are generally more stages of testing that can be undertaken. Data requirements will be site-specific and may include information such as moisture content and calorimetric characteristics if the soil has a high organic content.



Bench tests comprise the first stage of treatability testing, to assess the ability of thermal desorption to meet the previously established remediation objectives and its applicability to the specific waste type. In many cases, this stage may be preceded by some testing of discrete soil samples at the site assessment stage as a preliminary options screening, and as part of determining suitable materials for the treatability tests.

4.1.1 Bench Tests

Bench testing aims to assess whether temperature (T) T can meet the remediation objectives and its applicability to the specific waste type under the specific site conditions.

The next stage of treatability testing is to evaluate the application of the thermal desorption process for the specific site conditions. This test work is significantly more expensive than the initial screening testing and generally takes several months to plan and implement. These tests have the objective of more closely replicating the physical and chemical parameters of the site under investigation and the specific thermal desorption process being considered. This test work will usually involve much larger soil volumes and a pilot treatment unit. This stage of testing will usually involve multiple test runs, and the samples tested should be representative for site conditions and contamination concentrations, as well as being as homogenous as possible. Moisture content is an important factor that affects volatilisation, and the moisture content of the test samples should be chosen to be representative of the moisture content of the contaminated medium at the site. It will also need to be determined whether to use samples from hot spot areas, representing a worst-case scenario (in terms of contaminant concentrations) or to use composite samples to represent average conditions (perhaps indicative of blended soil) and use this information to extrapolate the expected outcome for the range of material to be treated.

The key objectives for the second stage of treatability testing are to:

- assess contaminant concentrations achieved following treatment (to determine whether the nominated remediation criteria can be met)
- determine the required heat input parameters and average temperatures as well as the residence time required for efficient treatment (While the important objective of this work is to confirm that the level of treatment will meet the objectives, characterisation of the chemical and physical composition of the material to be treated should also carried out)
- estimate the energy consumption per ton of treated soil
- obtain preliminary performance data for the off-gas treatment systems relevant to the contaminated medium. Note that while the separation efficiency will be highly site-specific and process-specific, typically thermal desorption processes achieve separation efficiencies of over 95%.

While the important objective of this work is to confirm that the level of treatment will meet the objectives, characterisation of the chemical and physical composition of the material to be treated should also carried out. Factors such as the variability in water content and calorific value, presence of volatile metals, presence of organic matter, presence of corrosive halides (F, Cl, Br), composition of material after treatment (e.g. residual metals and salts), size fraction and whether the material is of a form that will be handleable (e.g. clayey). The information obtained in the second stage of testing is usually sufficient to enable development of the RAP [1].



4.1.1 Pilot Trial

If insufficient data was obtained during the detailed screening tests to design the RAP, a third stage of treatability testing can be undertaken to obtain information necessary for designing the thermal desorption system, specific to the conditions of the site.

These studies usually take months to complete, and the cost is high so the benefit of obtaining more specific operating design parameters and cost estimates should be weighed against the cost of the overall remedial program.

This testing can be undertaken onsite using a pilot scale treatment unit or using an offsite unit if this is available. On completion of this testing, it should be possible to establish the requirements for the full-scale unit, the time scale for the completion of remedial works, and an improved estimate of the level of cost [1].

4.1.2 Process of Treatability Tests, Techniques and Objectives

The ISTD treatment system consists of an electrical power transformer, resistive heaters, heater wells, vacuum wells, a thermal oxidizer off-gas treatment system, and a process control system. The vacuum maintained in the vacuum wells collects off-gases, which are then piped to the trailer-mounted off-gas treatment system. The off-gas treatment system oxidizes organic emissions, thermal oxidation units to remove trace organics, and, if necessary, activated carbon absorbers to remove any remaining trace contaminants [3].

The remediation of source zones in soil and groundwater attains a high level of importance for the brownfield re-development of contaminated industrial sites. In situ remediation can make an important contribution to construction in existing contexts, insofar as it is integrated into the overall project planning with reliable deadlines and cost figures. Irrespective of the distribution of contaminants¹ at a site, schematically illustrated in Figure 4.2, in situ remediation must frequently lead to remediation success in source zone remediation within a given timeframe – often a period of only a few months [4].

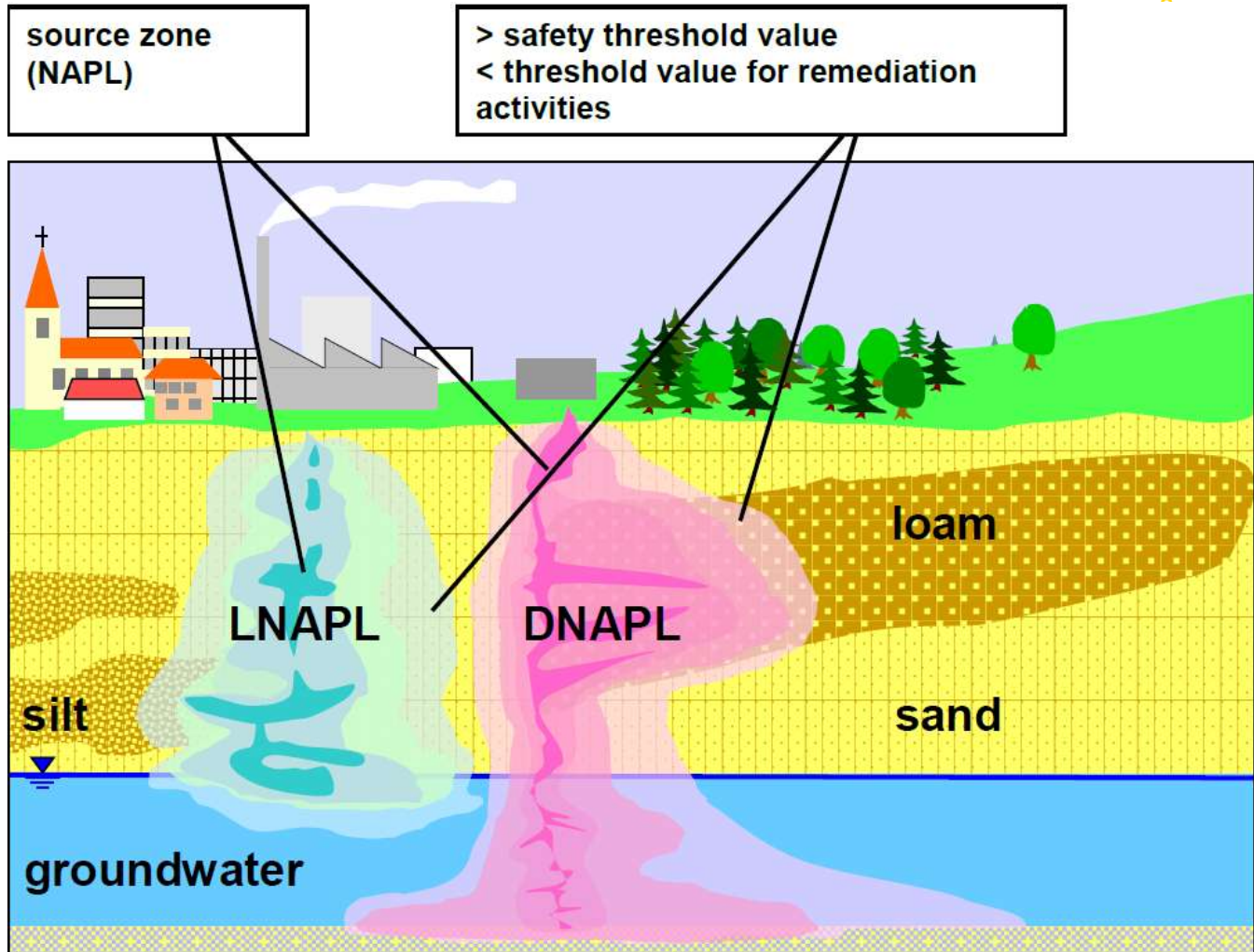


Figure 4.2. Schematic representation of a possible distribution of contaminants in the sub-surface. In situ thermal treatments (ISTT) are focussed on the removal of highly contaminated source zones rather than on the removal of low concentrations in the outer fringe or groundwater plume [4].

Conventional in situ remediation techniques for organic contaminants such as conventional "cold" soil vapour extraction (SVE) or hydraulic groundwater control like "pump & treat" often require several years or decades to clean-up a plot of land due to the diffusion-limited release of contaminants. In situ thermal treatment (ISTT) can provide effective solutions as it allows for the fast decontamination of source zones. Limitations arising from the characteristics of volatile contaminants (e. g. diffusion limitation) and substrates (e. g. inhomogeneity in the soil structure) can be overcome with ISTT by heating the entire remediation volume. Thus, the contaminants vaporise significantly faster, even in areas of low permeability.

The following text describes three types of in situ thermal treatments for efficient source zone remediation: steam-air injection, thermal wells and radio frequency (RF) energy. The described ISTT methods focus on the removal of source zone contaminations by vaporising the contaminants.



(NAPL = non-aqueous phase liquid) in the source zone through sub-surface heating and the subsequent extraction of the gas mixture from the sub-surface by soil vapour extraction. It is normally necessary to heat the sub-surface to 50 to 100°C (Figure 4.3).

Contaminants with a density both smaller and higher than water (LNAPL, DNAPL) can be remediated. Organic contaminants such as chlorinated or halogenated hydrocarbons (CHC, CVOC), benzene, toluene, ethylbenzene, and xylene (BTEX) or petroleum-derived hydrocarbons up to a boiling point of approx. 200°C can be removed by ISTT [HIESTER 2009]. The recovered, contaminated soil vapour is treated by air purification systems.

The described source-zone remediation projects have been executed in coarse-grained unconsolidated soil, cohesive or heterogeneous soil layers or fractured bedrock. Successful remediation has been achieved in the unsaturated as well as in the saturated zone (aquifer and aquitard).

At sub-surface temperatures above 120°C, processes take effect enabling some contaminants to be chemically transformed. Examples are gasification and hydrolysis (above approx. 120°C), steam cracking in the case of benzene derivatives and linear alkanes (above approx. 180°C), torrefaction (in the case of high carbon content) and anaerobic pyrolysis (above approx. 250°C), aerobic cracking or pyrolysis (above approx. 500°C) or sintering (above approx. 1,000°C). Since such temperature ranges are not achieved by the application of ISTT which is described herein, or since the contaminants described vaporise at lower temperatures, these processes are not relevant for a successful application of ISTT [4].

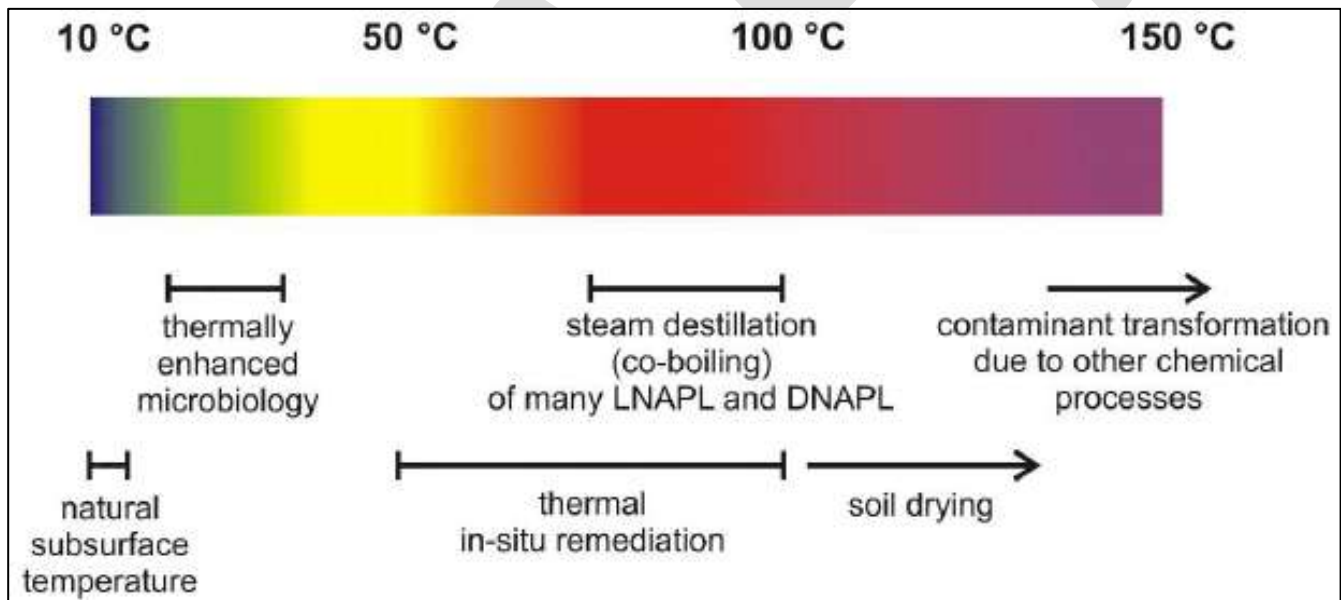


Figure 4.3. Application ranges of sub-surface heating for remediation and fields of application of these guidelines (significant process temperatures between 50°C and 100°C at atmospheric pressure) [4].

The field of application of sub-surface heating, including its use in combination with other remediation methods, is constantly expanding. Besides the ISTT methods presented herein, there are further techniques for sub-surface heating. These techniques include, for example, the injection of warm or hot air (e. g. ProAir technique, ThermoAir technique), the injection of warm or hot water, electrical resistance heating (ERH), sintering at temperatures of 1,600–2,000°C), the Thermopile© technique or thermally enhanced liquid phase



recovery. These applications are only mentioned in these guidelines since the scope of these guidelines would otherwise be exceeded significantly [4].

4.1.3 Sub Surface Heat Input

These design characteristic values, or ranges of values, are typical; the actual characteristic values depend on site conditions and the particular thermal desorption system design.

4.1.3.1 Steam air injection (SAI) test

To heat up the subsurface, preferably a mixture of steam and air is injected into the unsaturated or saturated zone of the contamination source or in its fringe. Less common is the injection of saturated steam (dried saturated water vapour). The convective heat input is dominated by the flow and expansion of the steam portion, while the air portion accelerates and ensures contaminant recovery through soil vapour extraction.

In the unsaturated zone with unconsolidated soil and finely fractured bedrock with good to moderate hydraulic conductivities (K-values) in the range of 10^{-2} to 5×10^{-5} m/s (gravel, sand, coarse silty soils), the injected steam condenses in the cold soil matrix, and releases its energy (enthalpy of vaporisation) to the soil matrix. On account of the ongoing condensation process (until the soil has reached the temperature of the steam), the steam propagates from the point of injection to the steam front. According to the amount of injected steam, a smaller or larger vertical heat front is formed which ideally (at homogeneous sub-surface conditions) expands from the point of injection in a horizontal way and in radial symmetry. In the heated area, the (often) residual, volatile to moderately volatile organic contaminants are vaporised. The air portion supports the contaminant transport towards the extraction wells of the thermally enhanced soil vapour extraction [4].

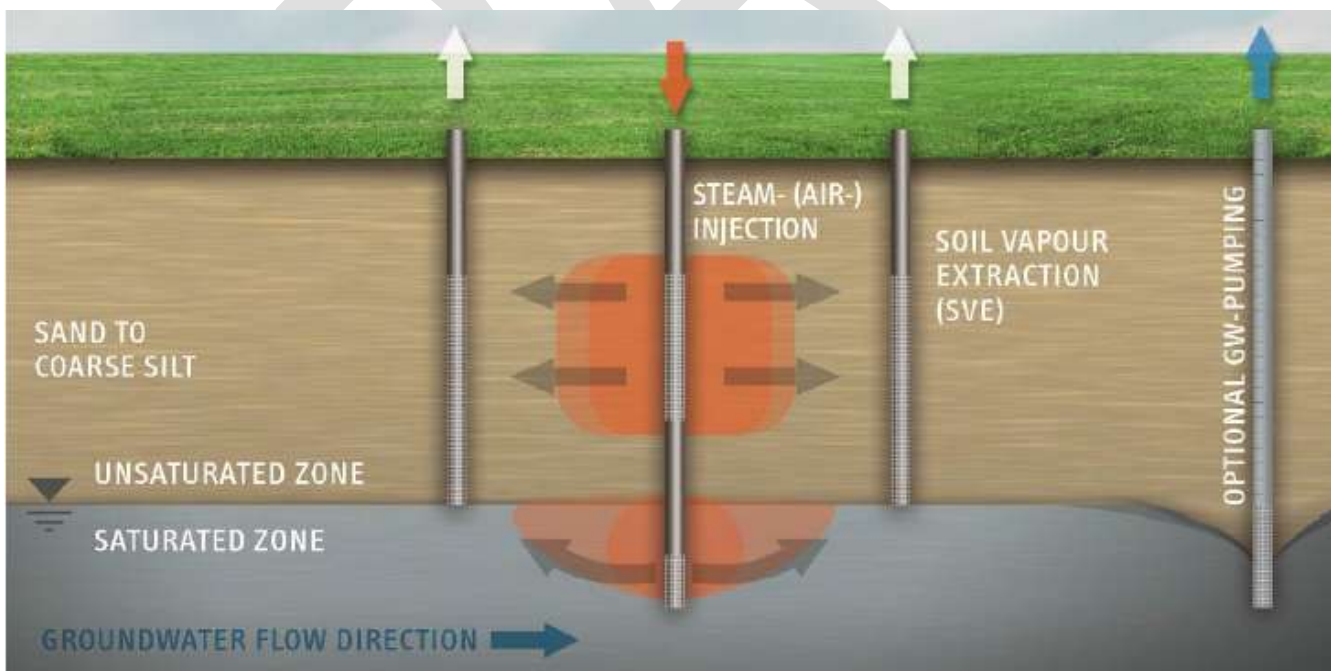


Figure 4.4. Steam-air injection into the unsaturated and saturated zone [4].



When the steam-air mixture is introduced into unconsolidated soil aquifers (i.e., within the saturated zone) with hydraulic permeability between 5×10^{-4} and 5×10^{-5} m/s (ranging from gravelly sands to silty sands), the steam spreads radially from the injection point, ideally forming a steam-saturated zone.

The size of this zone depends on the rate of injected steam and the permeability of the sub-surface. The existing groundwater is partially displaced in this process. The area to be remediated is heated by the ongoing condensation process. Although the steam is usually injected through vertical wells laterally into the aquifer, the steam also expands vertically due to its lower density compared to water. The frictional forces at high injection rates and the anisotropy due to the natural stratification in the porous aquifer (the vertical permeability is mostly lower than the horizontal permeability) act against the buoyant force. Accordingly, a more horizontal steam expansion is achieved, and thus, the achievable radius of influence is augmented. After the penetration of steam into the unsaturated zone, there is no more significant horizontal expansion in the saturated zone. The air injected with the steam flows as a carrier gas from the point of injection to the steam front, integrates the gaseous contaminants, and transports these contaminants from the aquifer upwards into the unsaturated zone. A relatively high proportion of air (10–20 mass %) should be considered to generate a secure transport of the vaporised contaminants from the steam-saturated zone through the saturated zone towards the soil vapour extraction wells. Then, the gaseous contaminants are removed by soil vapour extraction [4].

Continuous thermal desorption systems are more suited to contaminants requiring higher treatment temperatures. Batch thermal desorption systems require somewhat less layout area and less time for mobilization [4].

4.1.3.2 Thermal conductive heating (TCH) field tests: thermal wells

Thermal wells in the shape of electrically operated heating wells can be operated at temperatures of several hundred degrees Celsius and enable the heating of soil stratifications of low permeability by thermal conduction and heat-induced circulation processes. The conductive heat input does not rely on a heat-carrying medium, in contrast to steam injection. The heterogeneity of a subsurface is only of minor importance for the conductive heating of a subsurface since the thermal conductivity of different soil stratifications only varies moderately [5].

Nevertheless, the vaporised contaminants must always be intercepted by soil vapour extraction. Depending on the site-specific location of the source zone as well as the (hydro-) geological situation, it may be appropriate and particularly efficient to arrange the heating elements and soil vapour extraction wells at different depths in the subsurface [5].

The positioning and operating conditions of heating wells and soil air extraction wells may vary significantly depending on the site conditions and remediation goals. For alternating strata of cohesive and non-cohesive stratifications in the unsaturated zone, it has been demonstrated that it may suffice to heat the cohesive stratifications only and to apply soil vapour extraction solely to the non-cohesive stratifications in order to achieve an efficient remediation of the entire soil profile [5].

Also, in the case of cohesive stratifications of several metres of thickness, a direct SVE from the cohesive stratification with vacuum pumps can be efficient [5]. When installing heating elements in the saturated zone, sealing measures for protecting the electrical installations against water infiltration must be implemented. In principle, thermal wells enable the sub-surface to be dried completely and be heated to temperatures $> 100^{\circ}\text{C}$. However, in the fields of applications described in these guidelines, this effect is reached by the THERIS method



only after a long heating period and only close to the heating wells (approx. one to two decimetres around the thermal wells) [5].

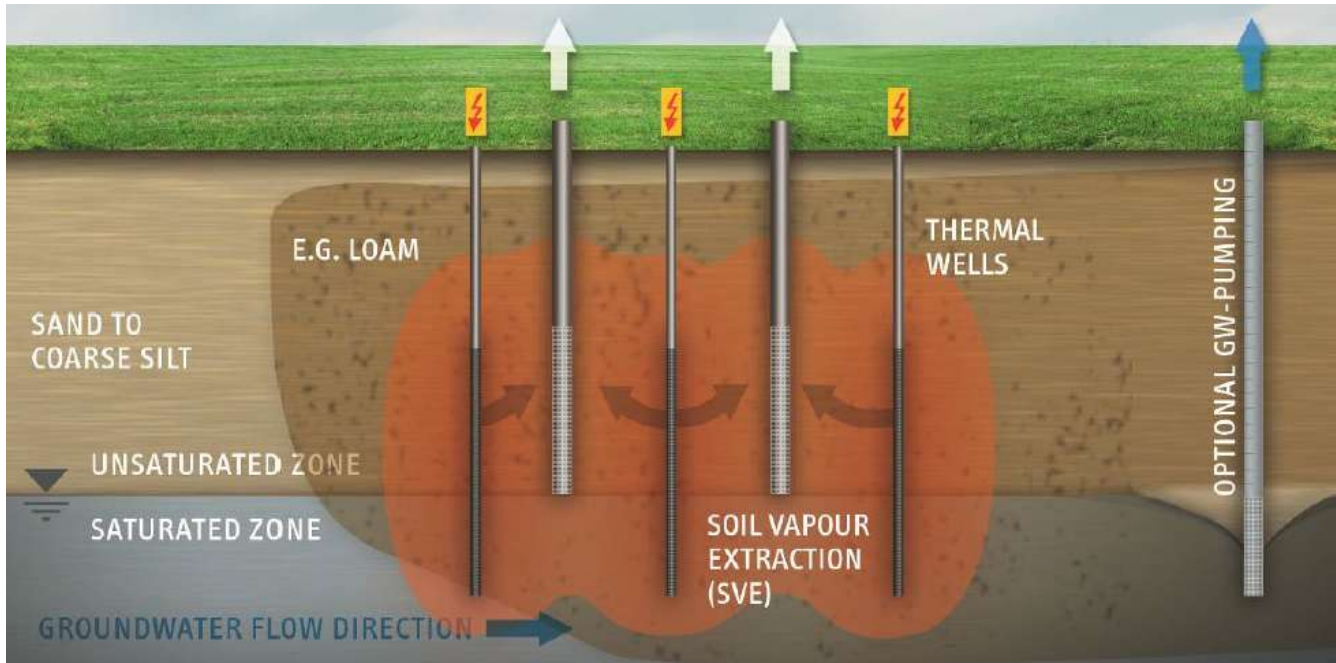


Figure 4.5. Schematic diagram of the Thermal conductive heating (TCH) [4].

4.1.3.3 Radio frequency heating (RFH) test

With radio frequency (RF) energy, the sub-surface (unsaturated and / or saturated zone) is heated by electromagnetic waves, similar to the operating principle of a microwave oven for heating food. Low MHz frequencies (3 to 50 MHz, RF range) are normally used. Dielectric heating on a volume basis does not rely on the availability of water. In comparison to microwaves, the penetration depths of the electromagnetic waves into the medium to be heated are significantly greater and within the technically relevant range of a few metres. Various soils (dry or wet, sandy or silty) can be heated by RF soil heating. In the soil, radio frequency (RF) energy is normally transformed into heat with an efficiency of more than 90 % [6,7]. The RF energy is generated in an RF generator and transferred by an electronic matchbox to the electrode system in the soil (Figure 4.6).

The electronic adjustment maximises the energy input due to the fact that the electrical output returning to the generator is offset to zero. Rod electrodes, plate electrodes or gauze electrodes are used as electrode systems. Rod electrodes that can be simultaneously used as soil vapour extraction wells have been established for thermally enhanced in situ remediation projects [6].

A specific design enables the energy to be transferred to selected depths in order to remediate the contamination in a defined manner (Figure 4.6). Parallel plate or gauze electrodes are effective in enhancing microbiological processes because they allow for a moderate temperature increase at low gradients. In principle, other types of antenna geometry are also available if very selective heating is desired [7].



In this case, the RF energy is introduced into the soil with the aid of a coaxial cable via the cable's unshielded area. In situ oxidation using catalysts directly placed within the electrode (acting simultaneously as extraction well) is also possible as part of the RF method under certain conditions (sufficiently high concentrations of hydrocarbons in waste air) [8].

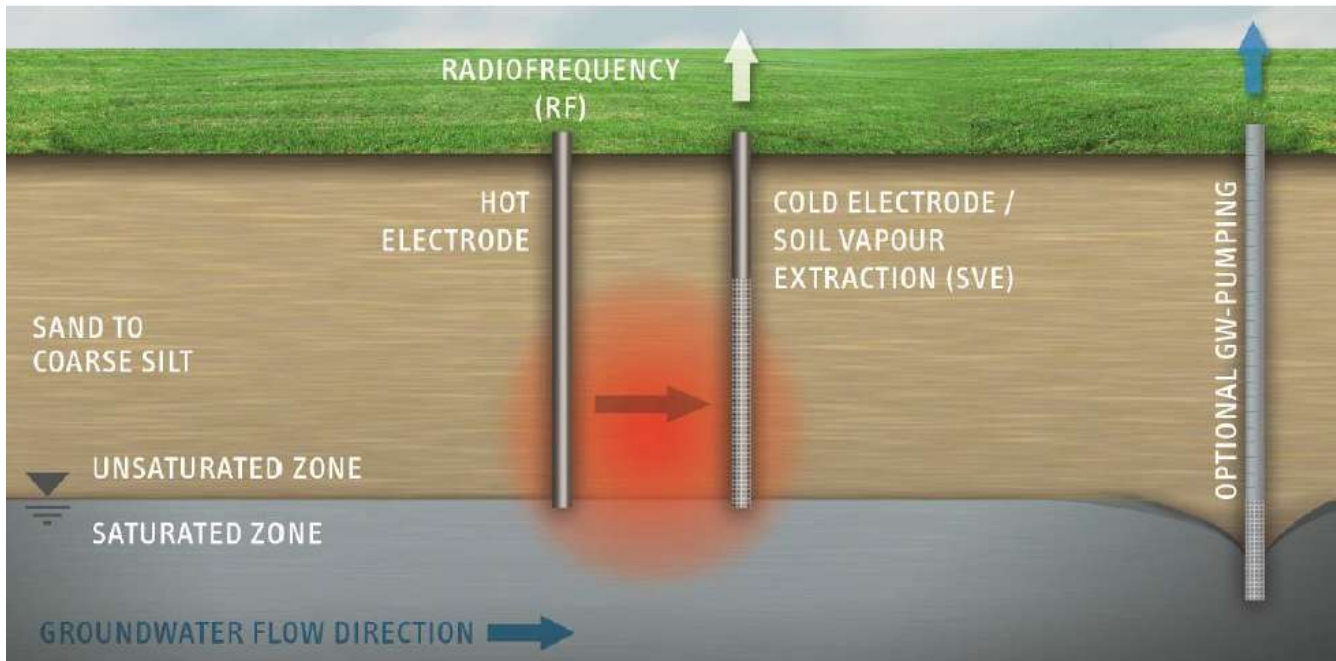


Figure 4.6. Schematic diagram of the Radio frequency heating (RFH) method [4].

4.1.4 Influence of important processes and site conditions on remediation operations

4.1.4.1 Phase transitions (liquid – gas – liquid)

In this case, the RF energy is introduced into the soil with the aid of a coaxial cable via the cable's unshielded area. In situ oxidation using catalysts directly placed within the electrode (acting simultaneously as extraction well) is also possible as part of the RF method under certain conditions (sufficiently high concentrations of hydrocarbons in waste air) [8].

In the case of in situ thermal treatment, the processes of phase transition between the liquid and gas phase are in many cases more important than the substance properties of the liquid contaminant. Substances with a vapour pressure of > 70 Pa at standard ambient temperature and pressure (SATP) are considered to be volatile. In an ideal two-phase liquid-air system, the phase transition can be described by the vapour pressure (p_v) which increases exponentially with the temperature T . For example, vapour pressure can be calculated for pure substances by using the ANTOINE or WAGNER equations. The substance-specific coefficients (A, B, C) can be found in [9] for example. When contaminated wet soil is heated, the NAPL is vaporised together with water (steam distillation). The vapour pressures (p_v) of the two immiscible phases "water" (index W) and "contaminant" (index NAPL) are combined in the process [Equation 1] to form the co-boiling vapour pressure p_d . The co-boiling vapour pressure always exceeds the vapour pressure of the low boiling phase (often water).



The co-boiling temperature (azeotropic temperature), therefore represents the optimum of the substance transfer from the NAPL to the gas phase.

$p_v = \exp(A_w - B_w / (C_w + T)) + \exp(A_{NAPL} - B_{NAPL} / (C_{NAPL} + T))$	Equation 1
--	-------------------

During the steam distillation of the components water and contaminant, the pressure dependent boiling temperature of the mixture in the open system (in this case: soil structure pores) is always lower than the boiling temperatures of the individual substances. As an example, the vapour pressure curves of PCE (tetrachloroethene) and water, in addition to the vapour pressure curve for co-boiling (PCE with water), are illustrated in Figure 4.7

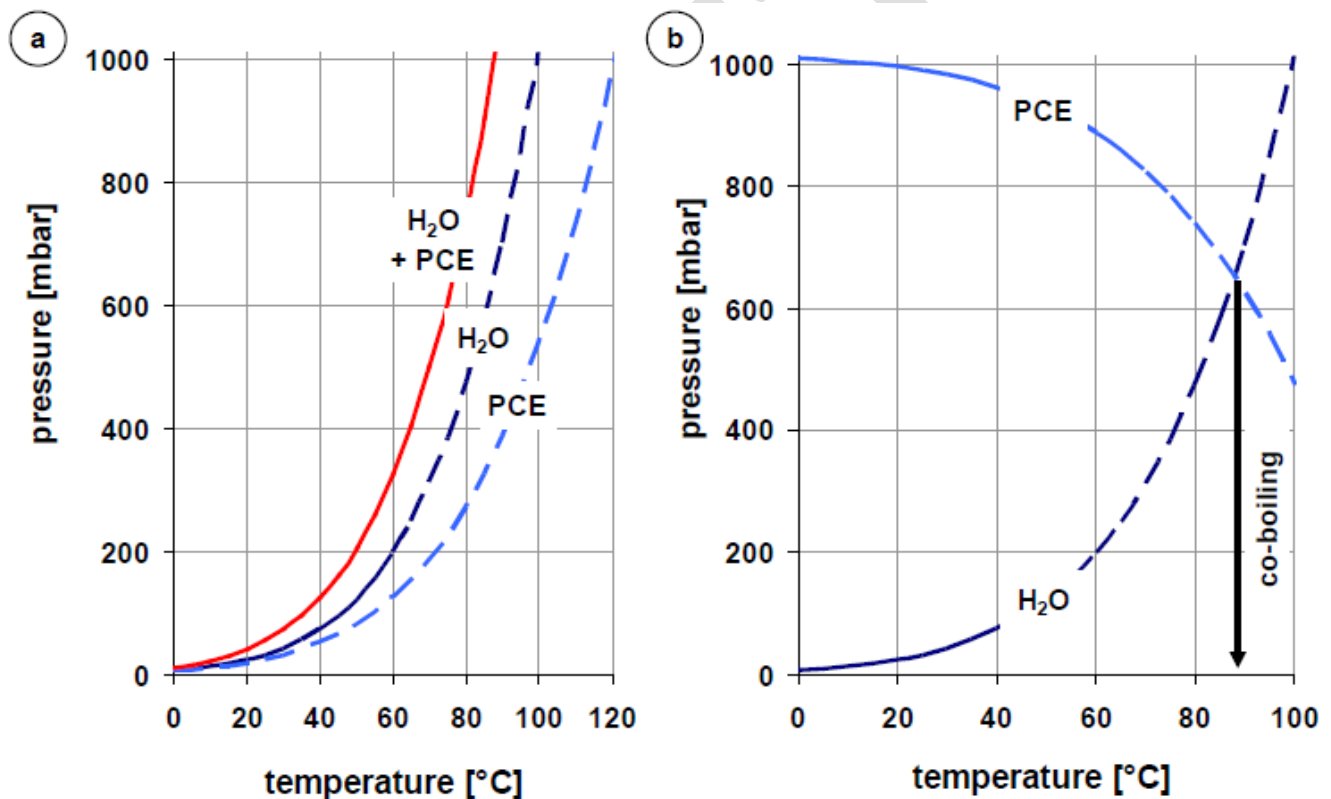


Figure 4.7. Vapour pressure curves of water and PCE [4];. Figure 4.7 a) illustrates Vapour pressure curve of the single substances (H₂O, PCE) and the mixture (H₂O + PCE) at co-boiling (azeotrop); Figure 4.7 b) Determination of the co-boiling temperature of PCE and water according to the method of Badger-McCabe [10]

To illustrate this process, it is possible to express the relationship of the vapour pressure of the water-contaminant mixture to the water-vapour pressure at normal pressure and on a temperature-dependent basis in form of the NAPL pressure coefficient (Table 4.1) [5]. For contaminants with a boiling point of approx. 200°C, the NAPL pressure coefficient is approx. 1 since the co-boiling only leads to slight decreases of the water-vapour pressure. Consequently, the process of steam distillation for contaminants with boiling points > 200°C is of minor importance.



Within the radius of influence of a soil vapour extraction operated with several hundred millibars of vacuum, the co-boiling temperature can be reduced for Chlorinated Hydrocarbons or Benzene Toluene Etylbenzene Xylenes contaminations by approx. 5–8°K.

In the saturated zone, a steam-saturated zone must be formed initially to vaporise contaminants. For this purpose, the energy losses arising through ISTT in the saturated zone by groundwater intake or groundwater pumping must be considered. Additionally, the hydrostatic pressure must be considered. The latter increases the boiling temperature of water and contaminants proportionally to the depth underneath the groundwater surface. This increase in temperature can amount to several degrees Celsius (Kelvin) compared to atmospheric conditions.

Table 4-1. Boiling temperatures and co-boiling temperatures of selected contaminants at normal pressure, derived from the source [5,9].

Contaminant	Boiling temperature of the contaminant	Co-boiling temperature with water (azeotrop)	NAPL-pressure-coefficient
	[°C]	[°C]	[-]
1,2-cis-dichloroethene	60	55	6,0–10,0
trichloroethene	87	73	2,8–3,9
benzene	80	69	3,4
toluene	111	84	1,8
tetrachloroethene	121	88	1,6–1,8
(m-) xylene	139	93	1,3
mesitylene, trimethylbenzene	165	97	1,1
dichlorobenzene	180	98	1,08
naphthalene	218	99	1,0

For mixtures consisting of several individual contaminants, the partial vapour pressure can be calculated according to RAOULT from the sum of the products of the mole fraction and the individual substance vapour pressure [11].

A simplified estimation of the boiling temperature of the mixture can be made on the basis of the vapour pressures of the remediation-relevant contaminant with the highest boiling temperature and water. The transition of the contaminant dissolved in the pore water or groundwater into the gas phase (soil vapour) can be calculated by using the HENRY coefficient. HENRY's law is defined either as the ratio between the partial pressure of the substance in the gas phase and the concentration in the aqueous phase, or as the dimensionless ratio of the equilibrium concentrations in the gas and liquid phase [12].

Accordingly, the volatility of a substance is a function of the HENRY coefficient (contaminants dissolved in water), the solubility in water and/or the vapour pressure (contaminant phase). This function depends on the pressure, the temperature and other water constituents like salts. An increase in the vapour pressure increases the solubility of the contaminants in the pore water or groundwater. A comprehensive collection of substance property data for calculating the temperature-dependent HENRY coefficient was compiled by SANDER [13].



4.1.4.2 Drying behaviour, relative permeability, transport processes

As a consequence of the subsurface heating and the water vaporisation, a humid soil tends to dry during an ISTT. In this process, the proportion of air-filled pores increases compared to the proportion of liquid-filled pores. During the steam injection, this effect is mostly compensated by supplying water vapour. Local drying effects can occur if thermal wells or RF applications are used. Because of the drying process, the proportion of vapour filled pores increases, as well as the relative permeability of the gaseous phase and the overall diffusion of the contaminants solved in pore water into the gas phase. In consequence, the contaminant recovery by soil vapour extraction is improved. This effect is more significant in cohesive soil types due to their high water-binding capacity compared to, e. g. unsaturated sandy soil types.

Complete drying processes as part of an ISTT normally occur only during the remediation process and in the close proximity of a few decimetres surrounding the thermal wells or rod-shaped RF probes. Even if ISTT is applied to the saturated zone (aquifer and aquitard), the formation of a steam-saturated zone does not necessarily imply a complete drying process [5]. Particularly in cohesive soils, a non-isothermal circulating air-water flow is induced (heat pipe effect) [14].

This flow of water and vapour is generated by a temperature gradient and the capillary forces in the soil. According to the temperature gradient, the gases flow from the heat source to colder areas. As the gases move away from the heat source, they cool, causing the previously vaporized liquid to condense once the saturation concentration in the gas phase is surpassed. This condensation amplifies the gradient created by vaporization in the liquid phase. Capillary forces can counteract this gradient, allowing pore water to move against the temperature gradient and towards the hotter region.

When ISTT is applied to sandy soils, the heat-pipe effect can be neglected due to the low capillary forces. In contrast, the heat-pipe effect for ISTT in soils with low permeability accelerates the expansion of heat since a convective heat transfer is induced in the direct proximity of the heating wells in addition to the conductive heat transport. Simultaneously, water that has already been heated is fed back into the hot area surrounding the heating elements, causing a significant time delay of complete soil drying [5].

4.1.4.3 Geology, hydrogeology, anisotropy, settlement

The hydraulic conductivity of the subsurface has a significant influence on the operating window of ISTT. While the advective or convective method of steam-air injection requires soils of good to moderate permeability, thermal wells or radio frequency heating can also be used in soils with low permeability.

A source remediation in aquifers containing structures of high conductivity or / and high hydraulic gradients using ISTT is usually less effective due to extensive heat losses. If the Darcy velocity v_f ($k_f \times i$) in unconsolidated soil aquifers exceeds the critical value of 0.5 m/d, a thermo-technical investigation is recommended. The geological structure of the sub-surface is mostly characterised by sedimentation and erosion processes. The thickness of stratified layers can be up to several metres and thus influences both a contaminant migration and the selected thermal treatment method. Thin alternating strata can lead to a dispersed contaminant migration, while thick homogeneous strata of cohesive soils might cause a concentration of liquid contaminant phase (pools). Cohesive soil strata are heated by thermal wells using the effects of heat conduction or by introducing RF energy in order to desorb the contaminants through thermally enhanced diffusion. An external conductive heating of cohesive strata by a steam flow around the layer can be economically viable up to a strata thickness of approx. 1m [15]. Stratifications of unconsolidated soil (sands, silty sands, and gravel) above or below cohesive soil formations and layers can be used for extracting the vaporised contaminants [5].



4.1.4.4 Third-Tier Treatability Testing

In the third tier of treatability testing, contaminated material would be processed through a pilot-scale unit that would be built in direct proportion to an existing or planned full-scale system. Because this testing involves larger equipment than used in the second tier, and the processing of up to several tons of actual material, it most likely would be carried out at the project site. The objectives of this tier of testing would be, to predict to the extent possible, how an existing or planned thermal desorption system would perform on actual site material and to reveal potential problems. Alternatively, it could serve to demonstrate operational parameters and costs that were estimated from the two previous tiers of testing. In view of the time required and the cost associated with this third tier of testing (perhaps several hundred thousand dollars), it would be undertaken only for complex or unusual sites, if at all [16].

The expected results during the treatability tests are as follows [17]:

- Air flow rates extracted from a venting well at different depressions.
- Depressions measured in the ground at different distances from the extraction well.
- The radius of influence of an extraction well and the intrinsic permeability of the soil (if requested)
- The evolution of the pollutant concentration (venting) in the air extracted from the well.
- Extractable mass flows (water or gas)
- Estimation of processing speeds (extraction) and processing duration
- The temperature rise time.
- The evolution of temperatures at different distances over time
- Heating energy supplied over time.
- A characterization of the quality of effluents over time.
- Potential inflows of water underground (infiltration, runoff water, etc.) within the non-residential zone saturated intended alone to be treated.

The treatment test must be carried out on a representative area of the site in terms of pollution (nature and concentration) and geology. The pilot tests described consist of [17]:

- thermal wells: a central extraction well surrounded by at least three heating wells. This module can be completed by other contiguous modules of a central extraction well for three wells of heating with pooling of heating wells.
- monitoring points: a network of thermocouples and pressure sensors is placed between the heating wells to characterize temperature and pressure gradients.
- a surface covering is placed to constitute a vapor barrier, limit losses of temperature and rainwater infiltration.
- a central extraction well, connected to a vapor recovery and treatment device the nature of which depends on the nature of the volatilized pollutants (thermal oxidation processes, photo oxidation, absorption in washing tower, adsorption on activated carbon, condensation)
- a device for measuring and characterizing gaseous emissions, placed at the pilot's exhaust.
- an ambient air measuring device to monitor the effectiveness of capturing the vapours generated.
- The depth of the heating wells is defined so that it allows you to get as close as possible to the source of pollution.



- In case of a complex mixture of pollutants, the floor heating temperature must be set accordingly safe, allowing the least volatile pollutants to be carried away.
- In the event of proximity to the water table, it is important to limit the extraction flow rates to limit depression in the structure which will generate a phenomenon of rising water (approximately 1m / 100mbar of depression).
- The evaluation of the performance of in situ thermal desorption is followed by the reconciliation between the total mass of pollutant (estimated at the Management Plan stage) to be extracted from the impacted area and the mass of pollutants extracted in the gas phase during the test. Tracing the evolution of the mass extracted in function of time until an asymptote is reached makes it possible to determine the limits of the treatment. This treatment performance is verified by soil sampling and analysis before, during and after the treatment.
- The flows of pollutants generated are quantified in such a way as to allow the sizing of the treatment of gas.
- Energy consumption can be translated into a finite element model to visualize the evolution of the temperature in the ground and over time.

4.1.4.5 Exemplary fields of application and project Performance Examples

Tables 4.2 summarize the performance of thermal desorption technologies on a variety of projects performed across Europe [18].

The list of projects is not intended to be all inclusive but is intended to show typical performance achievable.

Table 4.2. Overview of some completed thermal in situ remediation projects in Europe [17]

Case Studies	1	2	3	4	5	6	7	8	9	10	11	
General Information												
Thermal Method	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Steam Air injection	Steam Air injection	Radio Frequency Heating	Steam Air injection	Steam Air injection	Radio Frequency Heating	
Location	Odense, Denmark	Skuldelev, Denmark	Reelslev, Denmark	Zwölfaxing, Austria	Idstein, Germany	Schwenningen, Germany	Zeit, Germany	Manston, Kent, UK	Karlsruhe, Germany	City of Lanshut, Germany	Zeit, Germany	
Pilot test or Full scale	Full Scale	Full Scale	Full Scale	Full Scale	Pilot Test	Pilot Test	Pilot Test	Full Scale	Full Scale	Full Scale	Full Scale	
Company and year	Kruger A/S, 2008	Kruger A/S, 2008	Kruger A/S, 2008	Reconsite, 2010	Reconsite, 2010	Schwenningen+ Vegas, 2009	Vegas, 2008	Ecologia, 2010	Zublin, Umwelttechnik GmbH, 2010	Reconsite, Bauer, Umwelt, 2008	UFZ, 2008	
Site characteristic	Dry cleaning facility in operation	Residential area	Residential area, graveyard	Former dry cleaning facility	Former leather facility	Former incineration plant for liquid organic waste (CHC, BTEX)	Former hydrogeneration plant benzol factory	Decommissioned petrol station	Former dry cleaning company, remediation under historical building, built in 1547	Former dry cleaning company	Former hydrogeneration plant	
Hydrogeology												
Hydrogeology	Clay, sand, saturated and unsaturated	Clay, sand, saturated and	Clay, dry, sand, unsaturated	Silt, sand, clay, unsaturated	Medium clay, unsaturated	Fractured sandstone, saturated, unsaturated	Gravel, coarse clay, unsaturated sand, saturated	Sandy clayey flint, brick gravel porosity 39%, unsaturated	Fracture zone, coarse clay, fine and medium sand, gravel saturated and unsaturated	Gravel, clay, sand, unsaturated, saturated		
Estimated hydraulic conductivity	Clay 1,00E-9 Sand 5,00E-9	Clay 1,00E-9 Sand 5,00E-9	Clay 1,00E-9 Sand 5,00E-9	Clay 1,00E-9 Sand 5,00E-9	Not measured	Not measured	5,50E-05	Sand, clay 0,50 E-4	Coarse clay, 1,00E-5 Sand, 3,00E-4 Gravel 5,00E-3			
Contaminants												
Type	PCE, DNAPL	PCE	PCE	Mostly PCE	Mostly TCE	CHC	BTEX (Benzol)	BTEX, TPH	CHC, PCE	CHC, Mostly PCE, TCE), BTEX, TPH	BTEX	
Concentration before remediation	Soil max 13.000mg/kg	Soil max 2.500mg/kg	Soil max 7.000mg/kg	Soil air max 2.500 mg/m ³ GWmax 1500 µg/L	Soil max 160 mg/kg	Soil air max 4g/m ³ GWmax 40 µg/L	Soil air max 60 g/m ³	Soil 3,3g/kg GW 816 mg/L	TPH max 23.500 mg/kg Toluene 20.400 mg/kg Xylenes 38900mg/kg	Soil air max 1700mg/m ³ Soil 3820 mg/kg GW 850µg/L	Soil air 7,9 g/m ³ Soil 11 g/kg Strat a Gw 24 mg/l	Soil air max 90g/m ³ Soil max 250 mg/kg
Remediation target	Soil 5mg/kg	Soil 5mg/kg	Soil 1mg/kg	Soil air 10mg/m ³		Soil air 145mg/m ³	Soil air 3,4g/m ³	Soil 016 g/kg GW 1mg/L	TPH max 23.500 mg/kg Toluene 870 mg/kg Xylenes 480m	Soil air max 10mg/m ³ GW 10µg/L		

Table 4-3. Overview of some completed thermal in situ remediation projects in Europe [17]

Case Studies	1	2	3	4	5	6	7	8	9	10	11	
General Information												
Thermal Method	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Thermal conductive heating	Steam Air injection	Steam Air injection	Radio Frequency Heating	Steam Air injection	Steam Air injection	Radio Frequency Heating
Location	Odense, Denmark	Skuldelev, Denmark	Reelslev, Denmark	Zwölfaxing, Austria	Idstein, Germany	Schwenningen, Germany	Zeitz, Germany	Manston, Kent, United Kingdom	Karlsruhe, Germany	City of Lanshut, Germany	Zeitz, Germany	
Pilot test or Full scale	Full Scale	Full Scale	Full Scale	Full Scale	Pilot Test	Pilot Test	Pilot Test	Full Scale	Full Scale	Full Scale	Full Scale	
Company and year	Kruger A/S, 2008	Kruger A/S, 2008	Kruger A/S, 2008	Reconsite, 2010	Reconsite, 2010	Vegas+ City of Schwenningen, 2009	Vegas, 2008	Ecologia, 2010	Zublin, Umwelttechnik GmbH, 2010	Reconsite, Bauer, Umwelt, 2008	UFZ, 2008	
Site characteristic	Dry cleaning facility in operation	Residential area	Residential area, graveyard	Former dry cleaning facility	Former leather facility	Former incineration plant for liquid organic waste (CHC, BTEX)	Former hydrogeneration plant benzol factory	Decommissioned petrol station	Former dry cleaning company, remediation under historical building, built in 1547	Former dry cleaning company	Former hydrogeneration plant	
Technical Data												
Treatment Area	222	250	1300	540	20	100	135	121	220	362	100	
Depth of treatment	10	7,5	10-12	3-7	5	20	11,5	7,5	8	6 (heater), 10 (injection well)	8	
Treatment volume	1330	1180	11100	1600	100	2000	1500	907	1760	-	500	
Number of heater	45	53	147	70	7	1	3	3	8	120 (heater), 3 (injection well)	1	
Average temperature	100	100	100	69	107	50	75	49,1	92	110	54	
Heating period	105	73	169	290	43	175	252	117	294	90	100	
Remediation Results												
End Concentration	Mean: 0,5 mg/kg Max: 4,4 mg/kg	Mean: 0,0 mg/kg Max: 0,77 mg/kg	Mean: 0,0 mg/kg Max: 0,05 mg/kg	Soil air <10 mg/m ³ GW: 50-200 µg/L	Max 17 mg/kg	Soil air max: 120 mg/m ³ GW max: 180 µg/L	Soil air 0,175 g/m ³ Soil 0,1 mg/kg GW 201 mg/l	- Toluene 0,56 mg/kg Xylene 0,72 mg/kg	Soil air 10 g/m ³ - GW 10 mg/l	- - -	- -	- -
Removed amount of contaminants	4000	400	2350	Soil air 348 GW: 5	19,2	560	6870	945	500	546	660	
Total energy consumption	637.610	567.070	3990.000	564.800	21.500	-	333.000	46749	780000	-	54780	
Specific energy consumption	3500	1418	2350	1600	1120	-	48	49	1560	-	83	
Costs per tons of removed contaminants	-	-	-	-	-	-	-	-	1300	1648	-	
Remediation efficiency	>99	>99	>99	>99	90	95	For soil and soil air :99	>95	>99	-	-	



4.2 Bibliography of Chapter 4

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5 PERFORMANCE MONITORING

The monitoring of ISTD is mainly divided into operational phase monitoring, measures to verify the cleanup of the system, as well as critical criteria for its shutdown.

5.1 Operational phase monitoring

Operational monitoring involves monitoring system parameters and subsurface conditions indicative of proper operation (USEPA, 2014). Monitoring data can be obtained from instruments installed in wells and instruments buried at locations of interest. Buried instruments generally consist of instrument strings (i.e., assemblies of vertically spaced temperature and pressure transducers) installed in boreholes. [USACE, 2014].

Temperature and possibly pressure data are typically monitored in real-time to allow rapid assessment of heating progress and to enable timely calibration of the treatment system. The groundwater and vapour extraction rates and associated Chlorinated Organic Compounds (COC) concentrations are measured using field instruments (such as a Photo ionization Detector, PID), and periodically via samples sent to a fixed-base (offsite) laboratory. A short description of the main parameters that is necessary to consider during routine monitoring is given below.

Temperature is the most critical parameter to be monitored on an TD project, requiring the best resolution. Temperature data have the following uses [USACE, 2014; EPA, 2014]:

- Evaluation of heat migration, distribution, and energy delivery effectiveness to the subsurface.
- Determination of the presence of groundwater (groundwater will be present at locations where the temperature is below the boiling point).
- Estimating steam pressures and evaluating steam flow patterns (when the temperature is above the boiling point, saturated-steam pressure can be calculated directly from the temperature).

Monitoring temperature at multiple depths and multiple locations is recommended. Temperature measuring point sensors are typically thermocouples installed in vertical strings set in the filter packs of injection or extraction wells, in backfilled boreholes between each well. Temperature can alternatively be measured by fibre optic sensors or electrical resistance tomography. A typical vertical spacing for temperature sensors is 1 to 2 m.

In general, there are three types of temperature-measuring locations [USACE, 2014]:

- In or near electrodes, thermal wells, or steam injection wells will show the maximum temperatures being achieved at the site.
- Measuring points between electrodes, thermal wells, or steam injection wells can help determine when target temperatures have been achieved within the treatment zone and if energy penetrates adequately to areas away from electrodes and wells.
- Measuring points at the edges of the treatment zone indicate the achievement of target temperatures to the full extent of the material to be treated.

Pressure data has several uses for ISTD [USACE, 2014]:

- Helping to prevent blowouts, leakage, or fugitive emissions.
- Interpretation of subsurface flow patterns.
- Helping to evaluate if volatilised contaminants are being captured.



A pressure gauge or transducer on the wellhead or associated piping may measure the gas pressure at each steam injection or groundwater extraction well. Installing pressure monitoring points at different depths can measure gas pressures away from extraction or injection wells. Capture of volatilised contaminants is indicated by negative pressures (vacuum) at treatment zone boundaries.

Fluid flows are monitored during conductive heating and ERH operations to estimate removal rates and manage the vapour extraction system.

Chemical testing of extracted fluids provides data for estimating mass removal rates and contaminant destruction rates. The analytical data can also be used to evaluate the overall effectiveness and duration of the treatment [USACE, 2014].

Liquids may be sampled directly from monitoring points or extraction wells via sampling taps on each wellhead. Many useful parameters, such as pH, conductivity/TDS, dissolved oxygen, carbon dioxide, and turbidity, can be measured daily with portable instruments and field kits.

A submerged screen monitoring well may pose a significant risk to samplers. If the well is opened while the subsurface is hot, this provides the conditions analogous to a natural geyser and steam may flash and blow hot water out of the well (IDEM, 2020).

Vapour samples are typically obtained from extraction wellheads. Because a portion of the hot vapour sample will condense when it cools, it is necessary to know the contaminant concentrations in both phases of the cooled sample to determine the original concentrations in the hot extracted vapour.

Electronic sensors are placed in well discharge lines to provide continuous readings of chemical parameters, including total organic carbon, pH, conductivity, and dissolved oxygen. Continuous TOC data are beneficial for tracking contaminant removal trends throughout each operational phase.

5.2 Confirmation of cleanup and system shutdown

The objective of the remediation process is generally the attainment of predetermined quality standards for different environmental matrices. During the operational phase, verifying subsurface concentrations and the real time effects of ISTD is difficult. The presence of pipes and cables makes access to the treatment area difficult. In addition, sampling hot soil and groundwater can pose safety problems (USACE, 2014). Hence, the decision to cease the operation is usually taken based on multiple indicators that consent to an indirect evaluation of ISTD performance.

Possible lines of evidence to be considered as shutdown criteria are as follows:

- Temperature distribution and duration, achieving and maintaining a target temperature throughout the treatment zone, is one the main objectives of ISTD.
- Mass removal and pollutant concentration in extracted vapour and groundwater can provide a gauge of contaminant mass removed and an indication of remedial progress. Concentrations are measured using qualitative (field instruments such as a PID) and quantitative methods (periodically sending samples to a fixed-base laboratory). Removing a certain percentage of the total contaminant mass can be one of the remediation goals. However, the estimation of the percentage of mass removed can be uncertain because of the difficulties in quantifying the present contaminant's mass. However, treatment generally continues until the amount of mass recovered reaches a point of diminishing return. That is, when concentrations approach an asymptotic value and an increase in applied energy does not correspond to an increase in contaminant removal rate.



- Groundwater quality in the vicinity of the treatment area and concentrations of dissolved contaminants in groundwater generally increase in the initial phase of remediation because high temperatures shift the balance between the solid and liquid phases towards the latter. When the boiling point of the contaminant mixture is achieved, groundwater concentrations decline (USACE, 2014). A thorough understanding of the degradation products of the contaminants of concern is useful for developing an effective monitoring program. For example, for some chlorinated ethenes, ethanes and methanes, analysis of chloride concentrations in addition to the parent volatile organic compounds can assist in mass removal calculations, especially when evaluating if applying electrical resistance heating enhanced biodegradation kinetics of the contaminants. Further, elevated temperatures can increase the rate of hydrolysis of many halogenated alkanes, pesticides and energetic compounds (e.g., explosives)” (NJDEP, 2017).
- Isotope analysis can be useful for understanding the transformation phenomena affecting the contaminants in groundwater. Heat-enhanced dissolution, volatilisation, and biodegradation can all determine isotope fractionation. In particular, enhanced dissolution in heat may result in reduced heavy isotopes. On the contrary, biodegradation produces an increase in both ^{13}C and ^{37}Cl . Volatilisation reduces ^{13}C while ^{37}Cl increases (Wanner, 2017; Zimmerman, 2020). Isotope analysis leads to a better understanding of the groundwater monitoring data, from which to make informed decisions on remedial progress and when systems may be shut down (USEPA, 2014).

5.2.1 Confirmation of cleanup

After all thermal units have ceased operation, the attainment of the remediation objectives (a regulatory or risk-based concentration standard) is verified by collecting soil and groundwater samples throughout the treatment zone, specifically targeting source and plume fringe areas. Sampling points should be located, in particular, in areas less impacted by the heating system.

Taking hot samples can pose safety problems. To avoid steam release, particular caution must be exercised when collecting water samples or drilling below the water table or in scarcely ventilated portions of soil. The temperature monitoring systems can reveal when the subsurface has cooled sufficiently to permit sampling. Subsurface temperature, however, may remain elevated for an extended period after system shutdown. Sites generally cool at a rate of approximately 1°C per day (EPA, 2014). If it is necessary to obtain information on the quality of environmental matrices quickly, a hot sampling procedure can be adopted (USACE, 2014).

The comparison between the treatment results and the remediation objectives leads to site closeout or, if concentration standards have not been achieved, to the application of a less invasive technique.

5.3 Bibliography of Chapter 5

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6 CONCLUSION

In the technology In Situ Thermal Desorption, a combination of heat and extraction technologies is applied simultaneously to subsurface soils as part of the soil remediation process. Heat transfer primarily occurs via thermal conduction, a process that gradually elevates the temperature of the contaminated soil. Notably, some contaminants may be destroyed while traversing the superheated soil zone before reaching the extraction wells. Conversely, those contaminants that persist and exist in the gaseous phase are subsequently extracted from the soil.

The ISTD is a versatile method that can be applied in sites where other remediation techniques may be less effective. This includes situations involving clayed soil and cases with diffuse contamination patterns. The overall timeframe for ISTD implementation encompasses various stages, including site preparation, heating, cooling, and continuous monitoring. Costs associated with ISTD encompass expenditures related to equipment acquisition, monitoring systems, and the necessary energy supply infrastructure.

ISTD efficiency is dependent on contaminants and site-specific characteristics. Variations in soil properties can, to some extent, influence the uniformity of the treatment's application. ISTD can successfully address a broad spectrum of contaminants, some of them persistent. Examples of contaminants that ISTD may treat include BTEX, PHC, PAHs or PCBs.

6.1 Advantages/disadvantages & ISTD effectiveness

In situ thermal desorption is effective for a wide range of contaminants and can be tailored to specific conditions, making it versatile for various sites. Unlike traditional excavation or ex-situ treatment methods, ISTD minimises site disruption (no excavation and transport).

By quickly raising the temperature of the contaminated soil to promote the removal of contaminants, ISTD can be considered an efficient method to remediate contaminated sites (compared with alternative methods). However, it is essential to note that the process may require substantial energy, potentially increasing remediation costs and environmental implications. Despite the initial set-up costs and energy expenditure, ISTD may have long-term cost savings by shorter durations or the absence of excavation or soil transport.

ISTD can treat contaminants at significant depths in the subsurface. From the parameters that should be assessed throughout ISTD execution, it is essential to prevent potential contaminant migration (uncontrolled conditions) when contaminants are vaporised. Ensuring effective capture, treatment, and disposal methods is crucial to achieving compliance.

ISTD performance can be affected by depth constraints or non-volatile compounds. These limitations may need complementary remediation approaches to address a broader range of environmental contaminants or to address any residual contamination. Additionally, after the heating process, some soil properties may be altered, which should be considered according to the site's future use. Meeting environmental regulations can be challenging, as it requires careful management of the treatment and control of vaporised contaminants, emissions, and potential impacts on neighbouring properties.

ISTD may provide long-term effectiveness in controlling and reducing the risk of contaminant migration. It can treat both the source of contamination and the surrounding impacted areas. In situ thermal desorption



systems may also often include real-time monitoring and control mechanisms, allowing for adjustments to optimise the remediation process and ensure its effectiveness.

6.2 Operational control for ISTD application

Operational control for ISTD encompasses various critical aspects to ensure effective soil remediation while minimising risks and environmental impacts. This includes temperature control to maintain specified operational ranges, monitoring of heat distribution to assess to ensure uniformity and prevent cold spots, adjustment of vacuum levels (if needed) to efficiently remove vaporised contaminants from soil, and guaranteeing adequate residence times to ensure contaminant destruction or vaporisation at target temperatures.

Concomitantly, enhancement of bulk permeability, especially in impermeable soil layers and convection enhancement promoting the flow of air and vapour into the treatment zone should be promoted. Cross-cutting measures include safety protocols to monitor potential hazards like gas emissions and overheating, regulatory compliance, periodic checks to verify technology effectiveness, compliance with remediation goals and potential closure.

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