European Union Network for the Implementation and Enforcement of Environmental Law

COMMON FORUM

NICOLE
Network for Industrially Co-ordinated Sustainable Land Management in Europe

Working Group Contamination
EIONET

In-situ Thermal Desorption (ISTD) monograph

Final Report

Date of report: 11 December 2024
Report number: 2022/11 ISTD EN

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.

Information on the IMPEL Network is also available through its website at: www.impel.eu

Suggested citation:
Falconi M. et al. (2025), In Situ Thermal Desorption Monograph. IMPEL, COMMON FORUM, EIONET, NICOLE report no 2022/11 ISTD, 342 pages. Brussels, ISBN 978-2-931225-35-6

ISBN 978-2-931225-35-6
9 782931 225356

Title of the report: In-situ Thermal Desorption (ISTD) monograph	**Number report:** 2022/11 ISTD EN
Report adopted at IMPEL General Assembly Meeting: Budapest 27-29 November 2024	**Total number of pages:** 342 **Report:** 56 pages **Annexes:** 286 pages

Project Managers:

Marco Falconi (IT)	IMPEL	ISPRA
Dietmar Müller-Grabherr (AT)	Common Forum	Umweltbundesamt AT
Frank Swartjes (NL)	EIONET WG Contamination	RIVM
Wouter Gevaerts (NL)	NICOLE	Arcadis

Authors:

Stefan Colombano (FR)		BRGM
Nazaré Couto (PT)		CENSE
Pavlos Tyrologou (GR)		CERTH
Eleni Gianni (GR)		CERTH
Marco Falconi (IT)	IMPEL	ISPRA
Federico Fuin (IT)	IMPEL	ARPA VENETO
Gokberk Kara (TR)		RSK
Antonio Laganà (IT)	IMPEL	ARPA VENETO
Dietmar Müller-Grabherr (AT)	Common Forum	Umweltbundesamt AT
Iustina Popescu (RO)		Geological Institute of Romania
Joao Silva (PT)	IMPEL	Inspeção Regional do Ambiente - Açores

Contributors to Annex 1 ISTD:

Laura Bieber (DE)	RECONSITE
Léa Deceuninck (BE)	HAEMERS TECHNOLOGIES
Ysaline Depasse (BE)	HAEMERS TECHNOLOGIES
Willian Felipe Do Prado (BE)	HAEMERS TECHNOLOGIES
Hans-Georg Edel (DE)	ZÜBLIN
Christian Gambelli (IT)	GREENTHESIS
Antonio Greco (CH)	CSD INGENIEURE
Uwe Hiester (DE)	RECONSITE
Malte Horstmann (DE)	HANSEATISCHES UMWELTKONTOR
Rabih Jenadri (BE)	HAEMERS TECHNOLOGIES
Aline Jordens (BE)	HAEMERS TECHNOLOGIES
Daniel Klopp (DE)	ZÜBLIN
Yannick Loliver (BE)	HAEMERS TECHNOLOGIES
Maël Makoudi (BE)	HAEMERS TECHNOLOGIES
Thomas Meyer (DE)	ZÜBLIN
Frederik Mönter (DE)	ZÜBLIN
Jean Rhone (BE)	HAEMERS TECHNOLOGIES
Niklas Rigol (DE)	ZÜBLIN
Edoardo Robortella Stacul (IT)	INVITALIA
Alessandro Teani (IT)	GREENTHESIS

Laurent Thannberger (FR)	VALGO
Oliver Trötschler (DE)	VEGAS UNIVERSITY OF STUTTGART
Reviewers:	
Uwe Hiester (DE)	RECONSITE
Florian Ludwig (DE)	ARCADIS
Nicolas van Tilburg Bernardes (BR)	RMC2

Executive Summary

Keywords
In Situ Thermal Desorption, Source Zone Treatment, 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 Water and Land Remediation (2020/09) project 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.

Some countries, regions, or local authorities may have also 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.

Marco Falconi – IMPEL
Dietmar Müller Grabherr – COMMON FORUM on Contaminated Land in Europe
Frank Swartjes – EEA EIONET WG Contamination
Wouter Gevaerts – NICOLE

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
'*in-situ* 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 remediaton, 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

TABLE OF CONTENTS

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, the 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 in situ thermal desorption (ISTD) knowledge. More generally, all technologies used for situ thermal remediation/treatment (ISTR/ISTT) induce heat (a rise of temperature) in the subsurface treatment zone to increase mobility and/or destroy contaminants **[1].**

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 remediate the medium more efficiently by either vaporizing the chemicals, enhancing the chemical degradation, increasing the solubility or the mobility of the chemicals. 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, assessing 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 Thermal Desorption	**Ex-situ Thermal Desorption**
Advantages	Effluent treatment and monitoring systems occupy a small area	Processing on the ground, easy to control the entire process
	Less secondary contamination	Easy to specify whether the soil reaches the standards
	Saving costs due to the lack of need for soil excavation, transportation and backfilling procedures	Easy pre-treatment
	No need for excavation as it can be used under existing infrastructure	Easier to implement higher temperature applications due to more controlled energy losses

Disadvantages	Difficult to predict and control underground processes	An ex-situ restoration site is needed, that may occupy a large land area
	Uncertainties in determining the treatment endpoint	Excavation and transport of contaminated soil is needed. Thus, contaminantmay duffuse. 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 on larger scales	When direct TD is used, it may produce harmful pollutants due to exhaust gas combustion. Improper operation may produce carcinogens and dioxins.
	More susceptible to site underground characteristics	It cannot be used under existing buildings and structures.

In situ thermal desorption is a remediation process in which heat is applied to the subsurface soils to change the contaminant characteristics, enabling a more effective pollutant removal mechanism. 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 surface[6] 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 **[2]**.

The low-temperature ISTD is suitable for treating a wide range of contaminants in soils, including both volatile and semi-volatile contaminants. At the same time, TCH high-temperature applications may also be 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 the site-specific contaminants of concern **[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, for high-temperature applications (>100°C), most contaminants undergo volatilization while traversing to the extraction wells through the superheated soil zone. As the soil undergoes heating, the resulting vaporized water, contaminants, and some volatilised inorganic compounds are directed counter-currently to the

---

[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]**.

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.

1.2 ISTD applicability

ISTD may involve destroying or removing contaminants present in the 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 (TCH) process, the transportation of vaporized contaminants is enhanced due to increased 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 vapour extraction wells **[6]**. ISTD demonstrates versatility in treating a diverse array of materials and soil types, offering a distinctive advantage in its ability to remediate clay-rich soils efficiently. At temperatures of approximately 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 volatile organic contaminants (VOC), including but not limited to benzene, toluene, ethylbenzene, and xylene (BTEX); naphthalene and phenanthrene; total petroleum hydrocarbons (TPH) 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. Furthermore, ISTD can be applied with mobilisation and enhancing the extraction of light oil phases (LNAPL) captured at the capillary fringe and in low permeability soil layers.

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, lowe temperatures (below 100 °C) are suitable for addressing gasoline, benzene, TCE, and PCE contaminants, while higher temperatures (up to 300 °C) are necessary for effectively treating diesel, naphthalene, and certain PAH compounds. At even higher temperature ranges, destruction processes are becoming governing processes and may allow the treatment of 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, some ISTD applications use an extraction and treatment system, working simultaneously to remove contaminants and treating them for the correct destination/disposal.

Contaminants need to be exposed to target temperatures sufficiently long to guarantee their effective treatment. 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 heaters, generating the necessary heat for the process; temperature sensors and control panels for temperature monitoring and control; vacuum pumps and extraction wells for the extraction of 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. Extraction wells may function as horizontal barrier systems when entirely located around the treatment zone.

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.

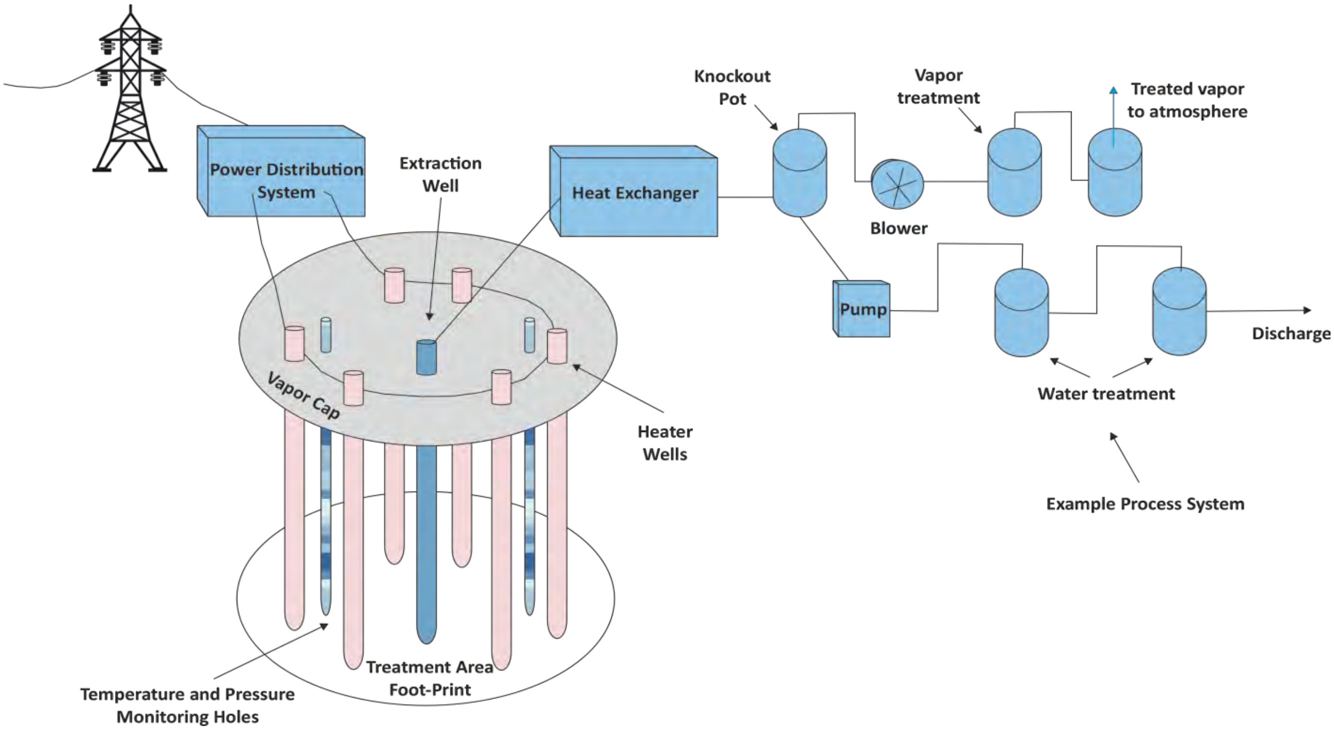


Figure 2.1 – In situ thermal desorption by thermal well utilising the thermal conduction heating (Based on [8]).

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

1. A container power distribution system can 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 heat loss to the atmosphere and protecting cooling rainwater from passing through the heated zone. It is made of transparency or lightweight concrete. Site-specifically and depending on the technique used plastic liners can be considered.
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 using 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]** at temperatures > 120 °C (see 2.1). A further application of ISTD technologies is the combined use of thermal conductive heating (TCH) to enhance oil phase extraction and recovery.

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. In contrast, the upper limit for LTTD gets referenced at temperatures where desorption is the crucial process (< 120 °C) and the lower boundary line for HTTD is usually within 300 to 350 ˚C **[4, 10]**. In lower temperatures, where the LTTD takes place, treating VOCs with low boiling points (< 200 °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]**.

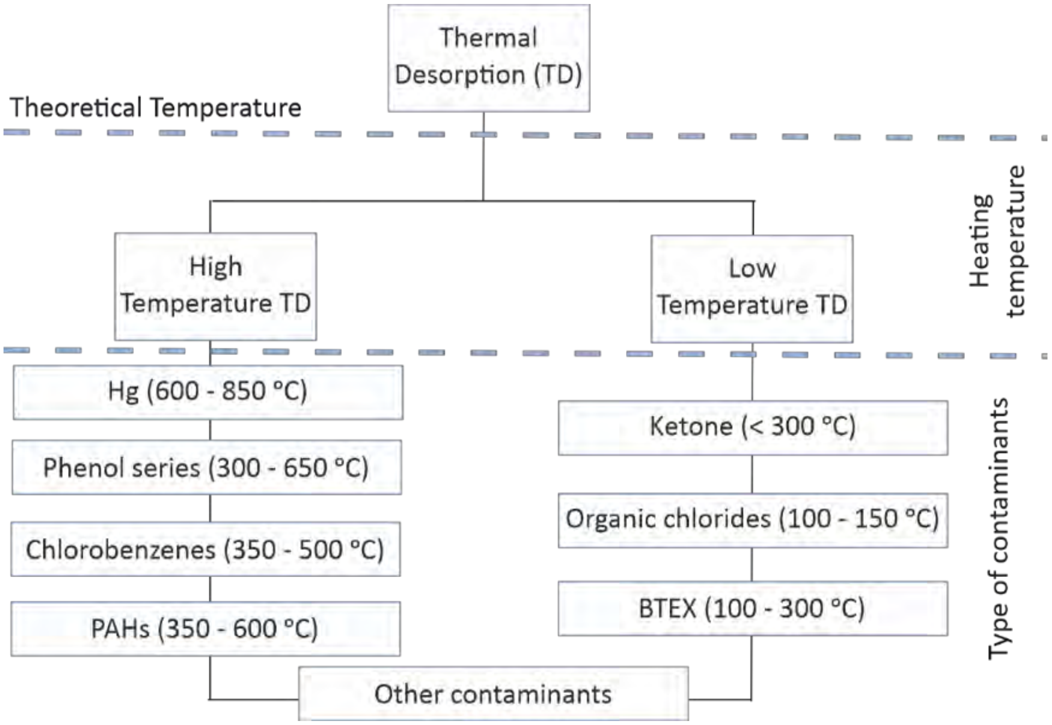


Figure 2.2 – Theoretical temperatures for the decontamination of specific components via Thermal Desorption (based on [4]).

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 heat to the contaminated area through 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 remediating a contaminated area.
3. Based on Joule's law, electrical resistance heating (ERH) 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 %. If the target temperature is above water boiling point, water management needs to be considered as all as water needs to be vaporized to achieve target temperature.
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 3-8 months.
4. It is characterised as a relatively stable process.
5. No excavation is needed, which also minimises any secondary environmental impacts in terms of traffic (mass transport via trucks)
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 the water table (saturated zone, groundwater).
13. It is unlimited about the contamination depth.

3 FEASIBILITY STUDY

Knowledge management and technical innovations are some of the keys to achieving sustainable remediation, especially since subsurface is getting busier.

In urban environments, many contaminations, such as chlorinated solvents are often mixed and spread underneath buildings. This leads to technical problems for remediation and liability and financial discussions, impacting society. An integrated 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 methods for many sites if the feasibility session is studied perfectly **[2].**

In more detail, volatile, semi-volatile and non-volatile organic contaminants in the soil are mainly vaporized or even destroyed in some very special situations. The main physical mechanisms are evaporation, dissolution and steam distillation, but even oxidation and pyrolysis (chemical decomposition in the absence of oxygen) can occur. In most cases, contaminants are vaporised (as they are with some chlorinated solvents) and extracted via an extraction system.

Feasibility techniques based solely on the transport of fluids to deliver reagents or remove dissolved contaminants are dependent on (amongst other factors) the permeability of the 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 diffusion limits the emission of contaminants from low permeable zones into high(er) permeability zones, where the air and groundwater flow takes place. 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 in removing 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 uniform heating and subsequent treatment within a contaminated zone **[23].**

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 **[23].**

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) **[2].**

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, ISTR focuses on mitigating source zone contamination by heat-enhanced removal of contaminants using an aboveground extraction system. For the typical organic contaminations (with density smaller and higher than water (LNAPL, DNAPL), it is necessary to heat the sub-surface to temperatures ranging from 50°C to 100°C. The destruction of some contaminants like PCB can be achieved at higher temperatures. The extracted contaminated and partially hot soil gas mixture must be 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

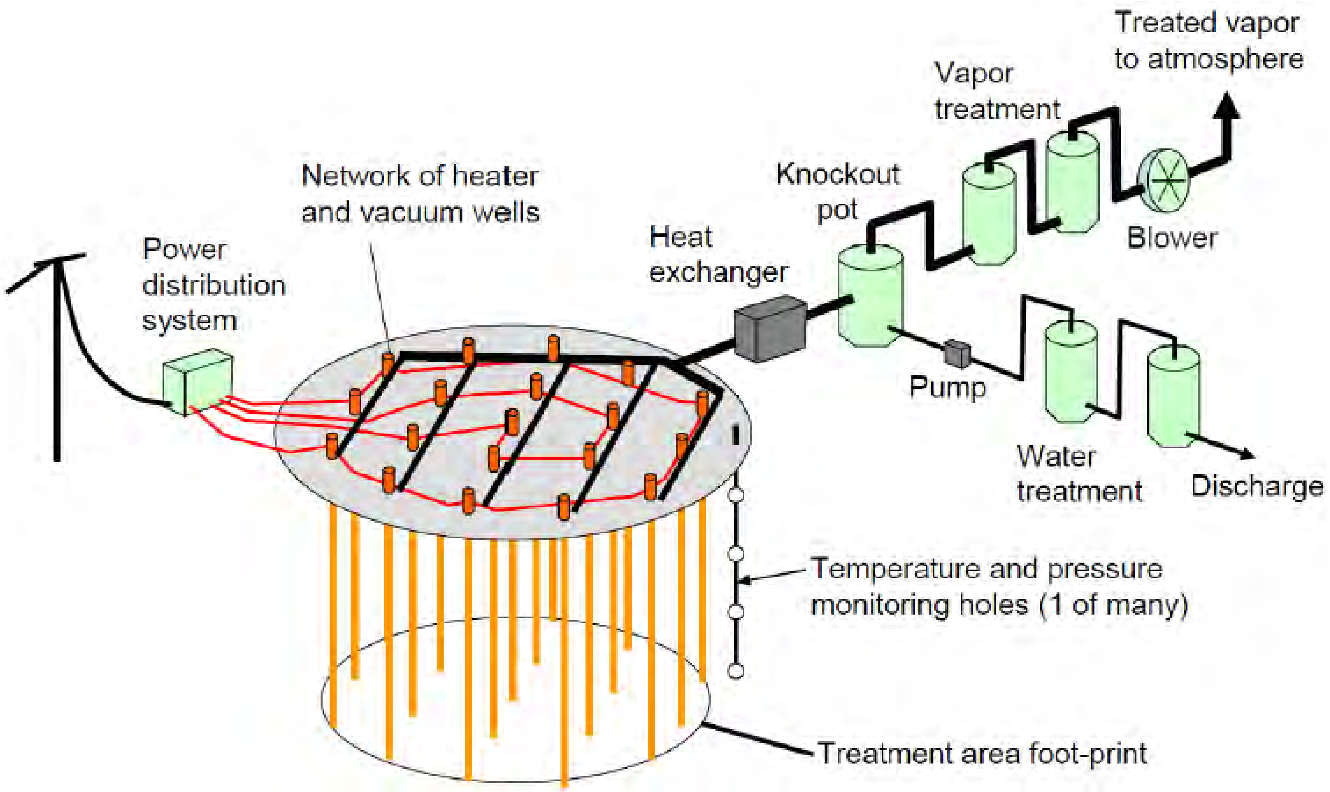


Figure 3.1. Conceptual design of a thermal conduction heating application [2].

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 for in situ thermal desorption can be distinguished:

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.
2. Steam air injection (SAI) or steam enhanced extraction (SEE): heat is transferred convectively via steam with possible co-injection of 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 soil structure for TCH and ERH ist not less important but different to what is required for SEE, 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 3.4, small layers or lenses of dense soil material can be heated by a steam injection underneath **[24].**

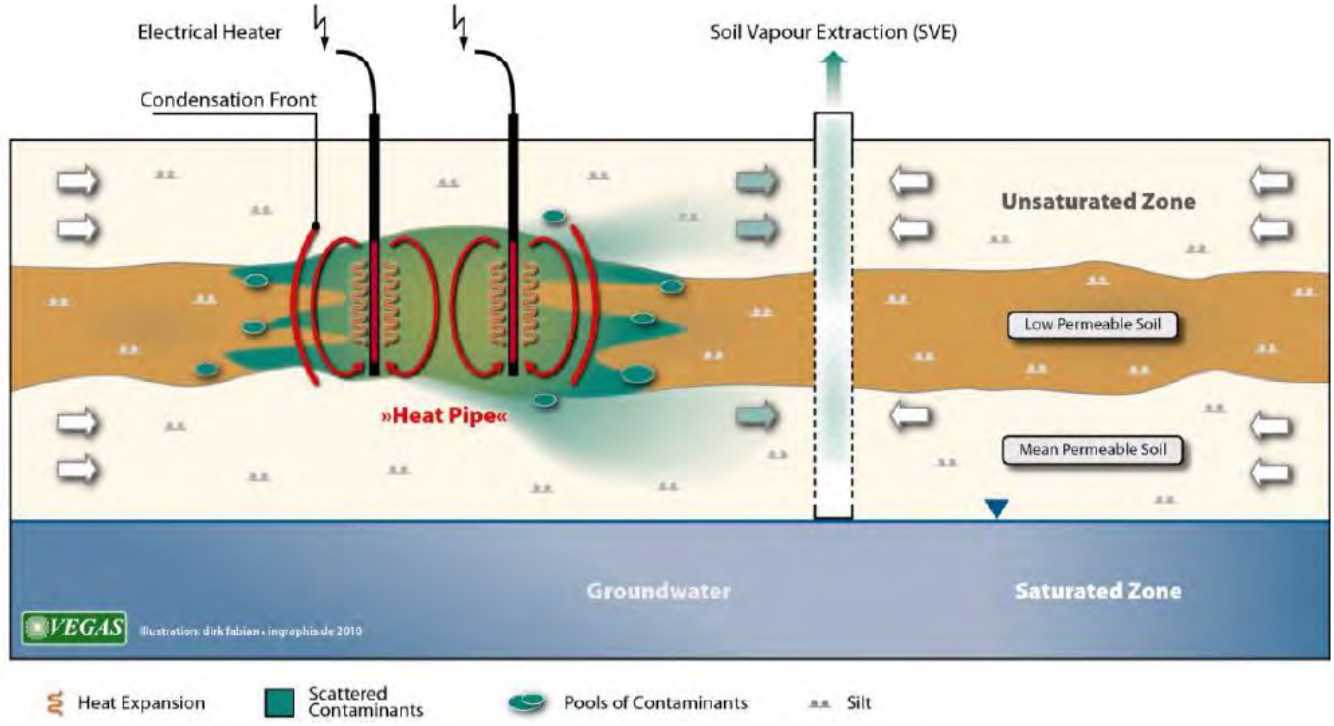
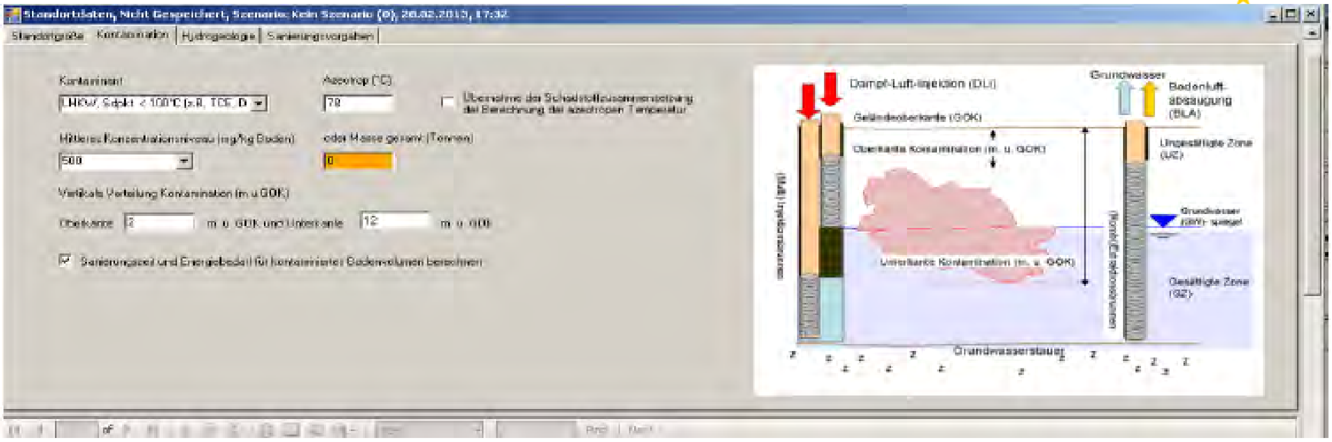


Figure 3.2. Principle of thermal conductive heating (TCH) [30].

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 3.3. The tool enables quick pre-planning of the remediation process, the field equipment (injection- and monitoring wells) and the installation engineering.



Standortdaten, Nicht Gespeichert, Scenario: Kein Scenario (0), 28.02.2013, 17:32

Kontaminant: LHKW, Sdpkt. < 100°C (z.B. TCE, D

Azeotrop (°C): 78

☐ Übernahme der Schadstoffzusammensetzung der Berechnung der azeotropen Temperatur

Mittleres Konzentrationsniveau (mg/kg Boden): 500

oder Masse gesamt (Tonnen): 0

Vertikale Verteilung Kontamination (m u GOK)

Oberkante 2 m u. GOK und Unterkante 12 m u. GOK

☑ Sanierungszeit und Energiebedarf für kontaminiertes Bodenvolumen berechnen

Figure 3.3. Software Tool for design of a steam air injection [30].

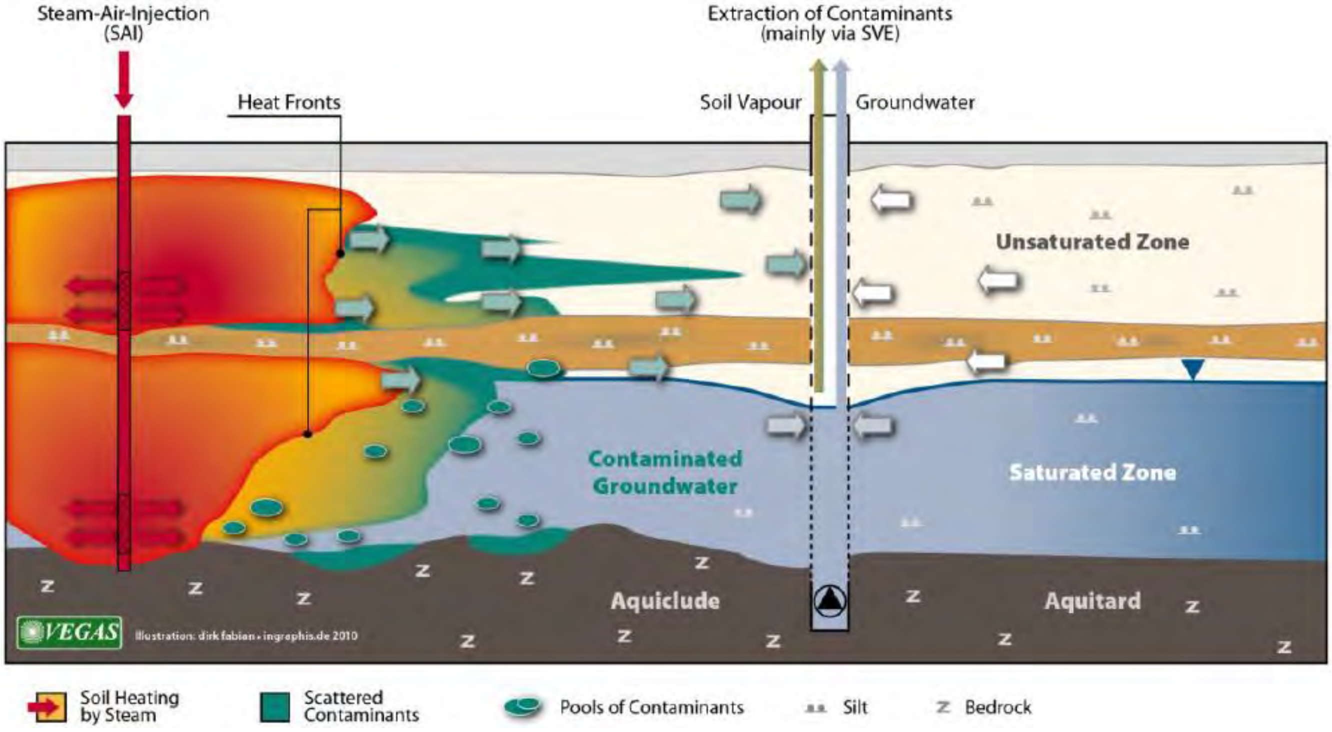


Figure 3.4. Steam air injection in the saturated and unsaturated zone [30]

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 efficiently. Economic and effective heat delivery into the subsurface is the main success factor for thermal treatment. Each technique has a different maximum temperature level. All techniques must reach the necessary temperature level according to site properties and facility design for the remediation of chlorinated solvents. 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 **[25].**

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 3.5. 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 volatized gases **[26].**

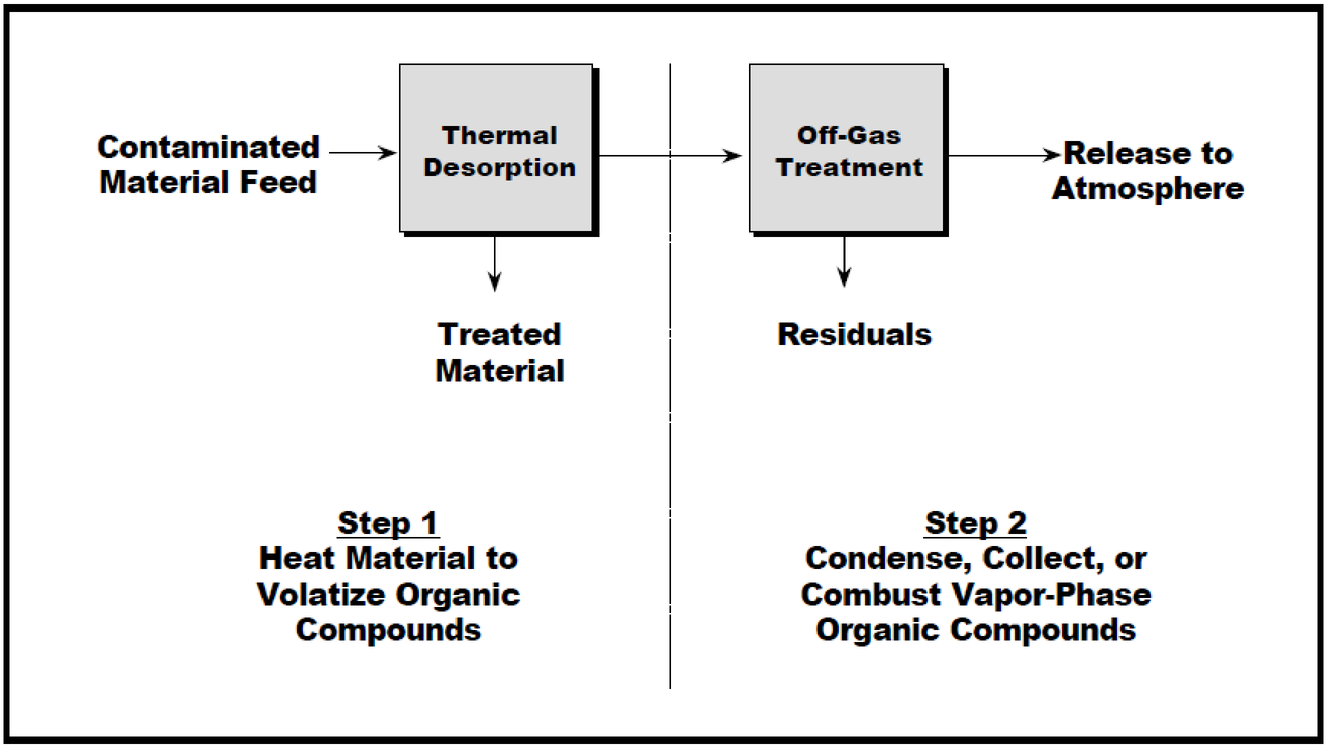


Figure 3.5. Generic Thermal Desorption Process [32]

Thermal desorption is fundamentally a thermally induced physical separation process. Contaminants are vaporized from a solid matrix and transferred into a gas stream, which 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 **[26].**

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 is typically 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 can 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 **[26].**

Many factors should be considered when selecting thermal desorption as a remedy for contaminated soil. Suppose there is reasonable confidence that thermal desorption will achieve the required treatment outcome. In that case, 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 **[2].**

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?
- Can the treated material be used or disposed of economically for on-site treatment? 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 summarises 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 key factors to consider. Section 3.2 continues the stages of feasibility, including data requirements, 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 in-situ technologies) and, consequently, 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) logistic challenges to apply next to infrastructures related to occupied/active sites and for application beneath buildings; (2) they require sophisticated design and operation; (3) which is also crucial to avoid 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).

ISTD may solve remediation problems that cannot be solved in an adequate and quick manner with any other technique. The short timeframe of the remediation and the possibility of remediating under existing buildings are crucial for the use of ISTD. This can support the development off of urban areas.To deliver ISTD in a cost-effective manner, the implementation must be tailored to site-specific conditions. For ISTD, higher drilling and energy costs depend on the size of the site and the hydrogeology. Costs for planning and monitoring are high, regardless of the size of the sites. Adapting the technique to site-specific conditions can be a further cost factor and time-consuming, particularly in urban environments. In urban environments, the costs of supervising neighboured buildings must be taken into account **[2].** As ISTD generates high energy consumption and costs in a short timeframe. A thorough planning and supervision are prerequisite to realise a shortened time treatment time, which allows for energy and cost savings.

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 **[2].**

3.2.1.1 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 factor because most of the applied heat is used to vaporise water.
- 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 cause 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 – This is important in cases where electrical resistive in-situ heating is involved. Moisture content will affect resistivity, and sophisticated localised water injection may be needed to control resistivity and heat generation.

3.2.1.2 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 note 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.

3.2.1.3 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, higher temperatures, longer treatment times and smaller maximum soil particle sizes may be required for in-situ treatment, impacting 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. They 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.

3.2.1.4 Calorific value and water content

- Variations in the calorific value of the materials being treated and the maximum concentrations of volatile combustible contaminants could give rise to rapid temperature rise and gas release that would result in explosion or uncontrolled gas releases. 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 fuel consumption rate rises by approximately 3 to 5% for each percent of moisture, and fuel costs could make the technology unviable.

3.2.1.5 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 will these meet the remediation criteria?
- whether dewatering is accelerating the remediation process and increase effiency
- 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.

3.2.1.6 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 **[2]**.

3.2.2 Treatable Contaminants

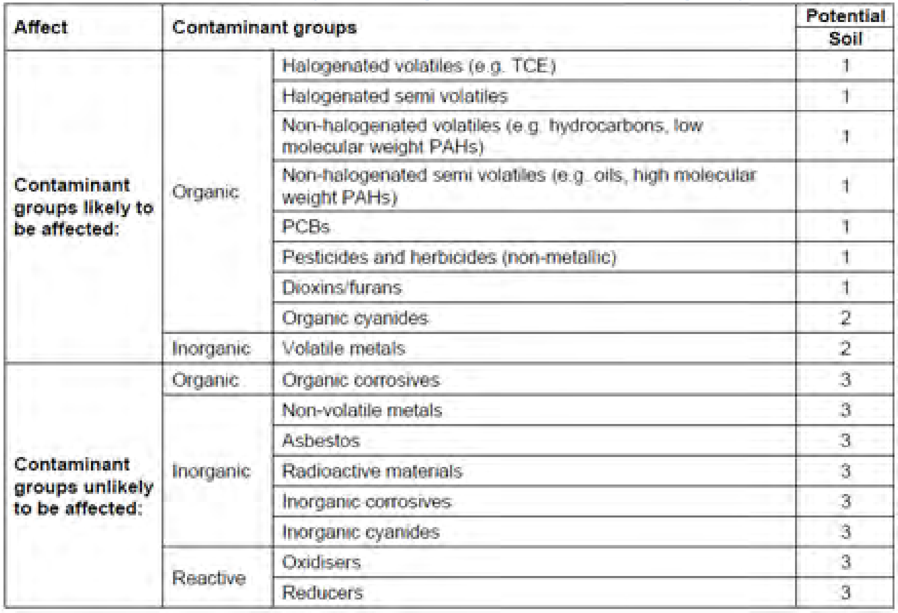
Thermal desorption is potentially applicable for the treatment of a wide range of

- Volatile organic compounds (VOCs)
- semi-volatile organic compounds (SVOCs),
- and even higher-boiling-point, chlorinated compounds such as polychlorinated biphenyls (PCBs),
- dioxins, and furans **[2]**

Generally, in situ thermal desorption is used for compounds with a boiling temperature lower than 550°C and a vapour pressure higher than 0.5 mm Hg **[27]**.

Table 3.1 summarises the contaminant types for which thermal desorption may be suitable.

Table 3.1: Effectiveness of thermal desorption on general contaminant groups for soil [2, 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
	Inorganic	Non-volatile metals	3
		Asbestos	3
		Radioactive materials	3
		Inorganic corrosives	3
		Inorganic cyanides	3
	Reactive	Oxidisers	3
		Reducers	3

3.2.3 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. Both TCH and ERH have limitations in terms of the thermal and electrical conductivity of the matrix. ERH has limitations for application to soil containing fresh water, which may not conduct electricity well.

3.2.3.1 Laboratory Screening

Whether a laboratory screening is site-specifically necessary as well as Tthe data from each stage of treatability testing should be reviewed and interpreted jointly by the consultant and remediation contractor, considering key results that will be achieved and support establishing requirements for full-scale implementation and operation. 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 (usually a few weeks or months to obtain results) and the cost is small concerning 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 initial testing results 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 applies 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 and are frequently 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 **[2].**

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, such as clay soils and soils with high content of organic matter. 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. A combination of different techniques may be necessary, especially for complex hydrogeological conditions with different layers (e.g., clay and gravel or sand layers) **[25].**

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

Primary fields of application		Steam-Enhanced Extraction (SEE)	Thermal Conductive Heating (TCH)	Radio Frequency Heating (RFH)
UNSATURATED ZONE				
Soil type				
NON-	Gravel	++	○	+
	Sand	++	○	++
	silty sand, sandy silt	+	++	++
COHESIVE	Silt	○	++	++
	loam, marl	-	++	+
	clay	-	++ to +	+
Contaminants				
VOC (i.e. chlorinated hydrocarbons)		++	++	++
BTEX		++	++	++
TPH (petroleum hydrocarbons)		○	+ to ○	+ to ○
PAH		-	○ to -	○
SATURATED ZONE				
Soil type				
AQUIFER	Gravel	+ to ○	-	○ to -
	Sand	++	-	○ to -
	silty sand, sandy silt	+	+ to ○	+
AQUITARD	Silt	-	+	++ to +
	loam, marl	-	++ to +	+
	clay	-	++ to +	+
Contaminants				
VOC (i.e. chlorinated hydrocarbons)		++ to+	++ to +	++ to +
BTEX		++ to +	++ to +	++ to +
TPH (petroleum hydrocarbons)		○	+ to ○	+ to ○
PAH		○	○	○

++	very good
+	good
○	partly possible / individual examination of boundary conditions
-	inappropriate boundary conditions for an economic application, individual examination necessary

3.2.3.2 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 to carry out a parametric study, following the temperature and 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 **[41].**

3.2.3.3 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. **[28]**.

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 equipment, making the results 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, 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 would probably cost less because some of the contingencies 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 **[28].**

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

3.2.4 Regulatory Requirements

The regulatory agencies (particularly those responsible for protecting 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 **[28]**.

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 **[2].**

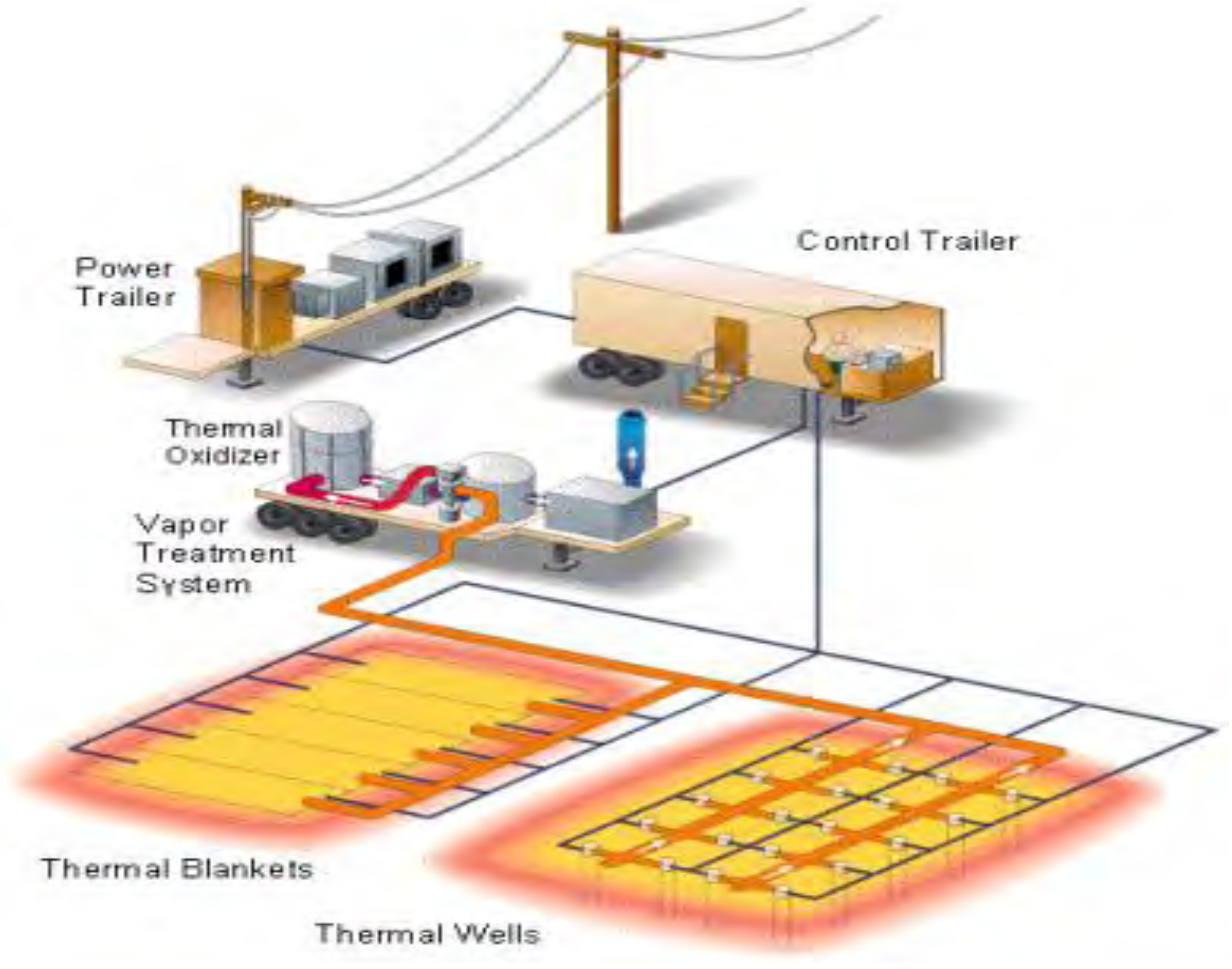


Figure 4.1 Typical elements of an in-situ thermal desorption system - Thermal Desorption process diagram [30]

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 develop the most appropriate implementation strategy.

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. Suppose the technology has been widely applied and the results are readily available. In that case, it may be possible to extrapolate the information from these previous case studies and avoid carrying out a treatability study to assess the technology's performance.
The additional information required may be determined by reviewing the published literature and information on case studies on the application of Thermal Desorption **[2].**

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's 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. Suppose it has been established that treatability testing is required to adequately assess the application of thermal desorption or to assist in cost appraisals. In that case, 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, which assesses 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) 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 aim to more closely replicate 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 of site conditions and contamination concentrations, as well as being as homogenous as possible. Moisture content is an important factor affecting volatilisation, and the moisture content of the test samples should be chosen to represent 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, the chemical and physical composition of the material to be treated should also be characterised. 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 the development of the RAP [1].

4.1.1 Pilot Trial

If data obtained during the detailed screening tests to design the RAP might be of site-specific limited reliability, a third stage of treatability testing can be undertaken to obtain information necessary for designing the thermal desorption system tailored 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 offsite unit if 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 **[2].**

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 **[29].**

The remediation of source zones in soil and groundwater is of high 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 contaminants 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 **[30].**

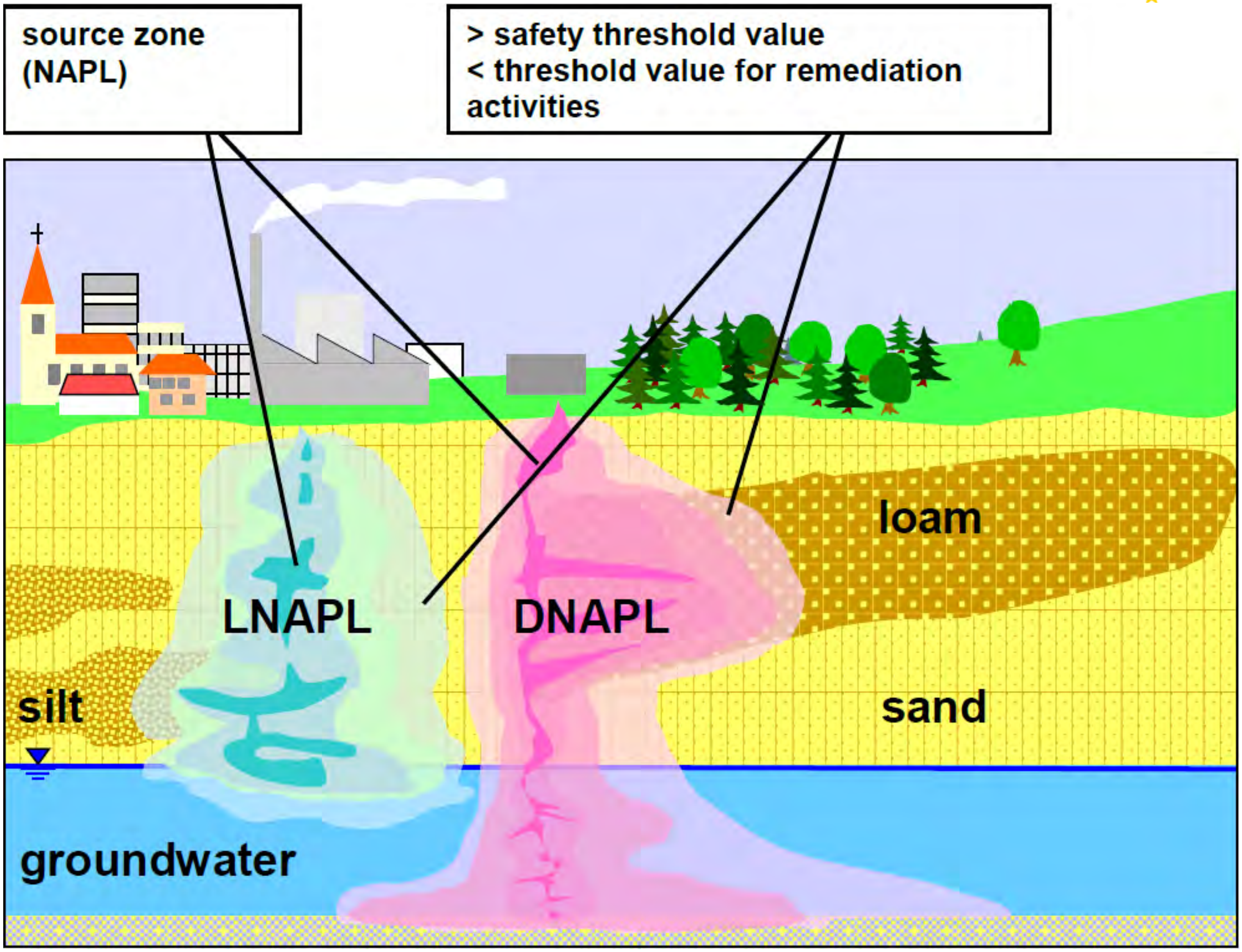


Figure 4.2. Schematic representation of a possible distribution of contaminants in the sub-surface. In situ thermal treatments (ISTT) are focussed on the removal of highly contaminated source zones rather than on the removal of low concentrations in the outer fringe or groundwater plume [30].

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 **[31]**, allowing 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 low permeability areas.

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 removing 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 approximately a boiling point. 200°C can be removed by ISTT **[18]**. 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 and saturated zones (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 to the successful application of ISTT **[30].**

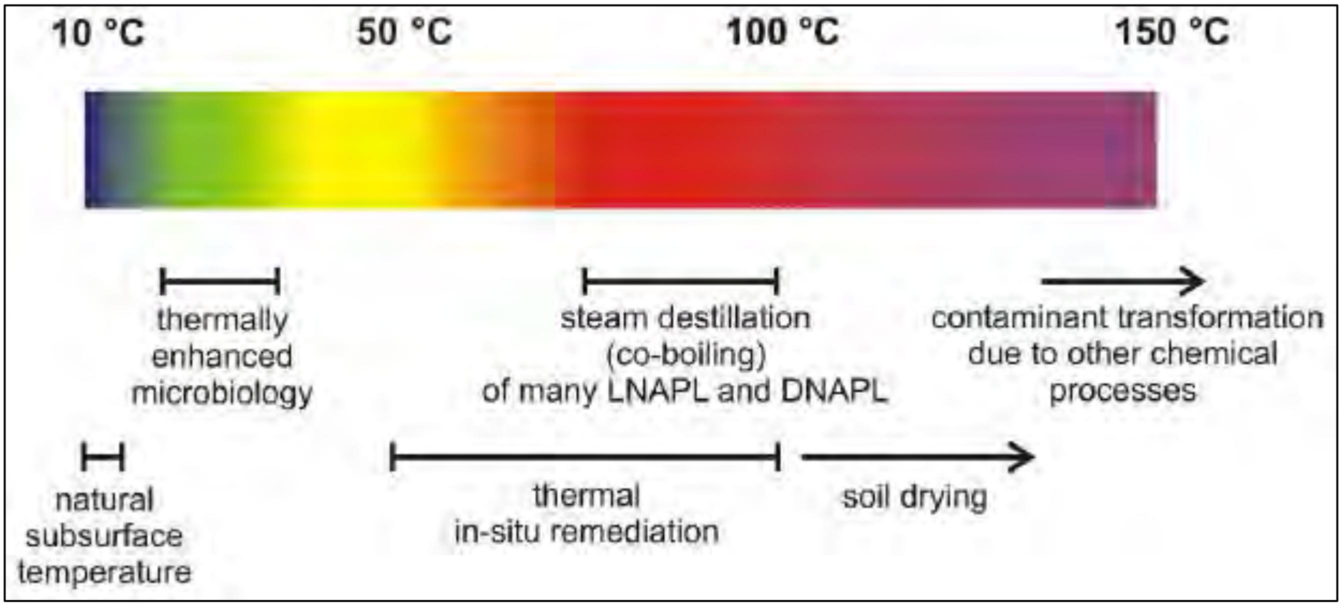


Figure 4.3. Application ranges of sub-surface heating for remediation and fields of application of these guidelines (significant process temperatures between 50°C and 100°C at atmospheric pressure) [30].

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 **[30].**

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 test

To heat up the subsurface, a mixture of steam and air is preferably 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 horizontally and in radial symmetry. The (often) residual, volatile to moderately volatile organic contaminants are vaporised in the heated area. The air portion supports the contaminant transport towards the extraction wells of the thermally enhanced soil vapour extraction **[30].**

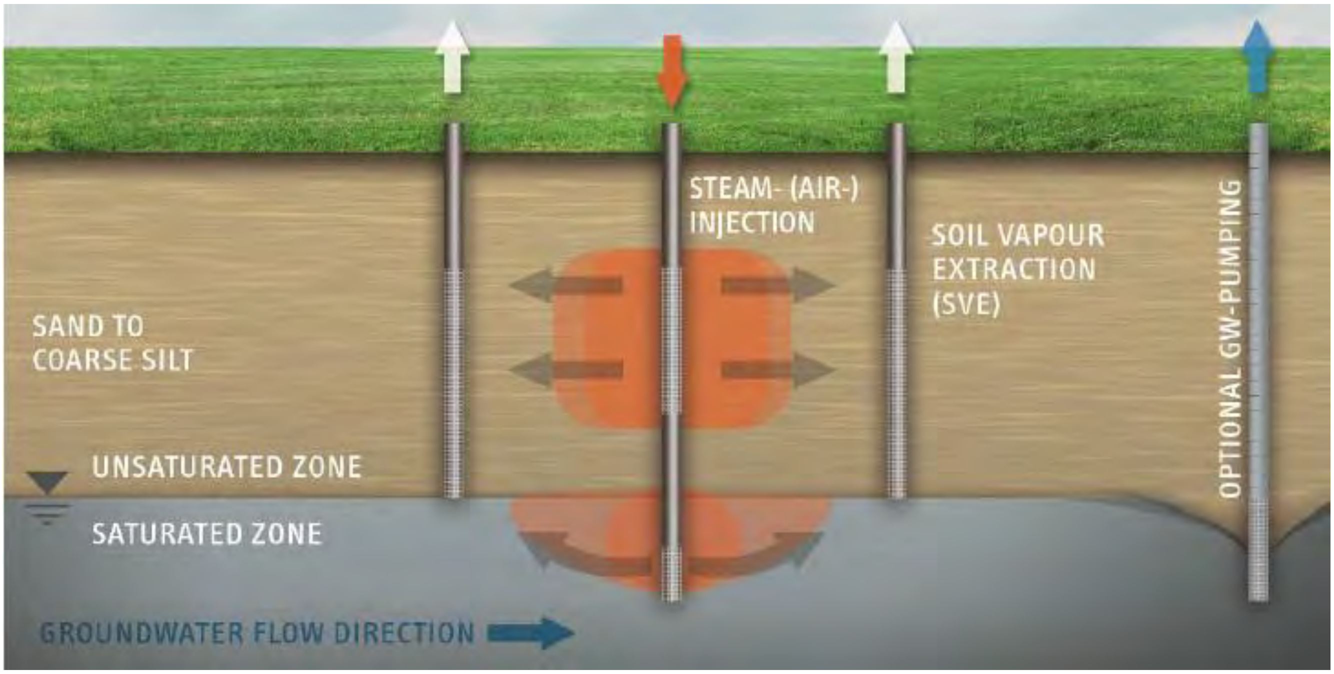


Figure 4.4. Steam-air injection into the unsaturated and saturated zone [30].

When the steam-air mixture is introduced into unconsolidated soil aquifers (i.e., within the saturated zone) with hydraulic permeability between 5 x 10^{-4} and 5 x 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 ongoing condensation process heats the area to be remediated. Although steam is usually injected through vertical wells laterally into the aquifer, it also expands vertically due to its lower density than 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; 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 **[30].**

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 **[30]**.

4.1.3.2 Thermal conductive heating 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 low permeability heating of soil stratifications 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 **[18]**.

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 **[18].**

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 to achieve an efficient remediation of the entire soil profile **[18].**

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]. Sealing measures for protecting the electrical installations against water infiltration must be implemented when installing heating elements in the saturated zone. In principle, thermal wells enable the sub-surface to be dried completely and be heated to temperatures > 100°C.

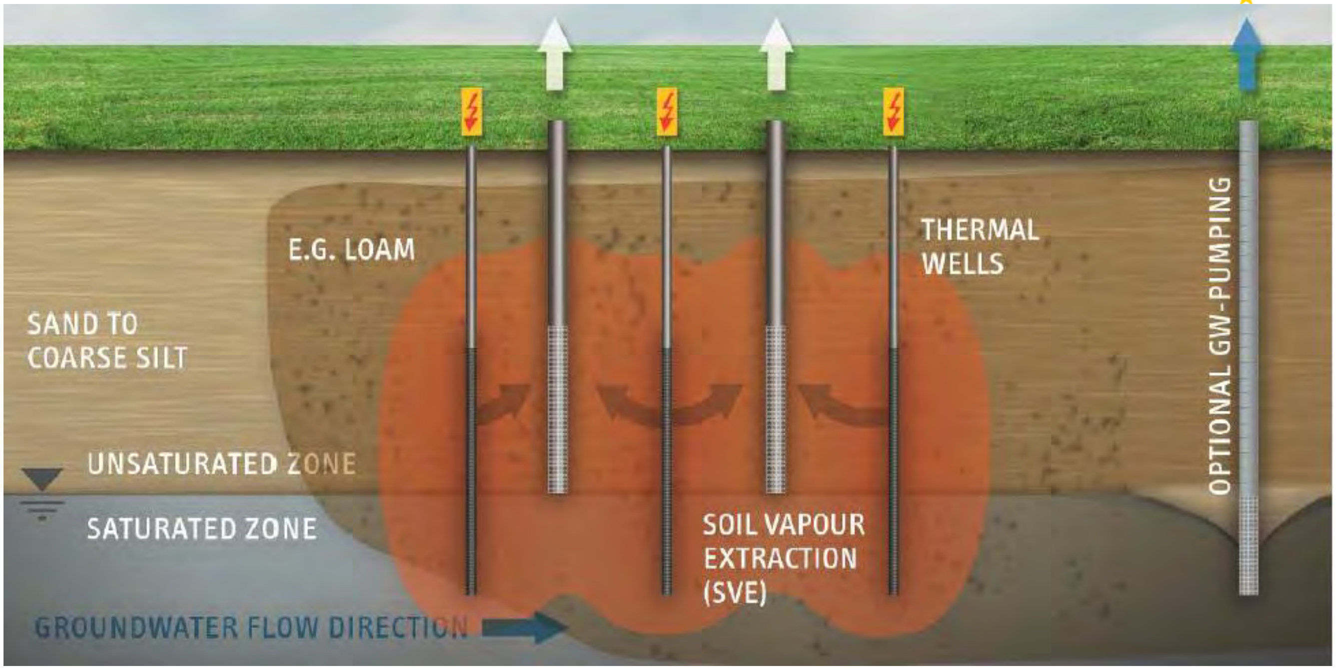


Figure 4.5. Schematic diagram of the Thermal conductive heating (TCH) [30].

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 % **[32,33].** 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 **[32].**

A specific design enables the energy to be transferred to selected depths to remediate the contamination in a defined manner (Figure 4.6). Parallel plate or gauze electrodes effectively enhance 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 **[33].**

In this case, the RF energy is introduced into the soil using 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) **[34].**

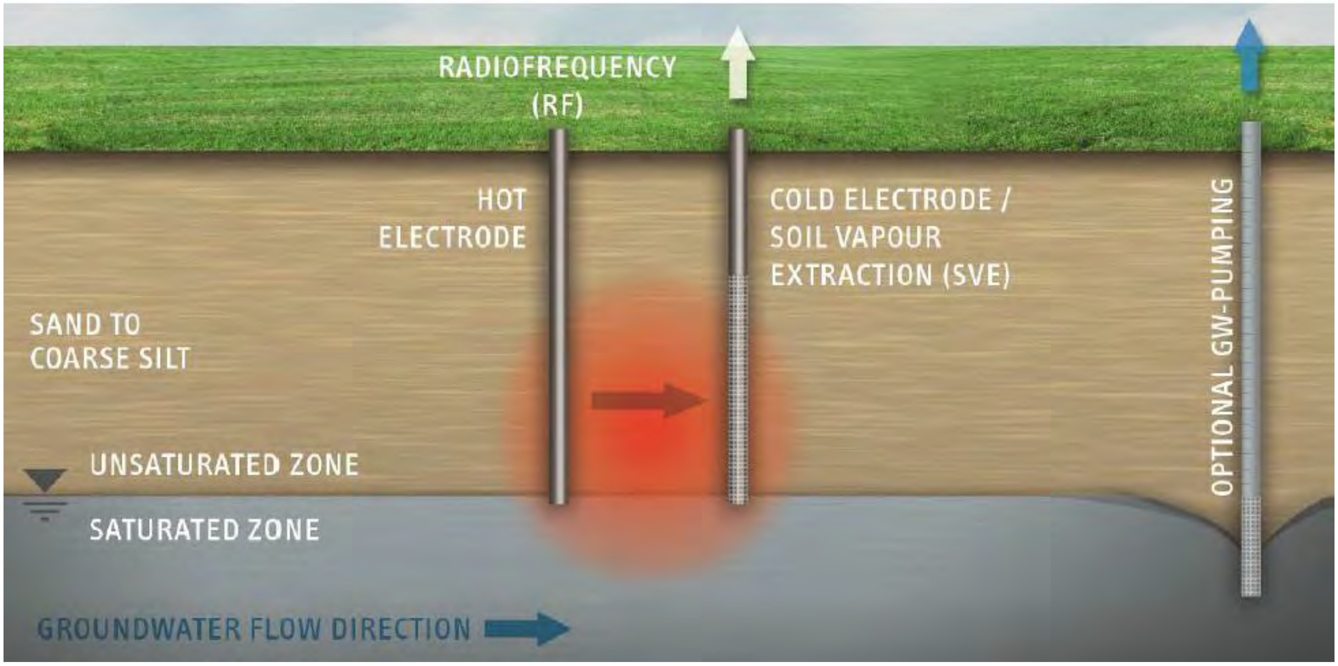


Figure 4.6. Schematic diagram of the Radio frequency heating (RFH) method [30].

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) **[34].**

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 (pv) which increases exponentially with the temperature T. For example, vapour pressure can be calculated for pure substances by using the ANTOINE or WAGNER equations. For example, the substance-specific coefficients (A, B, C) can be found in [9]. When contaminated wet soil is heated, the NAPL is vaporised together with water (steam distillation). The vapour pressures (pv) 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 pd. The co-boiling vapour pressure always exceeds the vapour pressure of the low boiling phase (often water). Therefore, the co-boiling temperature (azeotropic temperature) 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

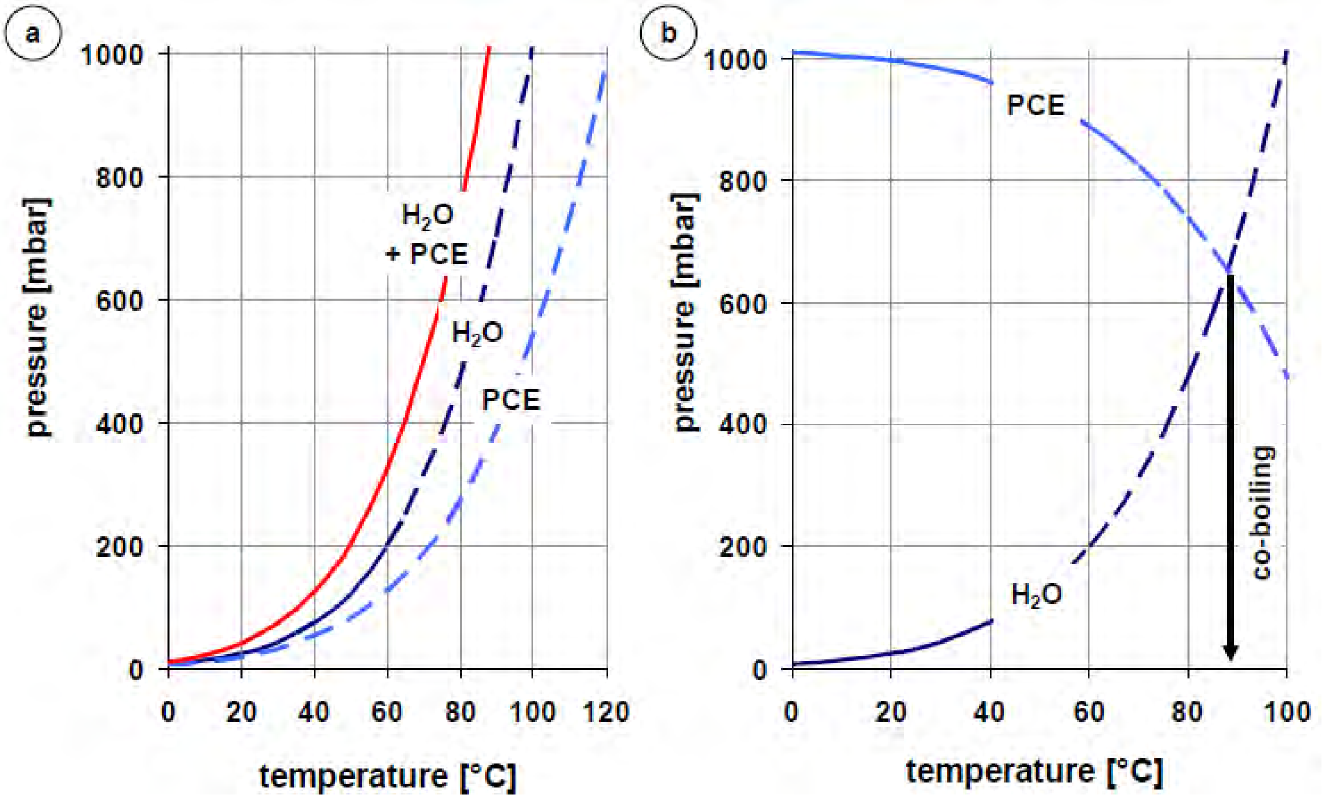


Figure 4.7. Vapour pressure curves of water and PCE [4];. Figure 4.7 a) illustrates Vapour pressure curve of the single substances (H20, PCE) and the mixture (H20 + PCE) at co-boiling (azeotrop); Figure 4.7 b) Determination of the co-boiling temperature of PCE and water according to the method of Badger-McCabe [35]

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) **[18].** 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 **[36].**

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 **[37].**

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 pressure, temperature, and other water constituents, such as 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 **[38].**

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. This effect is mostly compensated by supplying water vapour during the steam injection. 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 does 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 unsaturated sandy soil types.

Complete drying processes as part of an ISTT normally occur only during the remediation process and close to 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) **[39].**

A temperature gradient and the capillary forces in the soil generate this flow of water and vapour. 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.

The heat-pipe effect can be neglected when ISTT is applied to sandy soils 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 **[18].**

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 vf (kf x 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 **[40].** 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 **[18].**

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 is used in the second tier and involves processing 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 greatest possible extent, 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 estimated from the two previous testing tiers. Given the time required and the cost associated with this third tier of testing, it would be undertaken exceptionally for complex or unusual sites, if at all **[28].**

The expected results during the treatability tests are as follows **[27]**:

- 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 contamination (nature and concentration) and geology. The pilot tests described consist of **[27]:**

- 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 heating wells 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 as an option 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 is used to monitor the effectiveness of capturing the vapours generated.
- The depth of the heating wells is defined so that you can 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 to a safe temperature, 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 contaminants (estimated at the Management Plan stage) to be extracted from the impacted area and the mass of contaminants 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 contaminants 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 **[25]**.

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 [27; amended]

	Case Studies	1	2	3	4	5	6	7	8	9	10	11	12
General Information	Thermal Method	Thermal Conductive Heating	Thermal Conductive Heating	Thermal Conductive Heating	Thermal Conductive Heating	Thermal Conductive Heating	Steam Air injection	Radio Frequency Heating	Steam Air injection	Thermal Conductive Heating & Steam Air injection	Radio Frequency Heating	Steam Air injection	Thermal Conductive Heating & Steam Air injection
	Location	Odense, Denmark	Skuldelev, Denmark	Reelslev, Denmark	Zwölfaxing, Austria	Idstein, Germany	Schwenningen Germany	Manston, Kent, UK	Karlsruhe, Germany	Landshut, Germany	Zeitz, Germany	Hamburg , Germany	Gottingen, Germany
	Pilot test or Full scale	Full Scale	Full Scale	Full Scale	Full Scale	Pilot Test	Pilot Test	Full Scale	Full Scale	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	Ecologia,2010	Züblin, Umwelttechnik Gmbh, 2010	Reconsite, Bauer, Umwelt, 2008	UFZ,2008	Reconsite, 2020	Reconsite, 2018
	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)	Decommissioned petrol station	Former dry cleaning facility, (historical building, built in 1547)	Former dry cleaning company	Former hydrogeneration plant	Former tank farm site	Former dry-cleaning facility
Hydrogeology	Hydrogeology	Clay, sand, saturated and unsaturated	Clay, sand, saturated and unsaturated	Clay, dry, sand, unsaturated	Silt, sand, clay, unsaturated	Medium clay, unsaturated	Fractured sandstone, saturated, unsaturated	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		Sand, locally low permeable silt lenses and peat layers	Solid rock, firm fine sandstone, fractured clay stones and siltstones, saturated and unsaturated
	Estimated hydraulic conductivity [m/s]	Clay 1,00E-9 Sand 5,00E-9	Clay 1,00E-9 Sand5,00E-9	Clay 1,00E-9 Sand 5,00E-9	Clay 1,00 E-9 Sand 5,00 E-9	Not measured	Not measured	Sand, clay 0,50 E-4	Coarse clay, 1,00E-5 Sand, 3,00E-4 Gravel 5,00E-3	Gavely clay 1 x E -7 to 1 x E-8 sand aquifer 2,60E-4		Sand 2,30-4,40E-4 with several embedded silt layers	Claystone Fractured aquifer 3,00E-4
Contaminants	Type	PCE, DNAPL	PCE	PCE	Mostly PCE	Mostly TCE	CHC	BTEX, TPH	CHC, PCE	CHC (PCE,TCE), BTEX, TPH	BTEX	TPH	PCE
	Concentration before remediation	Soil max 13.000 mg/kg	Soil max 2.500 mg/kg	Soil max 7.000 mg/kg	Soil air max 2.500 mg/m^3 GW max 1.500 µg/L	Soil max 160 mg/kg	Soil air max 4.000 mg/m^3 GW max 40 µg/L	TPH max 23.500 mg/kg Toluene 20.400 mg/kg Xylenes 38.900 mg/kg	Soil air max 1.700mg/m^3 Soil 3.820 mg/kg GW 850 µg/L	Soil air 7.900 mg/m^3 Soil 1.000 mg/kg GW (Strata) 24.000 µg/L	Soil air max 90.000mg/m^3 Soil max 250 mg/kg	TPH / BTEX Soil max 19.000 / 7.000 mg/kg GW 4.500 / 45.000 µg/L	Soil air max. 5.300mg/m^3 Soil max 380mg/kg GW 20.000µg/l
	Remediation target value(s)	Soil 5mg/kg	Soil 5mg/kg	Soil 1mg/kg	Soil air 10mg/m^3	(controlled as mass removal)	Soil air 145mg/m^3	TPH max 23.500 mg/kg Toluene 870 mg/kg Xylenes 480m	Soil air max 10mg/m^3 GW 10µg/L	Mass removal (>97% of total CHC)		70 % mass removal TPH / BTEX 500 / 300 mg/kg	Mass removal (90-95%)

Table 4-3. Overview of some completed thermal in situ remediation projects in Europe [27; amended]

	Case Studies	1	2	3	4	5	6	7	8	9	10	11	12
General Information	Thermal Method	Thermal Conductive Heating (TCH)	Thermal Conductive Heating (TCH)	Thermal Conductive Heating (TCH)	Thermal Conductive Heating (TCH)	Thermal Conductive Heating (TCH)	Steam Air injection	Radio Frequency Heating	Steam Air injection	Thermal Conductive Heating & Steam Air injection	Radio Frequency Heating	Steam Air injection	Thermal Conductive Heating & Steam Air injection
	Location	Odense, Denmark	Skuldelev, Denmark	Reelslev, Denmark	Zwölfaxing, Austria	Idstein, Germany	Schwenningen Germany	Manston, Kent, United Kingdom	Karlsruhe, Germany	Landshut, Germany	Zeitz, Germany	Hamburg, Germany	Gottingen, Germany
	Pilot test or Full scale	Full Scale	Full Scale	Full Scale	Full Scale	Pilot Test	Pilot Test	Full Scale	Full Scale	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+ Schwenningen,2009	Ecologia,2010	Zublin, Umwelttechnik Gmbh, 2010	Reconsite, Bauer, Umwelt, 2008	UFZ,2008	Reconsite, 2020	Reconsite, 2018
	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)	Decommissioned petrol station	Former dry cleaning facility, (historical building, built in 1547)	Former dry cleaning company	Former hydrogeneration plant	Former tank farm site	Former dry-cleaning facility
Technical Data	Treatment Area [m^2]	222	250	1300	540	20	100	121	220	362	100	10.000	650
	Depth of treatment [m]	10	7,5	10-12	3-7	5	20	7,5	8	11	8	12	14
	Treatment volume [m^3]	1330	1180	11100	1600	100	2000	907	1760	-	500	100.000	9.100
	Number of heater [-]	45	53	147	70	7	1	3	8	120 (heater), 3 (steam-air injection well)	1	>120 (injection well)	39(heater), 12(injection well)
	Average temperature [°C]	100	100	100	69	107	50	49,1	92	90	54	85	85
	Heating period [days]	105	73	169	290	43	175	117	294	90	100	3 fields each <6 month in total 17 months	182d
Remediation Results	End Concentration	Mean:0,51mg/kg Max: 4,4mg/kg	Mean:0,02mg/kg Max: 0,77mg/kg	Mean:0,012 mg/kg Max: 0,057mg/kg	Soil air <10 mg/m^3 GW 50-200µg/L	Max 17 mg/kg	Soil air max:120mg/m3 GW max: 180µg/L	Toluene 0,56 mg/kg Xylene 0,72 mg/kg	Soil air 10 g/m3 - GW 10mg/l			Brownfield award 2022	
	Removed contaminants [kg]	4000	400	2350	Soil air 348 GW:5	19,2	560	945	500	548	660	>280.000kg	450 kg
	Energy consumption [kWh]	637.610	567.070	3.990.000	564.800	21.500	-	46.749	78.0000	590.000	54.780	10.080.000kWh	914.000kWh
	Specific energy consumption [kWh/kg]	3500	1418	2350	1600	1120	-	49	1560	1.076	83	36kWh/kg	2.067kWh/kg
	Specific Costs [€/kg contaminant]	-	-	-	-	-	-	-	1300	1.621	-	21€/kg	2.794€/kg
	Remediation efficiency [%]	>99	>99	>99	>99	90	95	>95	>99	>99%	-	>99%	Twice of estimated mass

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. **[6]**.

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 **[6; 41]**:

- 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 **[6]**:

- 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 **[6]**:

- 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 **[6]**.
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, the conditions are analogous to that of a natural geyser, and steam may flash and blow hot water out of the well **[42]**.

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 to attain 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 **[6]**. 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, as well as achieving and maintaining a target temperature throughout the treatment zone, are 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 **[6]**. 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)" **[43]**.
- 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 **[44, 45]**. 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 **[41]**.

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, 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 **[41]**. If it is necessary to quickly obtain information on the quality of environmental matrices, a hot sampling procedure can be adopted **[6]**.

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.

6 CONCLUSION

In the technology In Situ Thermal Desorption, heat and extraction technologies are 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. 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 require complementary remediation approaches to address a broader range of environmental contaminants or any residual contamination. Depending on the heating process, particularly for high temperature applications, some soil properties may get 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.

BIBLIOGRAPHY

[1]. Xu, Y. and E. Sun, Contaminated Soil Remediation through Thermal Desorption -- Synthesis of Case Histories and Comparison of In-situ and Ex-situ Applications, in Web Class Projects CE 176-Environmental Geotechnics, geoengineer, Editor. 2021.

[2]. CRC CARE 2019, Technology Guide: Soil – Thermal desorption, National Remediation Framework, CRC for Contamination Assessment and Remediation of the Environment, Newcastle, Australia.

[3]. Troxler, W.L., S.K. Goh, and L.W.R. Dicks, Treatment of Pesticide-Contaminated Soils with Thermal Desorption Technologies. Air & Waste, 1993. 43(12): p. 1610-1617.

[4]. Zhao, C., et al., Thermal desorption for remediation of contaminated soil: A review. Chemosphere, 2019. 221: p. 841-855.

[5]. Agency, U.S.E.P.A., Engineering Bulletin: Thermal Desorption Treatment (Superfund. May). 1991.

[6]. USACE 2014 Environmental Quality – Design: In Situ Thermal Remediation, Engineer Manual 200-1-21, 30 May 2014.

[7]. Kunkel, A.M., et al., Remediation of Elemental Mercury Using in Situ Thermal Desorption (ISTD). Environmental Science & Technology, 2006. 40(7): p. 2384-2389.

[8]. Lemming, G., et al., Optimising the Environmental Performance of In Situ Thermal Remediation Technologies Using Life Cycle Assessment. Groundwater Monitoring & Remediation, 2013. 33(3): p. 38-51.

[9]. Kruger, Soil remediation you can trust. In Situ Thermal Desorption, in Terra Therm Technology, V.W.S. Technologies, Editor. 2013.

[10]. Liu, J., et al., Thermal desorption of PCBs from contaminated soil using nano zerovalent iron. Environmental Science and Pollution Research, 2014. 21(22): p. 12739-12746.

[11]. Shi, Y., et al., New advances in in-situ thermal desorption technology for contaminated soil. Science China Technological Sciences, 2019. 62(11): p. 2075-2076.

[12]. Kueper, B.H., et al., Chlorinated solvent source zone remediation. 2014: Springer.

[13]. Vinegar, H.J. and G.L. Stegemeier, Low cost, self regulating heater for use in an in situ thermal desorption soil remediation system, in The University of Texas System, U.S.B.o. Regents, Editor. 2002.

[14]. Xue, Y., et al., Experimental investigation on electromagnetic induction thermal desorption for remediation of petroleum hydrocarbons contaminated soil. Journal of Environmental Management, 2023. 328: p. 117200.

[15]. Kastanek, F., et al., remediation of contaminated soils by thermal desorption; effect of benzoyl peroxide addition. Journal of Cleaner Production, 2016. 125: p. 309-313.

[16]. Liu, J., et al., Effect of oxygen content on the thermal desorption of polychlorinated biphenyl-contaminated soil. Environmental Science and Pollution Research, 2015. 22(16): p. 12289-12297.

[17]. Eva L. Davis., In Situ Thermal Remediation. US EPA Groundwater Issue Paper, 2023 EPA/600/R-23/062. For download: https://cluin.org/download/techfocus/thermal/In-Situ-Thermal-Remediation.pdf

[18]. Hiester, U. (2009): Technologieentwickluung zur in-situ-Sanierung der ungesättigten Bodenzone mite festen Wärmequellen: Promotionsschrift, Mitteilungsheft des Instituts für Wasserbau Nr. 178, Universität Stuttgart, 9/2009. ISBN: 978-3-933761-82-8.

[19]. Betz, C. (1998): Wasserdampfdestillation von Schadstoffen im porösen Medium: Entwicklung einer thermischen In-situ Sanierungstechnologie: Mitteilungsheft Nr. 097, (Dissertation) Institut für Wasserbau, Universität Stuttgart, 1998. ISBN: 3-921694-97-3BGR.

[20].Hiester, U. et al., Guidelines: In situ thermal treatment (ISTT) for source zone rmediation of soil and groundwwater. Funded by Federal Ministry of Education and Research (bmbf) and Helmholtz Centre for Environmental Research (UFZ), may 2013.

[21].Hiester, U. and Bieber, L. (2017): Dominierende Prozesse bei der thermischen In-situ Sanierung (TISS) kontaminierter Geringleiter, Grundwasser – Zeitschrift der Fachsektion Hydrogeologie 22: 185-195, ISSN 1430-483X print. DOI: 10.1007/s00767-017-0366-z

[22].Hiester, U. and Bieber, L. (2023): Energiesparende, nachhaltige Grundwassersanierug am Petroleumhafen Hambugr mit Dampf-Luft-Injektion (TUBA-Verfahren), Artikel 5716.01 in: Franzius/Altenbockum/Gerhold (Hrsg.): Handbuch Altlastensanierung und Flächenmanagement, Rehm Verlag, München, 95. Aktualisierung, Stand September 2023. ISBN: 978-3-8073-2781-5.

[23].HERON, G. AND BAKER, R. (2009): THERMAL CONDUCTION HEATING.- IN: JOHNSON, P.; DAHLEN, P., TRIPLETT, J.; FOOTE, E.; & WILLIAMS, S. (2009): Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment, State-of-the-practive Overview.- Environmental Security Technology Certification Program ESTCP Project ER-0314

[24].von Schnakenburg, P. (2013). In situ thermal remediation of contaminated sitesa technique for the remediation of source zones. Relatório técnico, CityChlor.

[25].CITYCHLOR, www.citychlor.eu

[26].NAVAL FACILITIES ENGINEERING SERVICE CENTER Port Hueneme, California 93043-4370 OVERVIEW OF THERMAL DESORPTION TECHNOLOGY An Investigation Conducted by Foster Wheeler Environmental Corporation and Battelle Corporation June1998

[27].Ademe (2019) PROJET ESTRAPOL, GUIDE TECHNIQUE, Essais de faisabilité de traitement des sols pollués, 193 p.

[28].FACILITIE, V., & CE, I. N. (1998). APPLICATION GUIDE FOR THERMAL DESORPTION SYSTEMS.

[29].Shaw, P., Nickelson, D., & Hyde, R. (1999). Operable Unit 7-13/14 in situ thermal desorption treatability study work plan (No. DOE/ID-13467). Idaho National Lab.(INL), Idaho Falls, ID (United States).

[30].Revitalisation-TASK, Site. "In situ thermal treatment (ISTT) for source zone remediation of soil and groundwater."

[31].https://remediationframework.com.au/cms/download-nrf-guidelines/4-guideline-on-regulatory-considerations/file

[32].ROLAND, U.; BUCHENHORST, D.; HOLZER, F.; KOPINKE, F.-D. (2008a): Engineering Aspects of Radio-Wave Heating for Soil Remediation and Compatibility with Biodegradation; Environ. Sci. Technol. 42, 1232-1237.

[33].ROLAND, U.; HOLZER, F.; BERGMANN, S.; BUCHENHORST, D.; KOPINKE, F.-D. (2008c): Thermisch unterstützte Bodenreinigung durch direkte Erwärmung mittels Radiowellen Teil 2: Kombination mit unterschiedlichen Sanierungsverfahren; Chem. Ing. Tech. 80, 295-306

[34].HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ (2008): Vorrichtung zur thermisch unterstützten in-situ-Reinigung von mit Schadstoffen belasteten Materialien, Gebrauchsmuster DE 202007014507.1, dated 13/12/2007 (applied for on 11/10/2007).

[35].BETZ, C. (1998): Wasserdampfdestillation von Schadstoffen im porösen Medium: Entwicklung einer thermischen In-situ-Sanierungstechnologie; Mitteilungsheft Nr. 097, (Dissertation) Institut für Wasserbau, Universität Stuttgart, 1998. ISBN: 3-921694-97-3BGR

[36].ATKINS, P. W. (1988): Physikalische Chemie. VCH Verlagsgesellschaft, Weinheim, 1st edition. ISBN 3-527-25913-9.

[37].LANDESANSTALT FÜR UMWELTSCHUTZ BADEN-WÜRTTEMBERG (LFU) (1995): Hydraulische und pneumatische in-situ Verfahren. Materialien zur Altlastenbearbeitung Band 16, Karlsruhe

[38]. SANDER, R. (1999): Compilation of Henry's Law Constants for Inorganic and Organic Species of Potential Importance in Environment Chemistry. http://www.mpchmainz.mpg.de/~sander/res/henry.html, 8 April 1999. Version 3.

[39]. UDELL, K.S. & J.S. FITCH (1985): Heat and Mass Transport in Capillary Porous Media Considering Evaporation, Condensation and Non Condensible

[40]. TRÖTSCHLER, O.; KOSCHITZKY, H.-P.; OCHS, S.O.; DENZEL, S.; STÖCKL, K. (2006): Dampf-Luft-Injektion in die gesättigte Zone: Pilotanwendung zur Sanierungsplanung an einem innerstädtischen Standort im Rheintal. In: Braun, J.; Koschitzky, H.-P. & M. Stuhrmann (eds.): VEGAS - Statuskolloquium 2006 (28. - 28. September 2006, Stuttgart). Mitteilungsheft des Instituts für Wasserbau 150. Eigenverlag, Institut für Wasserbau, Universität Stuttgart, 2006, 60 - 70. ISBN: 3-933761-53-0.

[41]. USEPA. 2014 Engineering Paper: In Situ Thermal Treatment Technologies: Lessons Learned. Office of Land and Emergency Management Agency EPA 542-R-14-012, May 2014

[42]. IDEM. 2010. In-Situ Thermal Treatment, Technical Guidance Document Indiana Department of Environmental Management. September 25, 2020

[43]. NJDEP. 2017. In-Situ Thermal Treatment. New Jersey Department of Environmental Protection Site Remediation and Waste Management Program

[44]. Wanner et al., 2017. Does sorption influence isotope ratios of chlorinated hydrocarbons under field conditions? Appl. Geochem., 84 (2017), pp. 348-359

[45]. J. Zimmermann, L.J.S. Halloran, D. Hunkeler Tracking chlorinated contaminants in the subsurface using compound-specific chlorine isotope analysis: a review of principles, current challenges and applications. Chemosphere, 244 (2020), Article 125476.

European Union Network for the Implementation
and Enforcement of Environmental Law

Annex 1

In Situ Thermal Desorption – Case studies

IMPEL Project no. 2023/12

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.1

1.1 Name and Surname	Laurent Thannberger
1.2 Country/Jurisdiction	France
1.3 Organisation	Valgo
1.4 Position	R&D manager
1.5 Duties	Expertise
1.6 Email address	laurent.thannberger@valgo.com
1.7 Phone number	+33 650191133

2. Site background

2.1 History of the site

An aluminium production plant in southwestern France had severe soil impacts to PCBs. To convert electricity from high-voltage lines into very high amperage current to ensure the electrolytic conversion of alumina into aluminium (Hall-Héroult process), an electrical substation consisted of many transformers. Until the ban on PCBs, they were used in oil baths, as electrical insulators. Numerous drains, and an accidental spill during a fire, impacted 3000 m^3 of soil in the affected area of the plant, with significant values.

Figure 1 - View of the former factory; circled zone shows the electrical substation and 2 high voltage line in the bottom.

2.2 Geological setting

Samples of polluted soil were taken with a hammered corer; 3 boreholes at a depth of 5 m were carried out in the most impacted area of the electrical substation (site of the accidental spill, which will become the area of the pilot test on site). After conventional quarter mixing, aliquot fractions of these samples were sent to the laboratory. Its GTR classification (guide for road earthworks), by the Ginger laboratory CEBTP was A1, with a description as "gravelly clay and reddish sandy clay with plant debris" (Table 1).

Parameter		**Result**
Granulometry	Max size	50 mm
	< 50 mm	100 %
	< 2 mm	68,1 %
	< 80 µm	41,3 %
	< 2 µm	13 %
Liquid limit	W_L	36 %
Plasticity limit	W_P	29 %
Plasticity index	W_L-W_P	7
Methylene blue value		0,49 g /100 g

Table 1 - Geotechnical properties of the soil

2.3 Contaminants of concern

Main groups of contaminants: PCB (Polychlorinated biphenyl). The soil showed traces of hydrocarbons at concentrations that did not require remediation, and this parameter was not monitored.

5900 t of soils were impacted by PCB above the threshold of 20 mg/kg dw, with concentrations raising up to 600 mg, and an average of 300 mg/kg dw.

2.4 Regulatory framework

The work is carried out as part of a procedure for the cessation of activity of an installation classified for the environment Article L. 511-1 of the French Environmental Code. The national methodology provides the prescription of works by a prefectural order. The thermal desorption treatment approach being innovative at the time of the construction site, each step was followed and validated by the Regional Directorate for the Environment, Planning and Housing (DREAL) depend on the Ministry of Ecological Transition, Territorial Cohesion and Energy Transition.

3. Pilot-scale

3.1 Laboratory Study

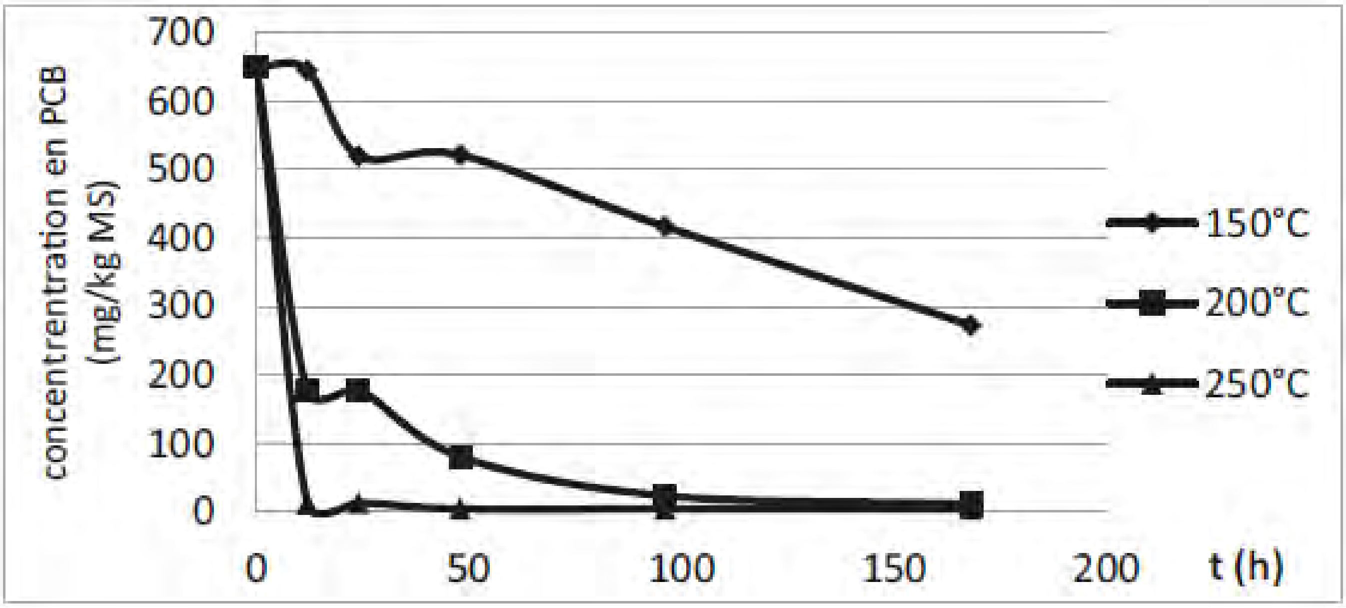


Figure 2 - Thermal desorption kinetics of PCBs in soils at several temperatures

- Application of a small part of contaminated soil to a muffle furnace
- Bench-scale laboratory equipment that simulates full-scale unit operations

The specificity of PCB pollution required the validation of several technical options by preliminary steps because no realization of this magnitude had ever been carried out under these conditions. VALGO's strategy includes several stages of data acquisition, implemented into the final design of the depollution facilities.

Fractions from the received samples were distributed into ventilated 1 L beakers, placed in ovens or furnace at various stabilized temperatures, and aliquots were sampled periodically. In each sample, an analysis of the PCB content was performed to establish desorption kinetics at different temperatures. This test determined that a temperature of at least 200°C allowed to obtain a reduction greater than 95% in 4 days; given the small size of the sample, it was decided, for safety reasons, to choose a set temperature of 250°C, which showed a more drastic reduction (Figure 2).

3.2 Treatment unit (pilot scale)

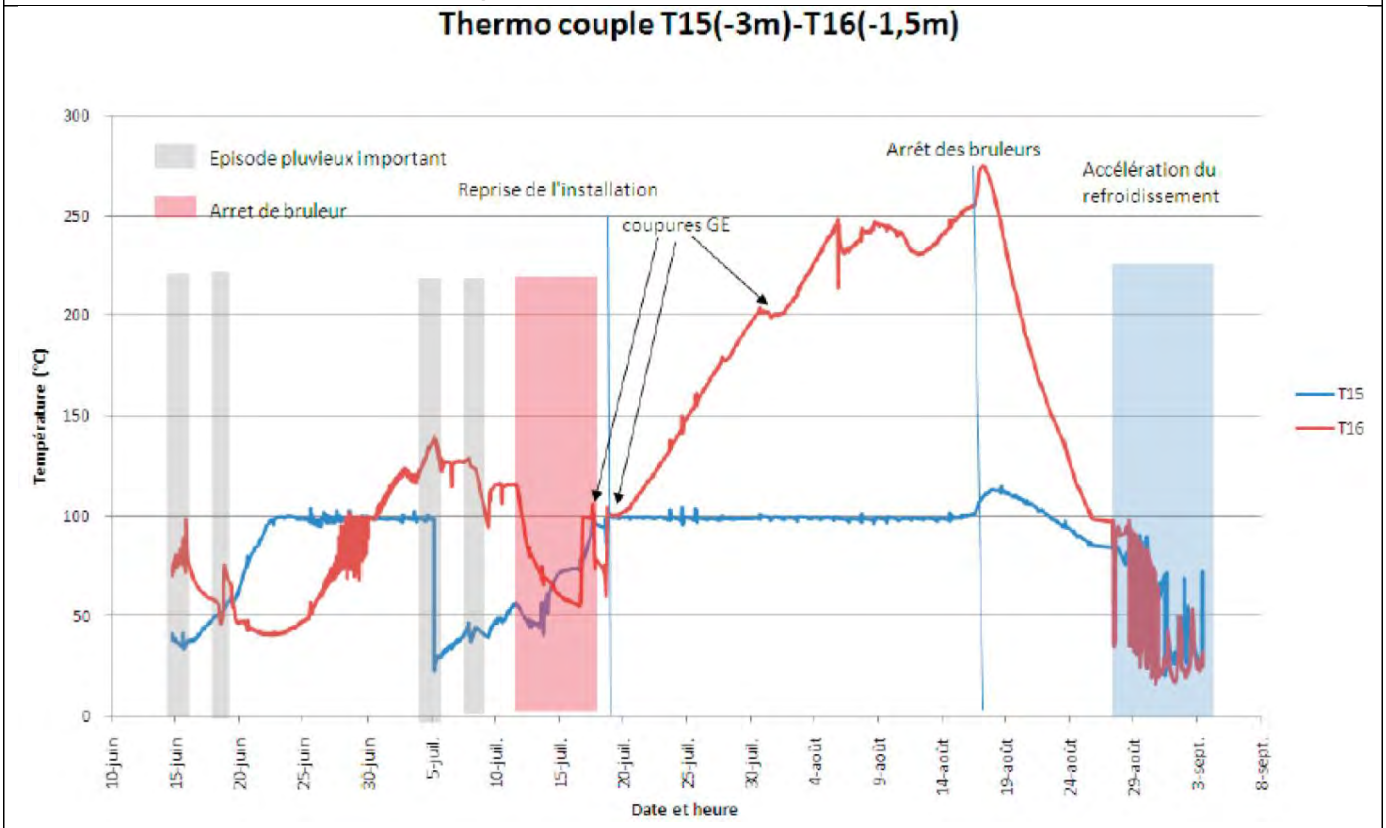


Figure 3 - Monitoring of in situ heating pilot temperatures at 2 depths

A 5 m x 5 m x 5 m lot was chosen on site to validate the technical choices determined during the sizing, such as the set temperature, and moreover that the measures taken allowed to ensure environmental and worker's safety. To remove doubt about air emissions of PCBs and oxidation products (dioxins and furans, Sato et al, 2010), it was agreed with the authorities to carry out this pilot in a containment tent and to analyze the indoor atmosphere.

The first lesson of this pilot was to note the impossibility of practicing in situ desorption at a depth of more than 2 m, because of the special hydrogeological behaviour of this site: the thermocouples at 3 m all presented a plateau at 100°C, related to the presence of water (Figure 3).

The treatment steps of the extracted vapours, including a condensation step, then filtration, made it possible to control the emissions of the process (Figure 4, on the monitoring of PCBs)

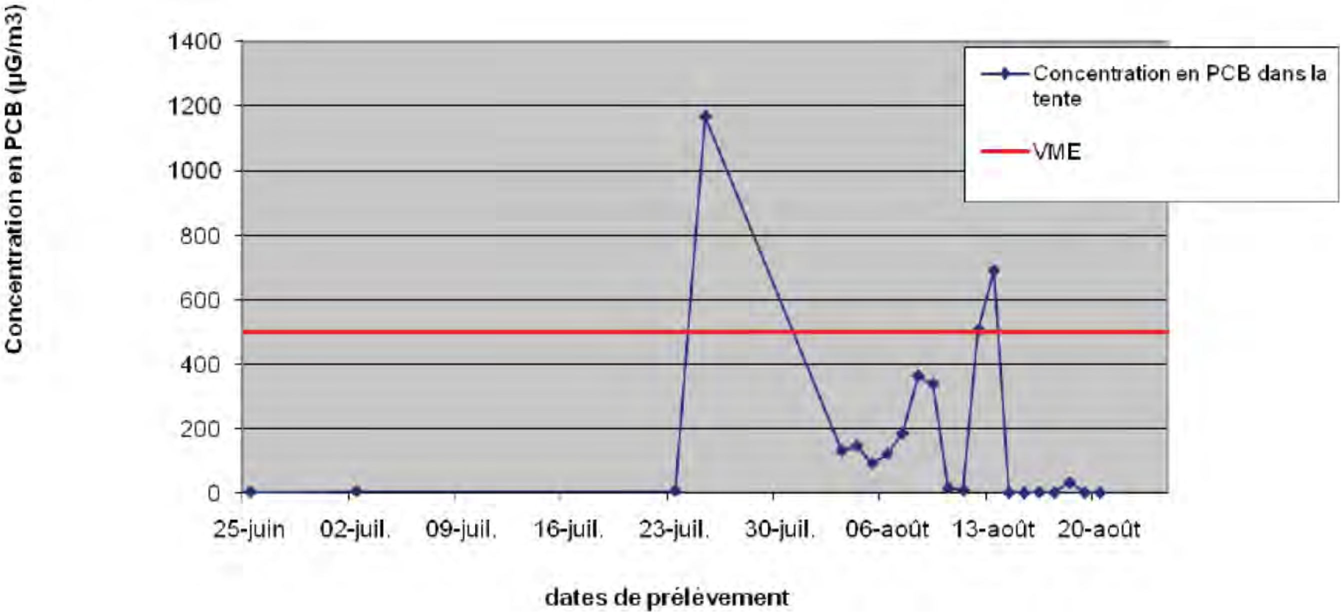


Figure 4 - Monitoring of PCB indoor concentrations, compared to an exposure threshold. (VME: maximum exposure value)

An exhaustive search for PCB degradation products was conducted. To quantify the proportion destroyed in anoxia (pyrolysis in particular), hydrochloric acid emissions were monitored in different compartments of the test (in and out of the tent, as well as at the point of discharge of the treated vapours) (Figure 5)

The particular focus on dioxins and furans being justified by the health impact that they carry, a specific analytical program concerned these PCBs' oxidation products.

In the gas's outlet, the reference value used was the one of the incinerators off-gas Regulation (European Directive 2000/76/EC), i.e. 0.1 ng/m3 in toxic equivalent (ITEQ).

Before activated carbon (before CA) traces of furans appear which are captured by the activated carbons and, consequently, the emissions into the air are much lower than this reference value.

In ambient air, the reference value used is that of inhalation of the Order of 20/09/02 on incineration plants, i.e. 38 µm toxic equivalent/m³. The measurements made show the presence of traces of furans well below this reference value (Table 2).

Echantillon	Débit en L/min	Temps de prélèvement (min)	Volume d'air en L	ITEQ (ng)	Concentration en ng TEQ/m³	Val. Ref (ng TEQ/m³)
Avant CA	2,378	1426	3391,028	2,3	**0,67**	0,1
Après CA	2,324	1607	3734,668	0,1	**0,02**	0,1
Extérieur	2,993	1423	4256,039	0,065	**0,000015**	38
Tente	2,247	1444	3244,668	6,9	**0,00212**	38

Table 2 - Dioxins and furans Concentrations in extracted gases and ambient air

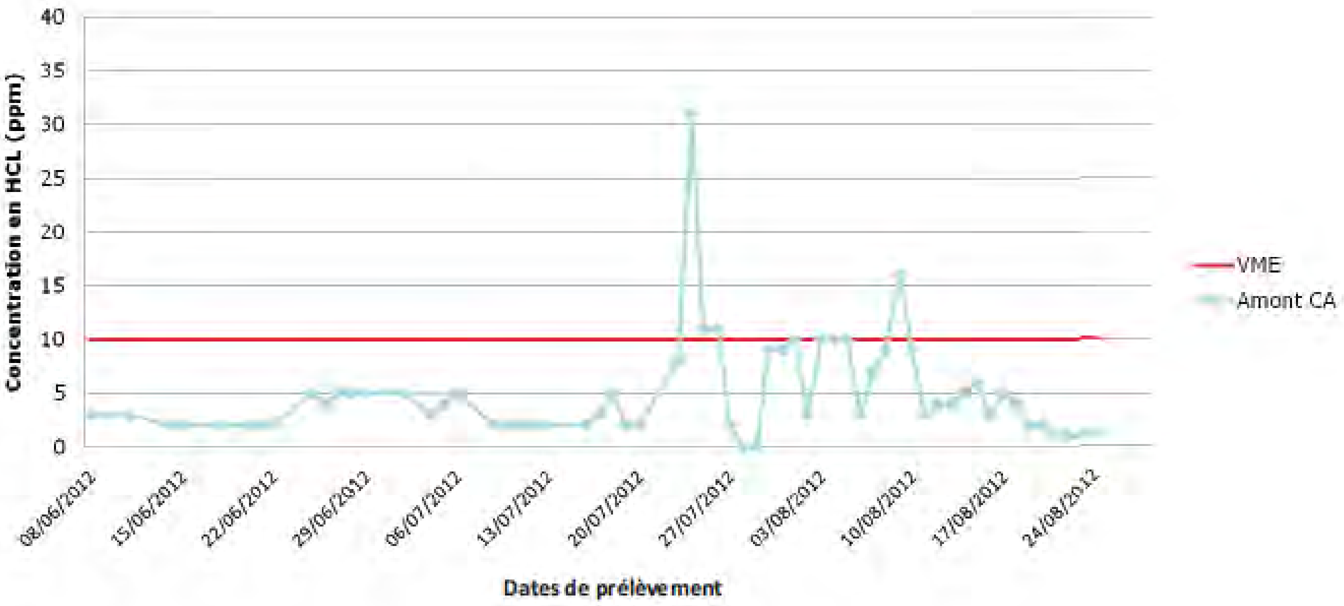


Figure 5 – HCl Before treatment (red threshold = VME: maximum exposure value; out CA: concentration at the outlet of activated carbon filter). Analysis by ATI Multigas Analyzer

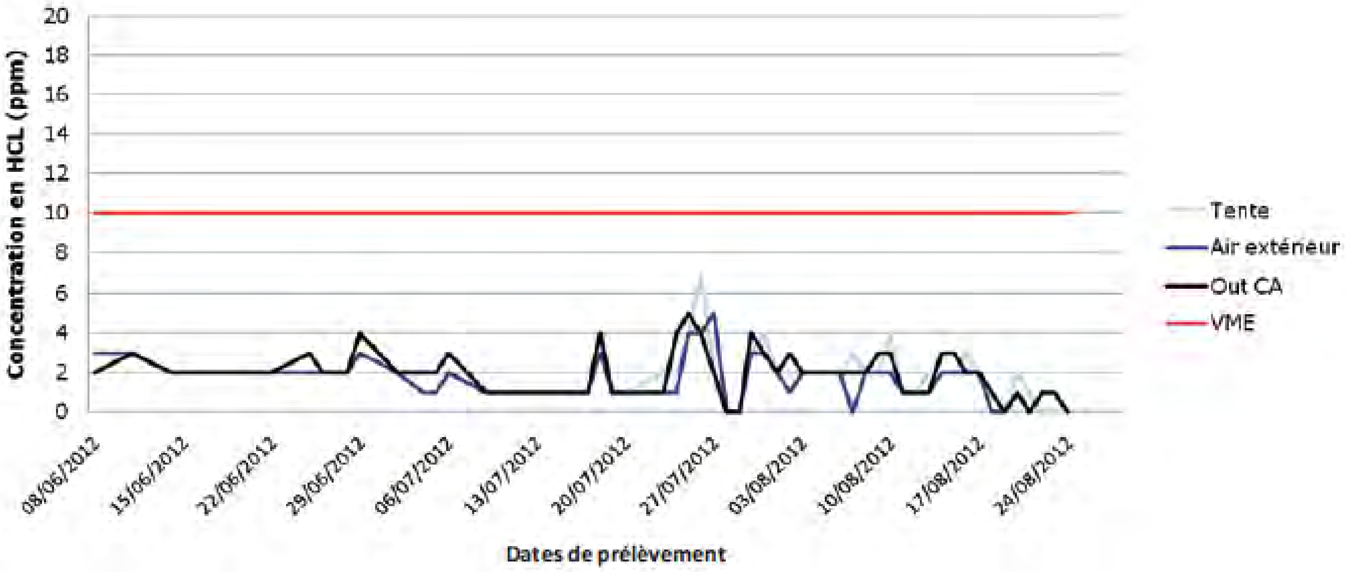


Figure 6 – HCl Concentration at exhaust and ambient air (red threshold = VME: maximum exposure value; out CA: concentration at the outlet of activated carbon filter). Analysis by ATI Multigas Analyzer

3.4 Post Treatment for effluent (pilot scale)

Small sized devices as cooler, demister and active carbon filter were ensuring the treatment of hot gases outing the pilot unit. Condensates were allowed to decant, and water was filtered on active carbon before return to storage industrial pond.

Those steps in the process were considered as known and focus was only given to desorption and PCB values.

4. Full-scale application

4.1 Main treatment unit

A thermopile was equipped with 47 hairpin shaped heating tubes and 96 screened venting tubes. Each 47-heating tube was equipped with a burner. The total heating power installed ranged between 470 kwh and 1200 kWh depending on the regulation and the phase of the treatment.

In the 96 venting tubes, a -10 to -15 kPa aspiration was applied, depending on soil's permeability.

Figure 7 – Main treatment unit (picture)

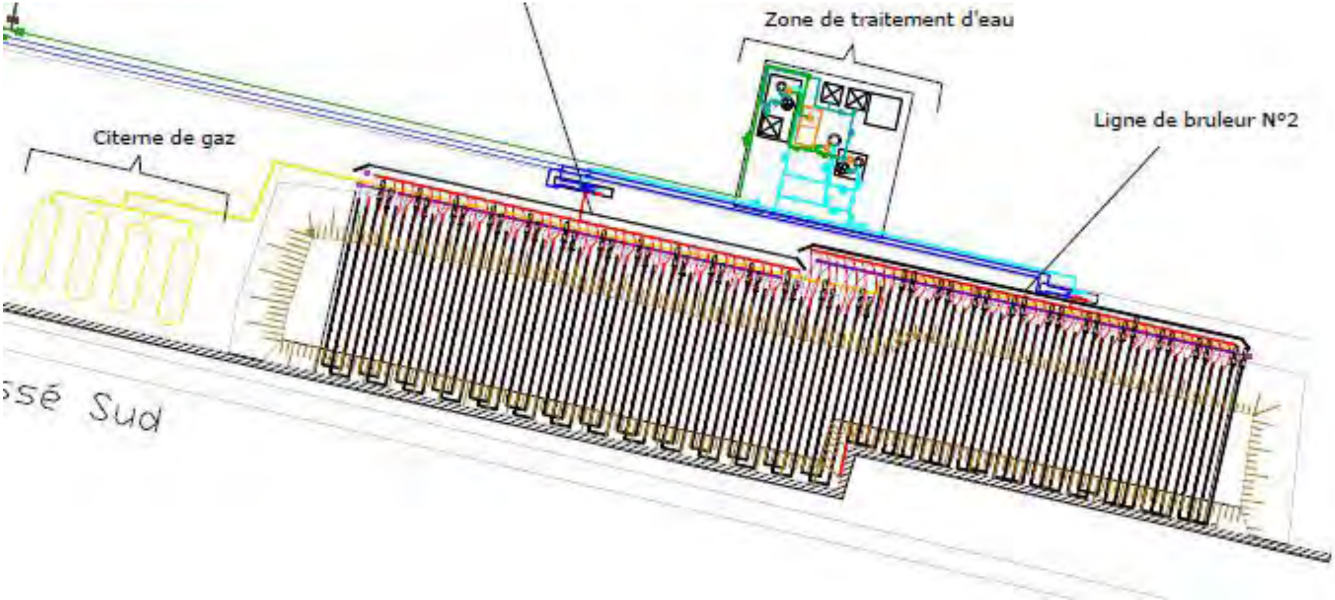


Figure 8 – Main treatment unit (scheme)

4.2 Pre Treatment

A pile was built with the polluted soil: L x W x H = 80 m x 12.5 m x 3.5 m;
Impacted crushed concrete was used to form a drainage bed at the bottom of the pile. Lightly impacted lots of soil were also used as heaps to contain the pile and as heat insulation cover.

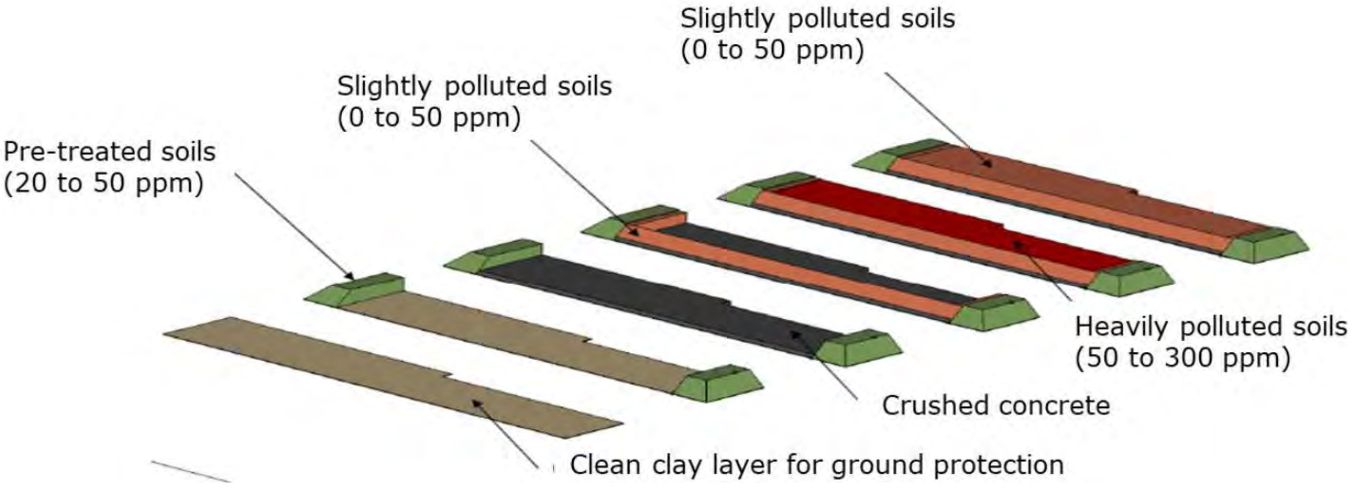


Figure 9 – Drainage bed

4.3 Post treatment for effluent

Vapours from the thermal desorption were pumped through 2 venting lines with strong blowers. Each line comprised a heat exchanger, a demister and 2 active carbon filters

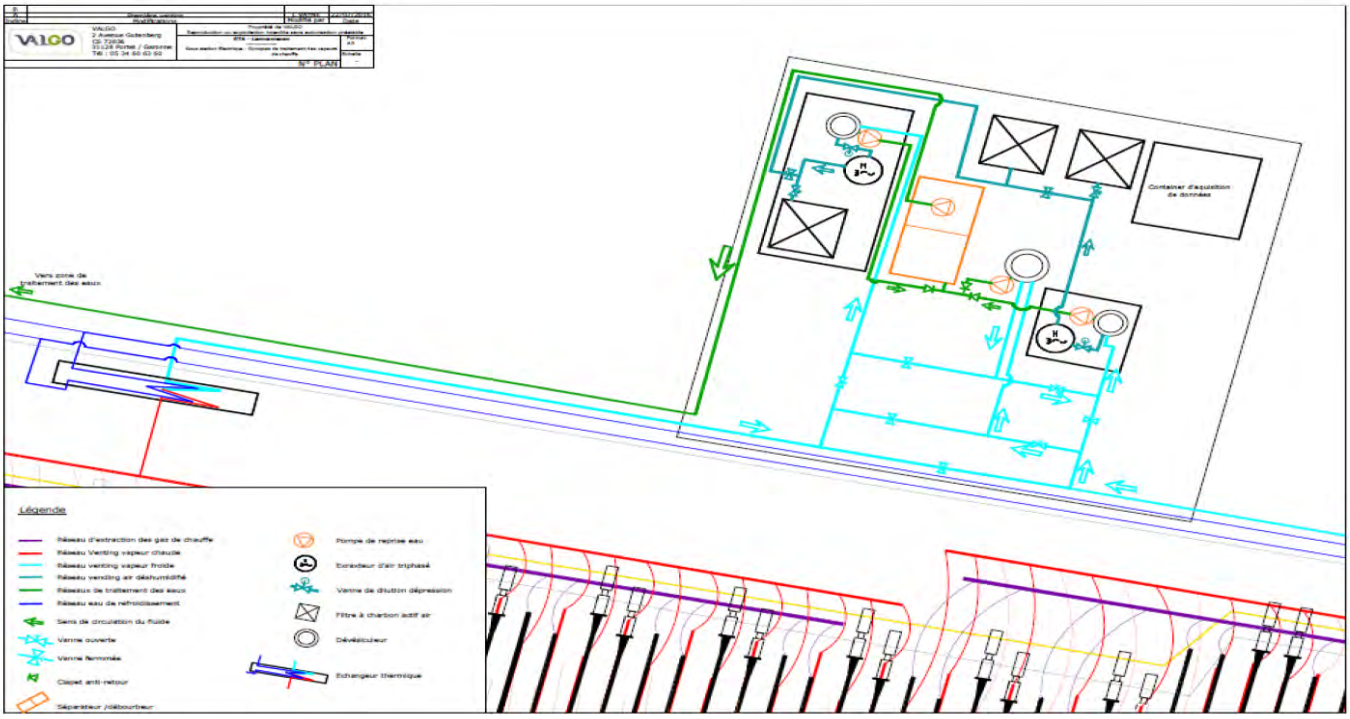


Figure 10 – Air treatment unit

Figure 11 – Heat exchanger

4.4 Post Treatment for water (pilot scale)

Huge amounts of condensates were generated during the temperature plateau at 100°C (up to 10 t per day). A dedicated siphon was designed to trap the dense resins of PCB in the condensates, then a series of active carbon filters treated the liquids, till meeting the mandatory request for water outlet.

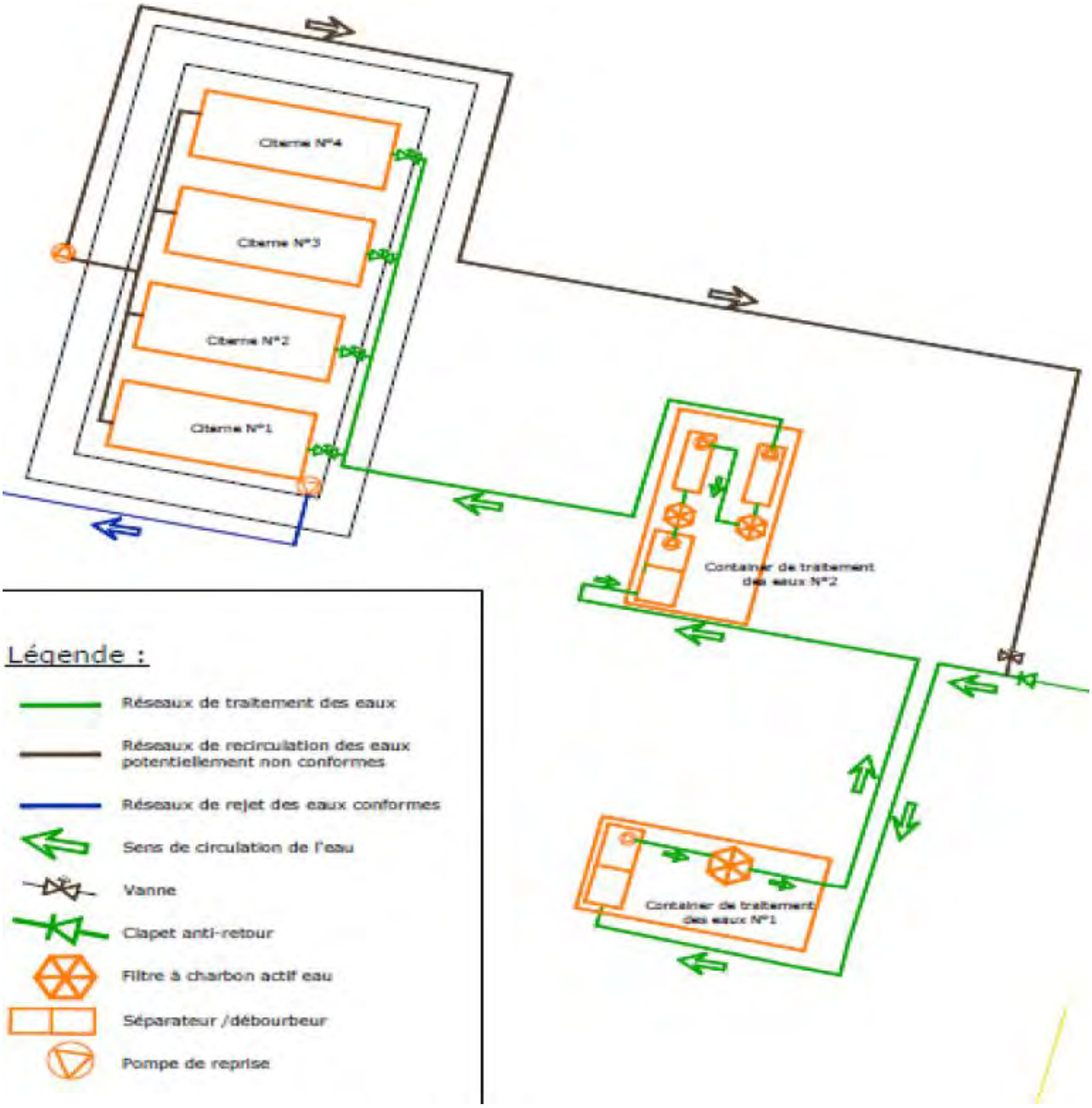


Figure 12 – Water treatment plan

4.5 Control parameters (full scale)

Several stages of survey were established for the different matrix: gases, liquids, ambient air and soil.

Analytical panel included PCB, HCl, dioxins and furans, fume's characters (NO_X, SO_X, CO, CO_2) and none the least temperature in about 100 points, in the mass of soil, or in pipings.

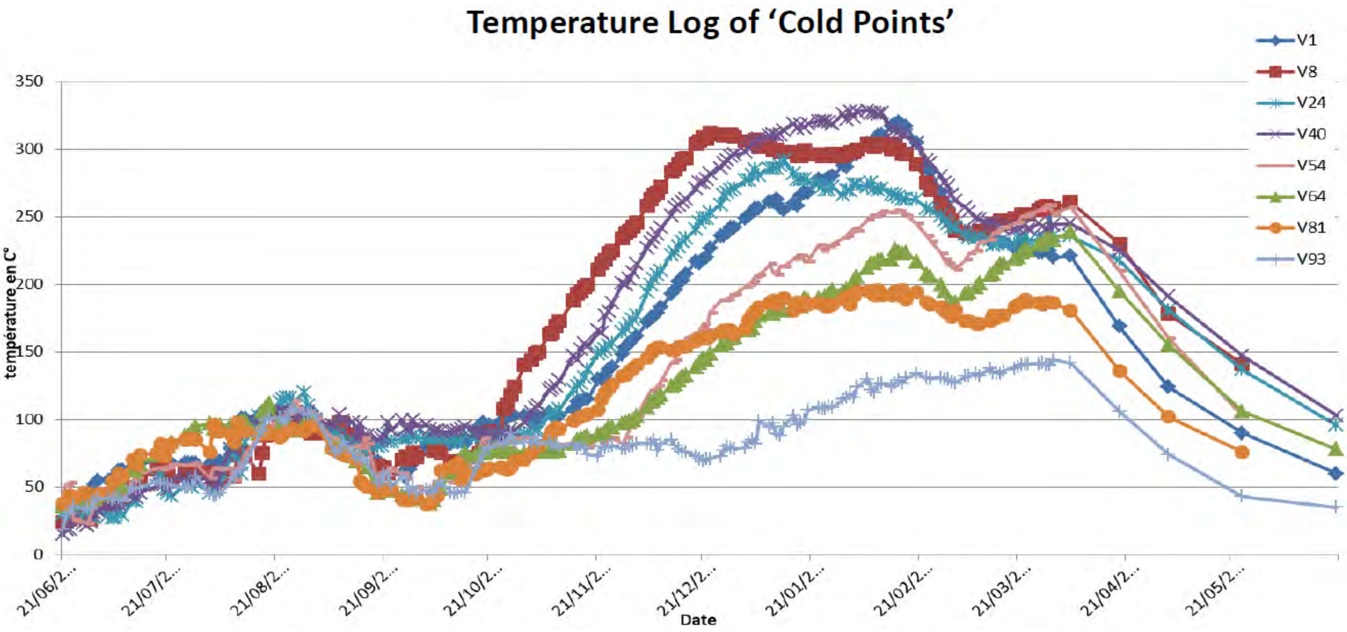


Figure 13 – Survey of temperature in the venting tubes, called cold points

5. Results

5.1 Removal rate

sample	*L2-1*	*L2-2*	*L2-3*	*L2-4*	*L1-1*	*L1-2*	*L1-3*	*L1-4*
[PCB] mg/Kg	*3,10*	*8,78*	*2,31*	*2,76*	*1,79*	*0,84*	*2,25*	*5,10*

Table 3 - Final Concentrations of PCBs after treatment

All results under the 10 ppm limit (average starts at 300 ppm) = 97% elimination.

6. Post treatment and/or Long Term Monitoring

6.1 Post treatment and/or Long Term Monitoring

After a cooling period, dismantling was performed, and cleaned soil was laid on the site.

7. Additional information

7.1 Lesson learnt

This thermal desorption of PCB's polluted soils was the first in the world at this level. Due to physical properties of pollutants, 95% of the removed mass was collected after the heat exchanger.

7.3 Training need

Beside the management of pollutions that our technicians and engineers can manage daily, they need to familiarize with burners, heating and thermodynamic process

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.2

1.1 Name and Surname	Edoardo Robortella Stacul
1.2 Country/Jurisdiction	Italy
1.3 Organisation	Invitalia
1.4 Position	Project Manager
1.5 Duties	Head of Environment Unit
1.6 Email address	estacul@invitalia.it
1.7 Phone number	+39 3473855091

2. Site background

2.1 History of the site

The site of concern is a multi-contaminant polluted soil and sediment area located in an Italian dismissed steelwork plant (metropolitan area of Naples - district of Bagnoli-Coroglio). Over the last century the site has been involved in high-impact industrial activities, from chemical research to steelwork and clinker production. The industrial shutoff occurred definitively in the middle of the ’90 when all the major facilities and plants were decommissioned.

During the following 22 years, the Bagnoli Area has been managed by the municipality of Naples to achieve the land remediation goals according to the new urban planning.

In 2015 Invitalia has been addressed by the Italian Government as the owner of the asset as well as charged of the task for land remediation and urban development.

The environmental heritage of the brownfield is very complex, ranging from wastewater pollution to sediment and soil contamination with several different toxic compounds, both organic and inorganic.

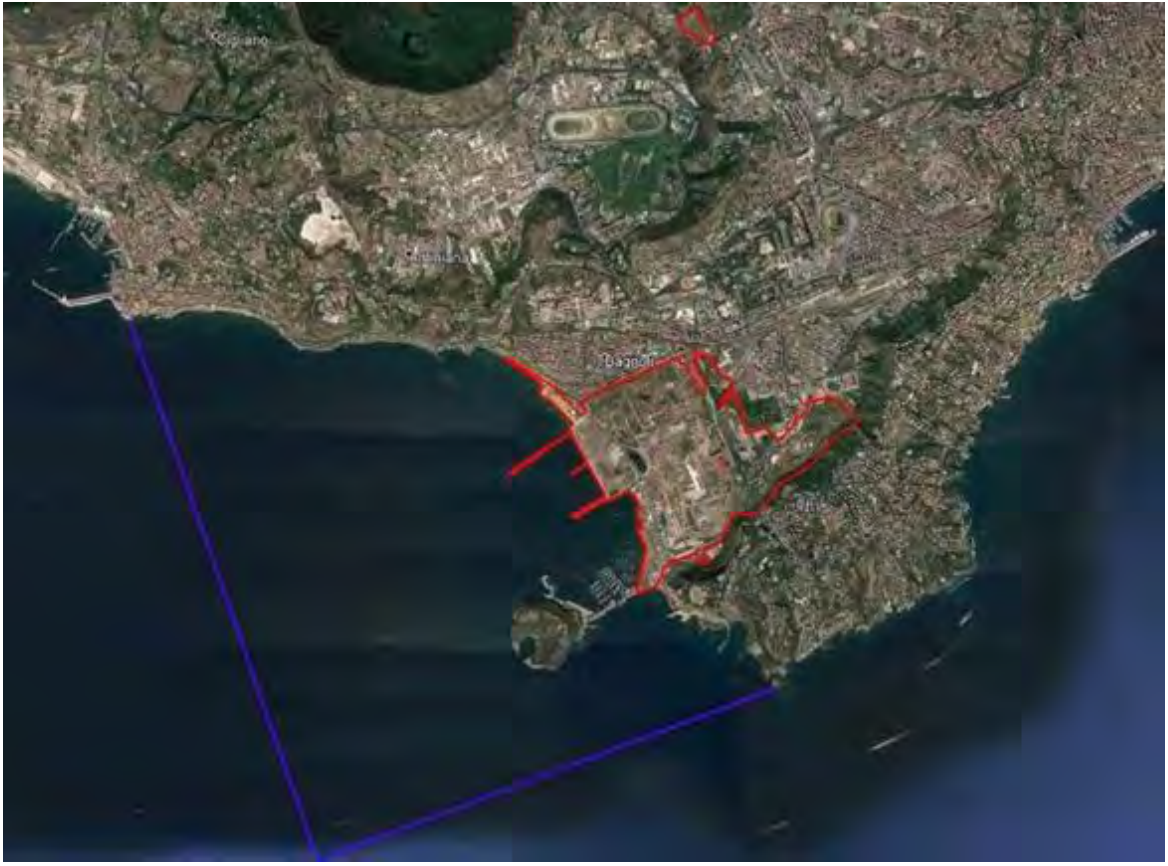


Figure 1 - Delimitation of the brownfield of Bagnoli – Coroglio (in red the inland area and in blue the marine area).

2.2 Geological setting

The study area is in the north-western sector of the Municipality of Naples, confined within the morphological unit of the Bagnoli-Fuorigrotta plain dominated, from a geological point of view, by the volcanic structure of the Campi Flegrei.

The main geological-structural element consists of the vast volcanic caldera which collapsed about 35,000 years ago following the eruption and consequent emplacement of the Campanian Ignimbrite (grey tuff from Campania). The products of this eruption constitute the main lithotypes outcropping along the scarps bordering the western and northern margins of the Flegrea depression and extending eastward along the Camaldoli- Poggioreale alignment (Orsi et al.1996), while they are absent within the area of Campi Flegrei, probably due to erosive processes or because they were covered by vulcanites from the successive eruptions of Campi Flegrei and Vesuvius and by alluvial soils.

Recent volcanic activity, ranging from 35,000 years ago to 1538 AD, can be divided into the following five main phases of activity:

- Volcanism pre-Ignimbrite Campana
- Eruption of the Campanian Ignimbrite and related caldera collapse (first)
- Volcanism between the Campanian Ignimbrite and the Neapolitan Yellow Tuff
- Eruption of Neapolitan Yellow Tuff and related caldera collapse (second)
- Post-Neapolitan yellow tuff volcanism

After the first caldera collapse, the sea entered the morphological depression; over time, the progressive filling of volcaniclastic material led to a new emergence of the area. The Yellow Neapolitan Tuff is the most typical lithoid pyroclastic deposit of this submarine eruptive phase (12,000 years ago). It outcrops along the slopes of the Posillipo hill which closes the area to the southeast, while it is located a few hundred meters below the plain of Bagnoli. The successive volcanic phases, which took place in a subaerial environment, with the works of numerous emission cones, erupted pyroclastic material alternating with paleosols in periods of eruptive quiescence.

The central area of Piana di Bagnoli takes the form of a vast depression behind the dunes bounded towards the sea by a coastal strip. This depression with depositional characteristics of the silty-marsh type was maintained as such at least from the Middle Ages until 1800 A.D., when reclamation and intense anthropization began. The urbanization and industrialization processes have led to a complete morphological transformation of the territory and consequently of the "natural" geological layer. An important blanket of fill land also formed by a component of lithoid material of "industrial" origin mixed with reshuffled ash products covered the entire plain in a non-uniform way to form a new lithological horizon.

Based on previous studies, in the area in which the site of national interest of Bagnoli-Coroglio falls, the following lithological sequences can be identified:

- eluvial, colluvial and torrential deposits
- reworked anthropic deposits, mainly filled with old watersheds
- slope debris and landslide heaps (mainly located at the base of the Posillipo hill) characterized by a high degree of remodelling, up to the coastal strip, in the Bagnoli area, where it is present the former Italsider factory and where there is man- made deposits (processing slag mixed with remodelled natural deposits) and where sands and silts of current and recent coastal environment emerge
- stratified yellow tuffs containing pumice and scoria which constitute a modest relief (altitude of 36 m a.s.l. compared to altitude of 14 m a.s.l. of the base of the relief) which represents the wreck of a small volcano, Monte di Santa Teresa, located near the Cavalleggeri d'Aosta railway station

In the sector closest to the Bagnoli coast, for most of the former Italsider area, there are:

- current and recent coastal sands and silts. These deposits are generally not thickened, often reworked and locally coalescing with anthropic deposits consisting of processing slag. There are also deposits of marshy origin with mainly silty granulometry with peaty levels

In the whole area of the Bagnoli-Fuorigrotta-Soccavo plain, except for the areas immediately below the hills and in the immediate surroundings of Monte di Santa Teresa, the volcanic sequences are quite deep; yellow tuff is generally found in these areas at depths greater than 50 ÷ 80 m below ground level.

The stratigraphies of the boreholes analysed, which go beyond the blanket of backfill, highlight the circumstances described above. In fact, sediments of marine origin, paleo-soils and fine sediments deposited in low-energy environments of a lagoon or marshy nature (peats, silts) are found at various depths.

From a geological point of view, the soils outcropping in the study area are mostly represented by manufactured backfill consisting of very heterogeneous materials by nature, size and degree of compaction, forming a blanket of variable thickness over the entire area.

Everything can be found in man-made deposits: natural material in every grain size and origin, quarry waste, brick artefacts and fragments, residual products of industrial activity, consisting of blast furnace slag, steel mill slag, lateritic remnants mixed with volcanic soils rearranged, stratified and distributed with different thicknesses according to the transformation, over the decades, of industrial processes, resting on a substrate mainly formed by limno-marshy and dune deposits.

At the Bagnoli-Coroglio site, the depth of the water table varies from a few centimetres near the coastline in the west to more than ten meters in the upstream areas in the east.

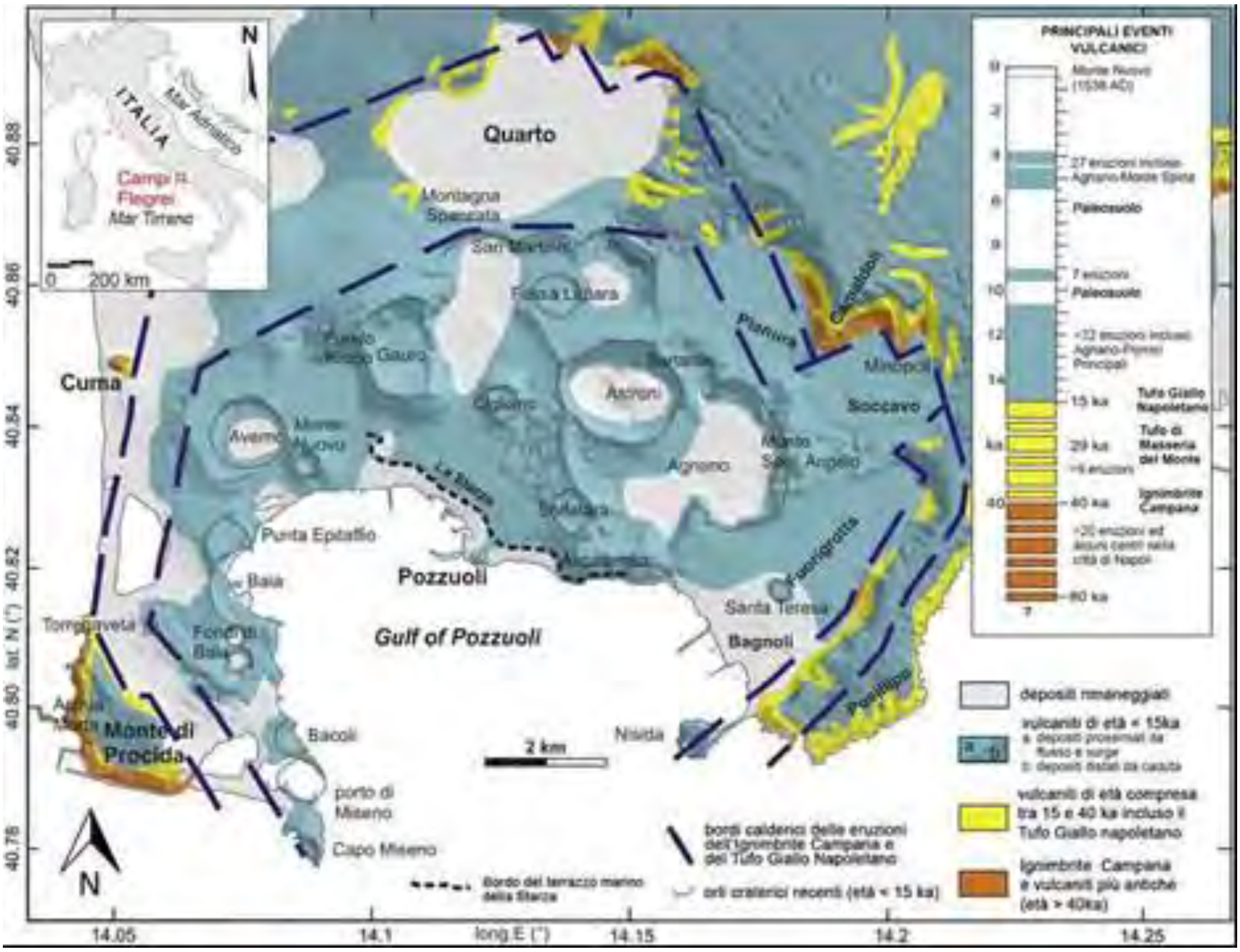
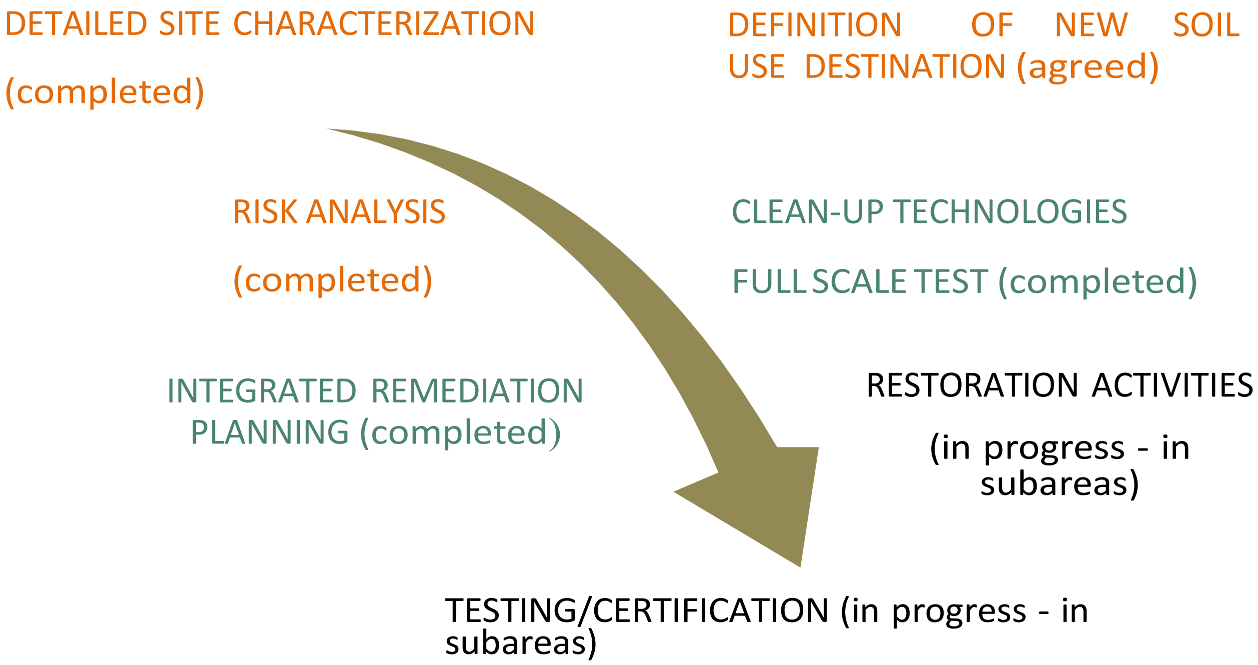


Figure 2 - Geological map of the Campi Flegrei (modified Isaia et al., 2019)

Figure 3 - Typical stratigraphy of the industrial site: fills on volcanic ash

2.3 Contaminants of concern

Environmental restoration activities are being carried out by a step-by-step approach, giving priority to eco-friendly technologies.



DETAILED SITE CHARACTERIZATION

(completed)

DEFINITION OF NEW SOIL USE DESTINATION (agreed)

RISK ANALYSIS

(completed)

CLEAN-UP TECHNOLOGIES

FULL SCALE TEST (completed)

INTEGRATED REMEDIATION PLANNING (completed)

RESTORATION ACTIVITIES

(in progress - in subareas)

TESTING/CERTIFICATION (in progress - in subareas)

In 2018 an updated investigation of the soil has been carried out, by means of 228 sub-superficial prospections and the chemical analysis of more than 900 samples collected. In the following Table 1 the highlights of the survey are presented, including the analytical set of parameters and their minimum and maximum value detected. C1, C2 and C3 refers to the average layer of soil investigated (C1: 0 to -1 m below ground level; C2: -1 m to -2 m below g.l.; C3: -2 m to capillary zone). Some thresholds (in particular: As, Be, Pb and Zn) settled by the Italian law on remediation procedures are replaced by the relative site-specific natural background levels.

Parameter	MAX value [mg/Kg$_{d.m.}$]			MIN value [mg/Kg$_{d.m.}$]			Italian threshold for residential use	Italian threshold for industrial use
	C1	C2	C3	C1	C2	C3		
As	126	181	249	29	30	29	29	50
Be	-	79	-	-	79	-	9	10
Cd	220	4,1	4,5	2.3	2	2	2	15
Co	-	181	147	-	181	147	120	250
Cr	306	3.620	2820	164	155	168	150	800
Hg	8.9	6.8	4.3	1	1.1	1.3	1	5
Ni	-	-	130	-	-	130	120	500
Pb	6.782	13.379	647	105	105	114	103	1.000
Cu	379	1.766	1.046	129	122	139	120	600
Sn	87	180	317	14	14	16	14	350
V	956	1.756	233	104	105	104	100	250
Zn	1.940	2.607	1.317	165	159	159	158	1.500
HC>12	827	11.984	11.890	50	50	52	50	750
HC<12	13	27	19	13	27	19	10	250
PAHS	334	1778	76	11	11	11	10	100
PCBs	52	35	16,6	0;06	0,06	0,07	0,06	5

Table 1 - Concentration levels of pollutants from the preliminary soil investigation in the brownfield.

Analytical data have been validated by the Italian National System of Environmental Protection (SNPA) and they are considered to set a preliminary grid of potentially applicable remediation technologies. The grid underwent the examination of the technical board at the Italian Ministry of the Environment and four main technologies have been selected: soil washing, thermal desorption, in-situ chemical oxidation (ISCO) and bio-In Situ Thermal Desorption.

2.4 Regulatory framework

Accumulation of heavy metals and organic compounds in environmental matrices such as soil, sediment and groundwater, especially those originating from anthropogenic sources, poses a major hazard for soil ecosystem and biosphere, due to the high risks to the human health and the natural habitats.

Despite the European Directive 2018/851/CE on wastes sets at the lower level of its hierarchy the excavation followed by disposal in permitted landfilling as industrial treatment, such practice is usually still carried out to manage contaminated soils, sediments and polluted materials.

Methods such as stabilization/solidification, vitrification, electro-remediation, soil washing, thermal desorption, phytostabilisation and phytoextraction have been assessed, both on lab and field scale, to reduce the concentration and declassify the toxicity of pollutants.

Successful combination of different treatment technologies has been tested as well and life cycle assessment (LCA), energy consumption and overall environmental impact and sustainability studies have been carried out in the last research decades.

Among the treatment technologies multiple-recycling oriented, soil washing and thermal desorption are among the most used techniques for contaminated site restoration, such brownfields, and they are regarded as reliable and permanent treatment alternatives to disposal to reduce and remove organic and inorganic pollutants from soils and sediments.

Properties of contaminated soil might differ from those of natural soil and considerably differ after a chemical/physical treatment, most of all in terms of agronomic properties. A preliminary soil characterization together with a detailed analysis and monitoring of soil properties throughout the whole process are therefore necessary to assess, on one hand, genotoxic effects and the consequences and impacts on fertility of the ecosystem and, on the other hand, to estimate the economic feasibility of a treatment technology for each specific remediation, particularly when a restoration activity of a brownfield is strictly intertwined with a requalification process and reuse of the soil such as the present case study.

The application of thermal desorption has been included in the overall feasibility study on the entire site, which underwent in August 2020 the examination of the scientific and control bodies to get permits and directions. Since 2017 a cooperation with the University of Milan – Department of Science of the Earth has been signed to have the scientific support for the full-scale application.

3. Pilot-scale

3.1 Laboratory Study

Soil and sediment samples were collected from six sub-areas (from A to F) of about 625 m2 each as showed in the Figure 4, five of those located inside the brownfield (in soil matrix) and the sixth on the shoreline by the former facility (in sediment matrix). All the sub-areas have been previously cleaned by vegetation and bulky materials.

On each sub-area five different zones were investigated to a maximum 2 m depth, using a truck crane equipped with digging buckets.

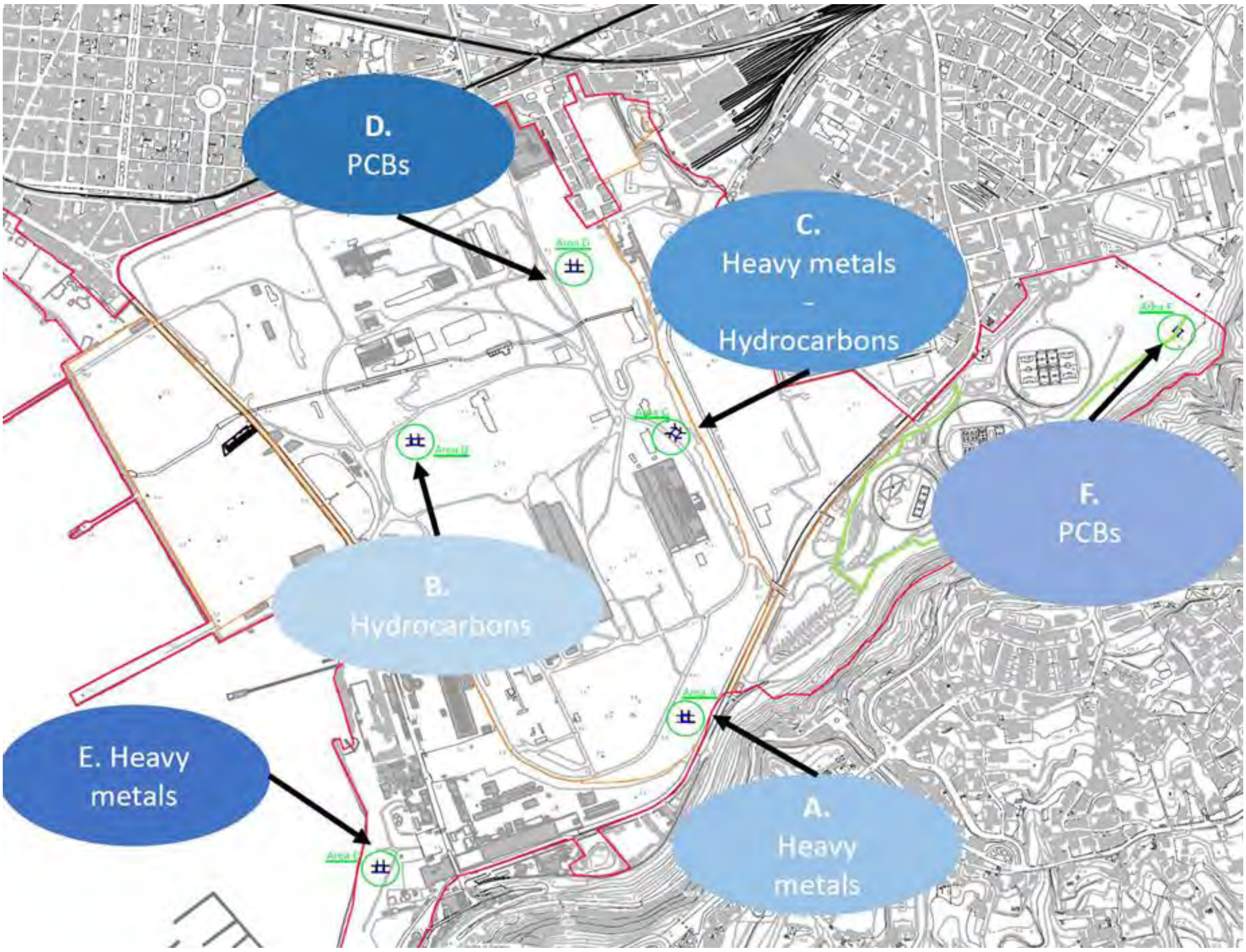


Figure 4 - Sub-areas location in the brownfield investigated

- Sample preparation on site

The amount of soil/sediment collected underwent an accurate cleaning step to remove eventual coarse impurity, then they are pooled into one composite sample of approximately 100 kg (wet weight), according to national guidelines UNI 10802:2013 on manual sampling of wastes. Size fraction below 2 cm from the dry sieving was used for further investing as shown in the following.

- Sample preparation in laboratory

The composite sample set for heavy metals and organic compounds quantification has been oven-dried at 45 °C, then manually disaggregated, homogenized and subsequently sub-divided by a splitter. The prepared samples were dry sieved into particle-size fraction

<2 mm through normalized sieves positioned in an analytical sieve shaker for 10 min.

The composite sample set for asbestos quantification has been oven-dried at 105 °C, then homogenized to a size fraction <100 nm.

Size fractions of the samples > 4 mm from the dry sieving were used for further leaching tests and extractions.

- Mineralization and extraction step

Samples surveyed underwent different extraction/dissolution procedures.

To detect the heavy metals, three aliquots of 300 mg for each soil sample have been weighed by a Mettler Toledo mod. XPR-204 and put in Teflon vessels. Such vessels underwent a single program of mineralization in high pressure microwave oven milestone mod. MLS 1200 mega, with a thermic cycle adding of 8 mL of acqua regia (HNO_3 + HCl, ratio 1:3) and 2 mL of H_2O_2 as shown in Table 2.

	Power (W)	Temperature (°C)	Time (min)
Step 1	1200	120	3
Step 2	1200	120	1
Step 3	1800	175	4
Step 4	1800	175	12

Table 2 - Thermic program of mineralization for standard solution

HF hasn't been used for digestion as recommended for soil samples because HF addition would have needed following neutralisation with boric acid and such further addition of acids to solution would have brought a strong depletion of signal during readings.

After cooling and centrifugation at 3000 rpm for 10 minutes, all the samples have been transferred into class A calibrated glass 50 mL (previously washed with an acid solution) and brought to final volume with deionized water. Eventually the particulate still present in the solution has been settled and a blank of reference with the same criteria of sample treatment has been produced.

To detect dioxins an extraction is carried out by ASE (automatic sample extraction) and the extract is subsequently purified in silica and alumina column.

- Pre- and post-treatment analytical characterization of collected samples

The list of the main reagents used is the following: HNO3 Honeywell Puriss. P.A. >=65%; HCl Honeywell Puriss. P.A. >=37%, and H2O2 30 vol v/v Sigma Puriss.

Soil pH and electrical conductivity were measured in 1:2 v/v soil-distilled H_2O suspensions by Hanna Instruments mod. HI7007L/C with a buffer solution at pH 7,01.

The concentrations of inorganic elements and organic compounds were measured using the following standard methods and instrumental analysis as reported in Table 3.

Element	**Method**	**Instrumental analysis**	**Model equipment**
Free cyanide	EPA 9014A 2014 L	Manual SP	Agilent Cary 60
Inorganic Anions (Cl, F, SO_4)	EPA 9056A 2007	IC	Dionex ICS 1000
Heavy Metals	EPA 6020B 2014	ICP-MS	Agilent 7500/7800
Cr VI	EPA 7199 1996	IC-UV detector	Dionex ICS VWD
Asbestos	CNR-IRSA Q64(3) 1996	SEM	Zeiss EVO MA10
TPH (C>12)	EPA 8015D 2003	GC-MS	GC Agilent 6890/7890
TPH (C≤12)	EPA 8015D 2003 (FP&T)	GC-FID	GC Agilent 6890/7890
BTEX	EPA 8260D 2018	GC-MS	GC Agilent 6890 + MS Agilent 5973 5975 5977
VOCs	EPA 8260D 2018	GC-MS	
Aromatic amines	EPA 8270E 2018 MixA	GC-MS	
Phenols and phthalates	EPA 8270E 2018 MixA	GC-MS	
Pesticides (DDT, DDE, DDD)	EPA 8270E 2018 MixA	GC-MS	
PAHs	EPA 8270E 2018 MixA	GC-MS	
PCBs	EPA 8082A 2007	GC-ECD	GC Agilent 6890 Thermo Finnigam MAT 95XP and Thermo Fischer Scientific DFS
PCCD/PCDF	EPA 1613B 1994	GC-HRMS	

Table 3 - Methods and analytical instruments used

Total organic carbon (TOC) was assessed to measure the organic content of bulk soil and particle size fractions with a TOC analyser (TOC-VCPH/CPN Shimadzu).

Oxidising	Na-Persulfate	-
	Na-Persulfate with basic activator	NaOH at pH 10
	Na-Persulfate with Fe_EDTA activator	-
	Na-Percarbonate	-
	Na-Percarbonate with basic activator	NaOH at pH 10

Table 4 - Characteristic of leaching agents used in the soil washing procedure

3.2 Treatment unit (pilot scale)

The pilot scale unit is an integrated system set up with a thermal desorber and a soil washing system. The integrated system is in a Research Centre in Belgium where all the activities have been carried out.
The post treatment units are part of a more general system which cover the entire Research Centre.

Soil washing procedure on lab-scale application

- Wet screening

The aliquot of sample sieved at a mesh width of 20 mm underwent a further wet screening using room-temperature tap water in 5:1 L/S ratio.
The fraction between the mesh width from 2 mm to 20 mm is then kept in a washing rotating drum for 15 minutes using room-temperature tap water in 2:1 L/S ratio.
The fraction between the mesh width from 63 µm to 2 mm is diverted to the soil washing treatment and/or to the attrition cells.
The fine fraction (mud) has been settled by gravity to separate the liquid phase from the solid one (thickened mud). Samples of thickened mud have been dried at air temperature and then stored for further control analysis.

- Application of leaching agents

The list of the starting different leaching agents (surfactants, chelants, acid/basic solutions, reducing/oxidising agents and two process waters) tested and evaluated on lab-scale is reported in the following Table 5.

	Leaching agent	**Model/Operative conditions**
Surfactants	Non-ionic surfactant_1	Tween 80, 2% solution
	Non-ionic surfactant_2	Brij 35, 2% solution
	Non-ionic surfactant_1 + anionic surfactant	Tween 80, 2% solution + SodiumDecylBenzeneSulfonate (SDBS)
	Non-ionic surfactant_2 + anionic surfactant	Brij 35, 2% solution+ SodiumDecylBenzeneSulfonate (SDBS)
	Saponin	2% solution
Chelants	Ethylenediaminetetracetate (EDTA)	pH 9 and pH 10.5
	Ethylenediaminedisuccinate (EDDS)	pH 7 and pH 9
	Citric acid	pH 9
Acid/Basic solutions	HCl 37% v/v or NaOH 1M	Adjustment to reach pH 5, 7 or 9 according to the starting pH

Table 5 – List of surfactants, chelants and solutions used

- Thermal desorption procedure on lab-scale application

A preliminary screening has been carried out through Thermo Gravimetric Analysis (TGA) using a mass spectrometer model Pfeiffer Omnistar GSD 301, followed by a thermal treatment in static furnace model Heraeus K 750/2 equipped with an air circulation system in a usable workspace of 55 L at rated temperature of 750 °C (heating-up time 105 min) and a rotary tube furnace for continuous process model Naberthrm RSRC 120/750/13.

- Additional lab-scale treatments

In addition to the treatments two more process were applied on lab-scale (scrubbing and density separation). The purpose of such treatments is to evaluate the effectiveness of the separation techniques for the soil washing process to achieve treatment targets set for specific granulometric fraction.

1. Attrition scrubbing

For each area a 500 gr sample of solid material - in the specific the fraction from the wet screening between the mesh width from 63 µm to 2 mm - underwent a separation process in attrition cells to scrub the surfaces of particulates and liberate polluted materials. A floating device mod. Denver D12 equipped with an attrition scrubber has been used, with a 15 minute detention time and a room-temperature water in 1:1 L/S ratio.

2. Density separation (Floatation)

For each area a 35 g sample of solid material - in the specific the fraction from the wet screening between the mesh width from 63 µm to 0,5 mm - underwent a density separation process in vertical glass cylinders by means of two dense fluid solutions prepared with sodium-metatungstate solutions (hexasodium tungstate hydrate or Poly-salt). The Poly-salt solutions were prepared at specific gravity of 2,0 g/ml and 2,8 g/ml, each in 2:1 L/S ratio.

4. Full scale application

4.1 Main treatment unit

From each area 300 tons of solid materials (150 tons dedicated to the full-scale application of soil washing and 150 tons dedicated to the thermal desorption) have been collected and then processed as previously reported.

Pre- and post-treatment analytical characterization of collected samples The same as previously reported.

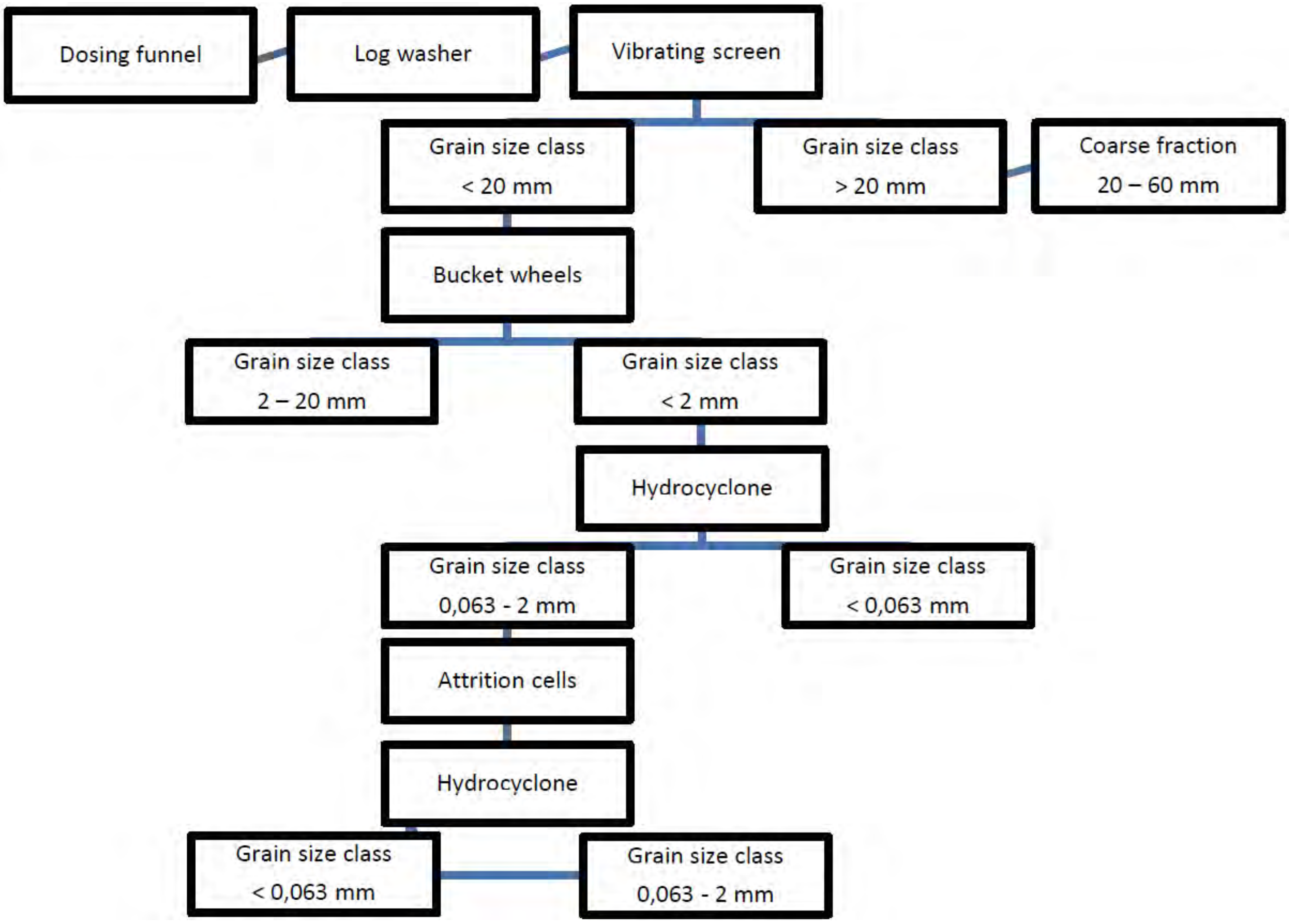


Table 6 – Flowchart for soil washing

Soil washing procedure on full-scale application

From each sub-area 150 tons of solid materials have been processed with two different washing tests: the first half (75 tons) has been treated with water at fixed pH (pH 6 +/- 0,5) while the second half with the same water added with chemicals in adherence to the outcomes of the lab-scale tests (treatment of sub-areas A, C and F using Na-

Persulfate; treatment of sub-areas B, D and E using EDTA).

The inlet of every run has been divided in four grain size classes: fine fraction (< 63 µm), sandy fraction (63 µm - 2 mm), gravelly fraction (2 mm - 20 mm) and coarse (20 mm - 60 mm).

According to the outcomes of the lab-scale tests, a short list of chemicals has been selected to pursue the full-scale application, in particular the leaching agents chosen are pH-adjusted water and pH-adjusted water + EDTA.

- Thermal desorption procedure on full-scale application

From each sub-area 150 tons of solid materials have been processed at two different temperatures: the first half (75 tons) at 480 – 500 °C while the second half at 550 °C in adherence to the outcomes of the lab-scale tests (TGA analysis).

The inlet of every run has been pre-heated for 20 min in a rotating drying drum using LPG as primary heat source. The full-scale plant is a rotating and inclined oven equipped with an exhaust gas treatment system (baghouse filters coupled with thermal oxidizer working at 850 °C and retention time of 2 seconds).

4.2 Monitoring of the chemical parameters

Precision and accuracy of analytical methods have been valued by means of different laboratory techniques and reference materials, involving both the pretreatment and the post-treatment analytical characterization for lab-scale and full-scale applications.

The analytical quantification of inorganic micropollutants and organic compounds in the reference materials selected have been carried out in the same experimental conditions as for the investigated samples.

The average single analytical batch is composed as follow: blank>increasing points on calibration curve>ICV>ICB>ICSA>ICSAB>MB>LCS>LCSD>run (20 samples)>CCV>CCB.

Blind samples of certified materials

Four different reference materials in soil matrix, produced in compliance with the ISO 17034:2016, have been used spot as blind samples during the runs, two for the determination of inorganic micropollutants and two for the organic compounds of interest, as shown in the next Tables 7 and 8.

	UAMB001RM		UAMB035RM	
	Certified	Detected	Certified	Detected
As	8.70 ± 0.4	9.60 ± 2.4	8.80 ± 0.8	9.70 ± 2.4
Be	1.10 ± 0.06	1.00 ± 0.25	0.61 ± 0.04	0.59 ± 0.15

Cd	2.40 ± 0.06	2.60 ± 0.65	1.42 ± 0.08	1.50 ± 0.38
Co	8.50 ± 0.4	10.0 ± 2.5	8.20 ± 0.4	9.5 ± 2.4
Cr	61 ± 4	71 ± 18	67 ± 4	77 ± 19
Cu	80 ± 3	86 ± 22	215 ± 9	230 ± 57
Hg	0.95 ± 0.06	0.94 ± 0.24	0.15 ± 0.01	0.16 ± 0.04
Ni	55 ± 2	61 ± 15	42 ± 2	43 ± 11
Pb	354 ± 10	340 ± 85	549 ± 20	540 ± 130
Sb	7.50 ± 0.4	8.7 ± 2.2	10.8 ± 0.6	12.0 ± 3.0
Se	2.20 ± 0.3	2.30 ± 0.58	0.70 ± 0.20	0.92 ± 0.23
Sn	7.00 ± 0.4	6.6 ± 1.7	18 ± 2	17 ± 4.3
Tl	2.50 ± 0.1	2.70 ± 0.67	0.26 ± 0.02	0.28 ± 0.07
V	42 ± 3	53 ± 13	43 ± 2	50 ± 12
Zn	360 ± 10	390 ± 96	550 ± 20	550 ± 140

Table 7 - Certified and found values of inorganic micropollutants (as mg/kg d.m.) detected in reference materials UAMB001RM and UAMB035RM (soil matrix)

	UAMB001RM		UAMB035RM	
	Certified	Detected	Certified	Detected
Anthracene	37.8 ± 2.7	30.0 ± 10	137 ± 16	149 ± 2.0
Benzo(h)anthracene	281 ±.12.9	220 ± 70	1239 ± 90	770 ± 170
Benzo(a)pyrene	237 ± 9.82	210 ± 60	950 ± 78	720 ± 160
Benzo(b)fluoranthene	281 ± 21.4	180 ± 50	1059 ± 94	1060 ± 140
Benzo(e)pyrene	202 ± 9.74	180 ± 60	656 ± 49	490 ± 120
Benzo(ghi)perylene	183 ± 8.86	150 ± 40	406 ± 28	420 ± 70
Benzo(k)fluoranthene	157 ± 8.78	97 ± 30	594 ± 53	380 ± 80
Benzo(j)fluoranthene	165 ± 11.3	150 ± 50	732 ± 73	530 ± 120
Chrysene	320 ± 14.6	230 ± 70	1366 ± 108	1590 ± 180
Fluoranthene	473 ± 19.5	400 ± 120	1956 ± 131	1860 ± 260
Indeno[1,2,3-cd]perylene	164 ± 9.48	110 ± 30	464 ± 43	430 ± 70
Perylene	47.7 ± 3.02	47.0 ± 10.0	153 ± 15	99 ± 30
Phenanthrene	219 ± 11.2	180 ± 50	850 ± 69	560 ± 110
Pyrene	515 ± 22	450 ± 140	2215 ± 132	1500 ± 310

Table 8 - Certified and detected values of inorganic micropollutants (as µg/kg d.m.) in the reference materials UAMB003RM and UAMB022RM (soil matrix)

Certified reference materials

Three different certified reference materials in soil/sediment matrix have been used to control the quality of the whole procedure, in particular: CRM NIST 1867a (bulk asbestos uncommon), CRM NIST 1866b (bulk asbestos common) and CRM Wellington WMS-01 (PCDDs and PCBs).

For asbestos and PCBs analysis, the score of round-robin tests has considered satisfactory.

In the following Table 9, a comparison between found and certified values for each single congener of dioxins present the certified reference material used is shown

	CRM Wellington WMS-01	
	Certified	Detected
2,3,7,8-TCDD	17.7 ± 5.6	18.9 ± 8.3
1,2,3,7,8-PeCDD	7.96 ± 2.8	8.79 ± 0.35
1,2,3,4,7,8-HxCDD	8.66 ± 2.7	7.18 ± 0.29
1,2,3,6,7,8-HxCDD	20.8 ± 4.8	22.4 ± 0.91
1,2,3,7,8,9-HxCDD	17.3 ± 8.0	17.6 ± 0.72
1,2,3,4,6,7,8-HpCDD	293 ± 63	302 ± 12
1,2,3,4,6,7,8,9-OCDD	1899 ± 456	1913 ± 80
2,3,7,8-TCDF	52.5 ± 16	56.2 ± 2.3
1,2,3,7,8-PeCDF	12.6 ± 5	13.2 ± 0.53
2,3,4,7,8-PeCDF	18.5 ± 6	20.0 ± 0.82
1,2,3,4,7,8-HxCDF	67.3 ± 24	60.7 ± 2.5
1,2,3,6,7,8-HxCDF	20.3 ± 8.7	20.2 ± 8,7
1,2,3,7,8,9-HxCDF	2.68 ± 4.0	2.68 ± 0.82
2,3,4,6,7,8-HxCDF	16.0 ± 8.0	15.1 ± 0,61
1,2,3,4,6,7,8-HpCDF	299 ± 73	307 ± 0.70
1,2,3,4,7,8,9-HpCDF	15.1 ± 4,6	15.1 ± 4,6
1,2,3,4,6,7,8,9-OCDF	509 ± 157	517 ± 21

Table 9 - Certified and detected values detected in the certified reference material CRM Wellington WMS-01

5. Results

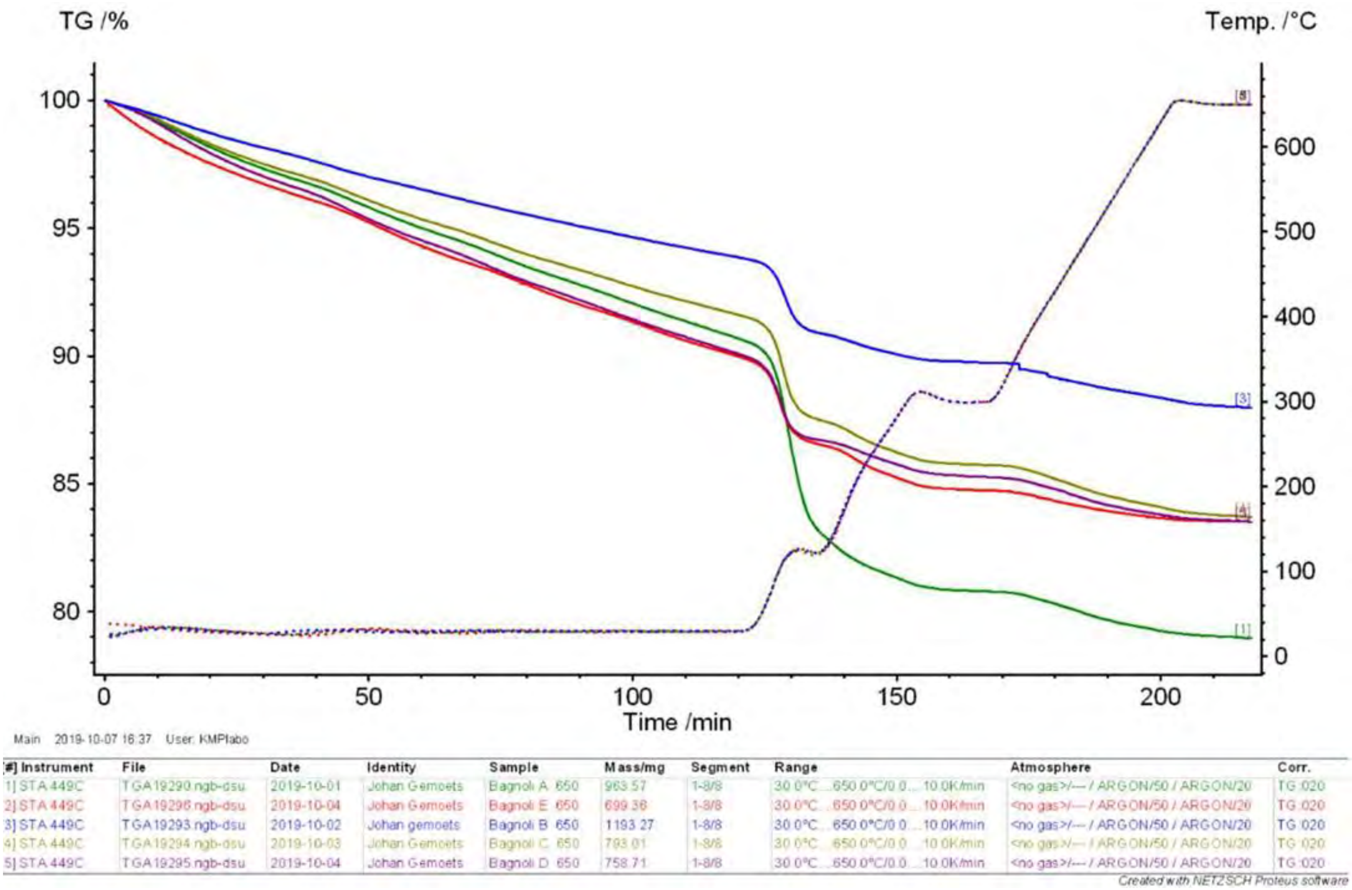
5.1 Removal rate

- Preliminary Thermo Gravimetric Analysis (TGA)

TGA analysis compares the temperature versus contaminant evaporation profiles, measuring the loss of mass of the soil sample in function of a rising oven temperature, and it is generally performed to project the suitable heating parameters for subsequent full scale treatments. The tests have been carried out on the five soil/sediment samples obtained after a further homogenization step and the removal of the soil fractions > 2 mm by means of dry screening. Tests have been performed within a temperature range of 20 °C to 650 °C under a flow of inert carrier gas.

The maximum heating of the soil was reached at a rate of 10°C/min, with temporary isothermal periods at 100 °C (water evaporation) and 300 °C (midrange temperature).

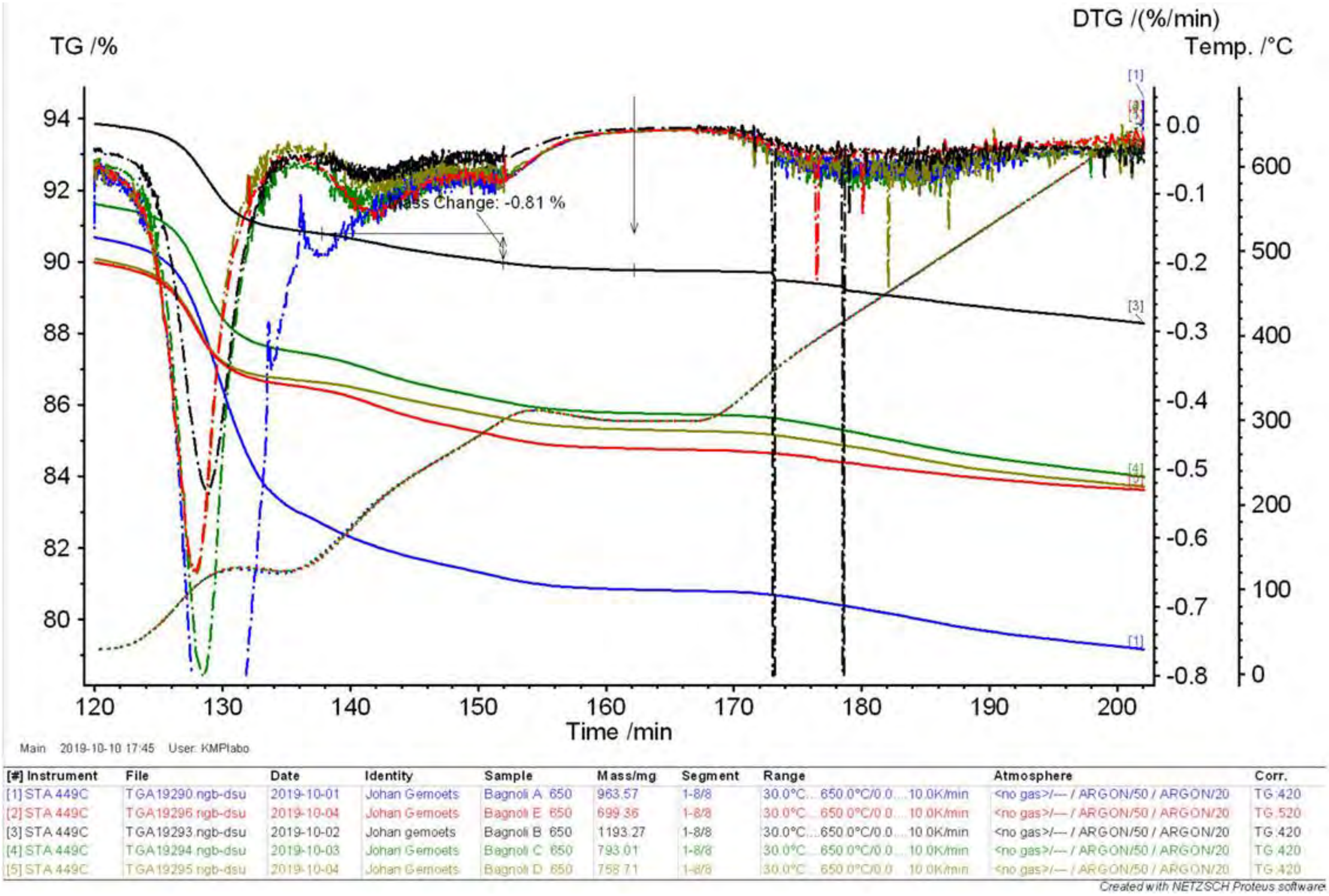
The graphs below (Figure 5 - 7) show the results in overlay format for the five soil samples investigated.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
1] STA 449C	TGA19290.ngb-dsu	2019-10-01	Johan Gemoets	Bagnoli A 650	963.57	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG 020
2] STA 449C	TGA19296.ngb-dsu	2019-10-04	Johan Gemoets	Bagnoli E 650	699.36	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG 020
3] STA 449C	TGA19293.ngb-dsu	2019-10-02	Johan gemoets	Bagnoli B 650	1193.27	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG 020
4] STA 449C	TGA19294.ngb-dsu	2019-10-03	Johan Gemoets	Bagnoli C 650	793.01	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG 020
5] STA 449C	TGA19295.ngb-dsu	2019-10-04	Johan Gemoets	Bagnoli D 650	758.71	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG 020

Figure 5 - Correlation between loss of mass versus time/temperature (expressed respectively as %, min and °C)

In the Figure 5 (loss of mass versus time/temperature), after an initial phase of slow and steady loss of mass during flushing at ambient temperature for all soil samples there is a first significant loss of mass at approximately 100 °C due to evaporation of water, followed by a less pronounced, but steady, loss of mass up to the high temperature range close to 600 °C.



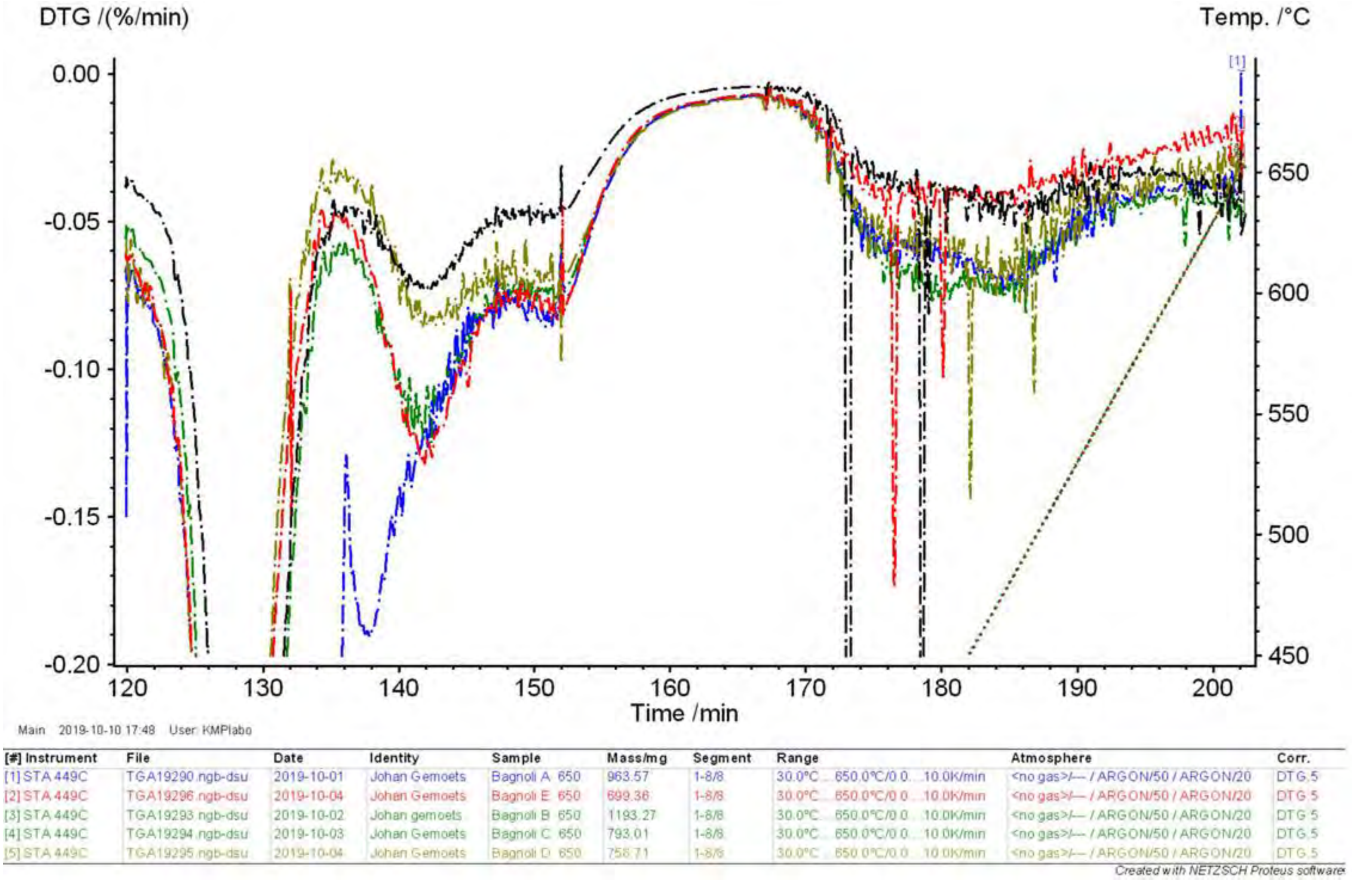
[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[1] STA 449C	TGA19290.ngb-dsu	2019-10-01	Johan Gemoets	Bagnoli A 650	963.57	1-8/8	30.0°C....650.0°C/0.0....10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG:420
[2] STA 449C	TGA19296.ngb-dsu	2019-10-04	Johan Gemoets	Bagnoli E 650	699.36	1-8/8	30.0°C....650.0°C/0.0....10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG:520
[3] STA 449C	TGA19293.ngb-dsu	2019-10-02	Johan gemoets	Bagnoli B 650	1193.27	1-8/8	30.0°C....650.0°C/0.0....10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG:420
[4] STA 449C	TGA19294.ngb-dsu	2019-10-03	Johan Gemoets	Bagnoli C 650	793.01	1-8/8	30.0°C....650.0°C/0.0....10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG:420
[5] STA 449C	TGA19295.ngb-dsu	2019-10-04	Johan Gemoets	Bagnoli D 650	758.71	1-8/8	30.0°C....650.0°C/0.0....10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	TG:420

Figure 6 - Correlation between differential of mass loss versus time/temperature (expressed respectively as %/min, min and °C)

In the Figures 6 and 7 the trend of differential of mass loss (DTG) versus time better reflects the changes in mass loss, the first as full profile and the second zoomed in at changes occurring in the high temperature range.

For all the five samples a first evaporation range is observed in the temperature range between 100°C and 300°C (excluding the large DTG-event due to loss of water at 100 °C) while a second evaporation range is observed in the temperature range between approximately 360 °C and 560 °C.

According to TGA tests the mass loss event between 360 and 560 °C indicates that relatively high treatment temperatures would be required to remove the high-boiling contaminants of concern (COC) such as PAHs, PCDDs and PCBs whose concentration exceeds the cleanup target in all the soil samples investigated. In particular benzo(a)pyrene shows a boiling point at 496 °C, the indeno(1,2,3-cd)pyrene at 536 °C, the dibenzo[a,l]pyrene at 631 °C whereas PCBs have a boiling point ranging between 285 °C and 486 °C.



[#] Instrument	File	Date	Identity	Sample	Mass/mg	Segment	Range	Atmosphere	Corr.
[1] STA 449C	TGA19290.ngb-dsu	2019-10-01	Johan Gemoets	Bagnoli A 650	963.57	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	DTG.5
[2] STA 449C	TGA19296.ngb-dsu	2019-10-04	Johan Gemoets	Bagnoli E 650	699.36	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	DTG.5
[3] STA 449C	TGA19293.ngb-dsu	2019-10-02	Johan gemoets	Bagnoli B 650	1193.27	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	DTG.5
[4] STA 449C	TGA19294.ngb-dsu	2019-10-03	Johan Gemoets	Bagnoli C 650	793.01	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	DTG.5
[5] STA 449C	TGA19295.ngb-dsu	2019-10-04	Johan Gemoets	Bagnoli D 650	758.71	1-8/8	30.0°C...650.0°C/0.0...10.0K/min	<no gas>/— / ARGON/50 / ARGON/20	DTG.5

Created with NETZSCH Proteus software

Figure 7 - As figure 6 but zoomed in the high-temperature zone

A first suggestion from the TGA analysis has been to evaluate an oven temperature ranging between 500 °C and 650 °C in the next full-scale treatment.

In Table 10 and 11, the removal efficiency of thermal desorption and the leaching behaviour of soil/sediment sampled from the five sub-areas investigated are respectively shown.

	Sub area A		Sub area B		Sub area C		Sub area D		Sub area E	
	500 °C	550 °C	500 °C	550 °C	500 °C	550 °C	500 °C	550 °C	500 °C	550 °C
Sb	82%	87%	-67%	-57%	-9%	5%	-24%	-47%	6%	9%
As	45%	-8%	-47%	-40%	-21%	-7%	19%	-38%	-10%	-40%
Be	6%	34%	-5%	0%	0%	6%	31%	5%	8%	-16%
Cd	-48%	-13%	-10%	-7%	0%	17%	15%	9%	27%	6%
Co	-60%	-19%	-76%	-33%	-54%	-27%	-16%	-61%	-16%	-9%
Cr	7%	28%	-24%	13%	13%	43%	-23%	-54%	25%	0%

Cr VI	44%	51%	41%	49%	35%	-4%	75%	69%	40%	40%
Hg	99%	99%	93%	93%	98%	98%	94%	-3%	92%	92%
Ni	-58%	-17%	-58%	-42%	-38%	-54%	-64%	-105%	-40%	-40%
Pb	82%	88%	-61%	-26%	-15%	-4%	-45%	-74%	6%	-21%
Cu	-40%	-10%	-72%	-28%	-47%	-27%	-24%	-24%	-17%	-42%
Se	26%	56%	-8%	-12%	-23%	15%	-94%	-244%	9%	7%
Tl	-7%	14%	-76%	-6%	-13%	22%	6%	-38%	-%	-29%
V	-15%	4%	-91%	-27%	8%	38%	0%	-22%	17%	-19%
Zn	-71%	-14%	-41%	-65%	-44%	-15%	-28%	-33%	-13%	-53%
PAH total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
benzo(a)anthracene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
benzo(a)pyrene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
benzo[b]fluoranthene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
benzo[g,h,i]perylene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
benzo[k]fluoranthene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
chrysene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
dibenzo[a,e]pyrene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
dibenzo[a,h]anthracene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
dibenzo[a,h]pyrene	99%	99%	100%	100%	98%	98%	97%	96%	100%	100%
dibenzo[a,i]pyrene	100%	100%	100%	100%	100%	100%	99%	99%	100%	100%
dibenzo[a,l]pyrene	100%	100%	100%	100%	100%	100%	99%	99%	100%	100%
indeno[1,2,3-cd]pyrene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
pyrene	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table 10 - Removal efficiency expressed as % w/w of lab-scale application of thermal desorption treatment on the five sub-areas investigated using two different operative temperatures (500 and 550 °C)

Parameters	Subareas										Reuse as non hazardous waste	Threshold for groundwater
	A		B		C		D		E			
	500 °C	550 °C	500 °C	550 °C	500	550 °C	500 °C	550 °C	500 °C	550 °C		
As	140	190	54	51	45	45	64	110	690	980	50	380
Ba	3.1	3.4	2.0	2.1	3.2	4.0	1.4	1.0	1.0	1.1	1000	-
Be	-	-	-	-	-		-	-	-	-	10	9
Cd	0.4	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	5	5
Co	0.1	0.2	0.4	0.2	0.2	0.2	0.1	0.1	0.8	0.8	250	50
Cr	1.3	1.0	8.7	5.3	18	54	0.7	2.6	0.2	1.5	50	50
Hg	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1	1
Ni	0.4	0.2	0.5	0.6	0.5	0.6	0.3	0.2	0.8	0.8	10	20
Pb	0.1	0.1	19	18	42	33	2.7	0.5	62	56	50	19
Cu	14	11	12	12	16	11	12	10	27	25	50	1000
Se	9.6	11	3.7	3.2	5.6	6.2	0.3	0.2	8.6	6.2	10	10
V	49	96	210	220	120	140	53	150	86	13	250	-

Zn	103	90	58	55	80	72	5.0	4.5	76	83	3000	3000
pH	8.9	9.4	9.4	9.8	9.9	10.1	8.5	8.6	7.8	7.5	5.5 - 12	-
COD	7500	7700	6700	6500	6500	6500	11000	11000	12500	12000	30000	-
Cyanide	-	-	-	.	-		-		-	-	50	50
Cl^-	4600	4100	2200	2800	3000	3900	2400	3100	2700	2200	10000	-
F^-	5000	5700	3100	4400	3100	4700	4000	4800	2200	2300	1500	4000
$NO3^-$	550	260	330	230	370	190	460	250	200	200	50000	-
$SO4^{--}$	140000	150000	34000	37000	7100	7100	33000	54000	7000	7300	250000	250000
Asbestos	< 0.58	< 0.58	< 0.58	< 0.58	<	<	< 0.58	< 0.58	< 0.58	< 0.58	30	-

Table 11 - Leaching behaviour of soil/sediment samples (expressed as µg/L) after the thermal desorption treatment

Full-scale application

In Table 12 the grain size distribution of the samples collected from the six sub-areas investigated is analysed. Among the three size classes (sand, gravel and coarse) investigated underwent to the thermal desorption full-scale treatment.

Grain size class	Sub-area A	Sub-area B	Sub-area C	Sub-area D	Sub-area E	Sub-area F
Sand (Ø < 2 mm)	56%	64%	66%	-	93%	80%
Gravel (2 mm <Ø< 2cm)	13%	26%	19%	-	2%	15%
Coarse (Ø > 2 cm)	31%	10%	16%	-	4%	2%
Sand (Ø < 2 mm)	64%	55%	56%	66%	91%	79%
Gravel (2 mm <Ø< 2cm)	17%	27%	17%	14%	1%	8%
Coarse (Ø > 2 cm)	21%	16%	25%	13%	7%	8%

Table 12 - Grain size distribution in soil/sediment samples from the six sub-areas investigated in the thermal desorption inflow

The Figure 8 shows the pH variation for the three grain size classes selected during the full scale soil washing treatment, using two different operative temperatures.

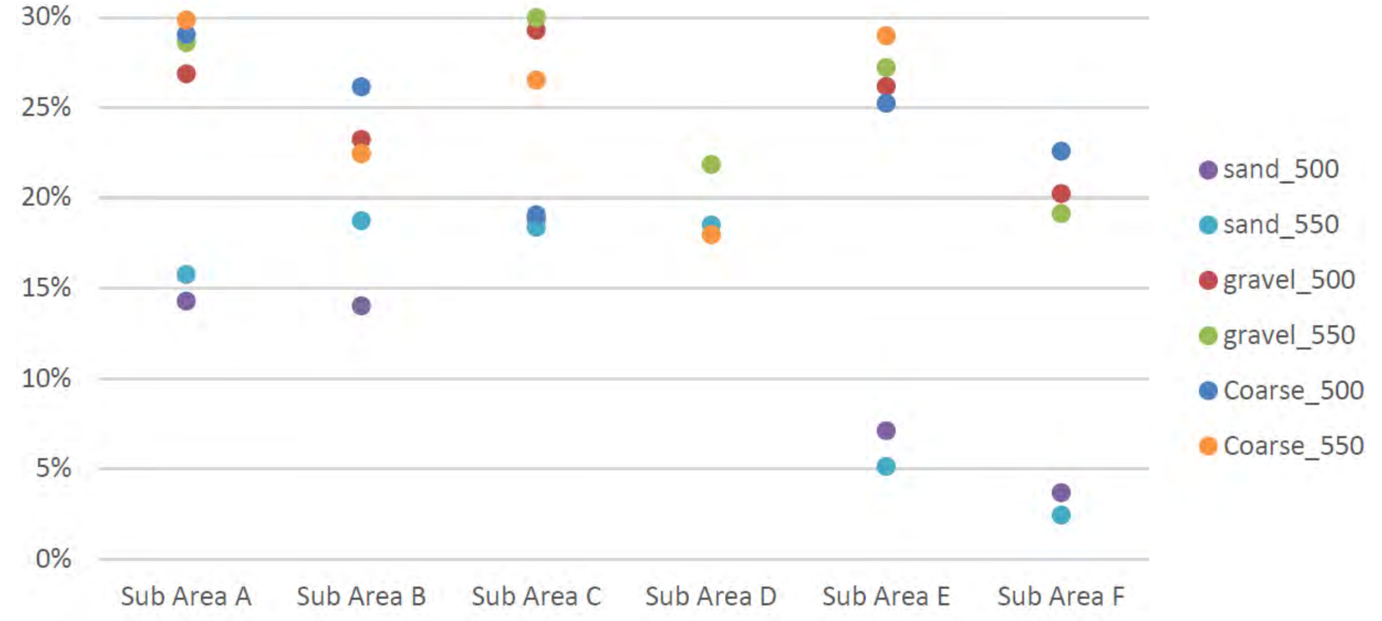


Figure 8 - pH variation (expressed as % of pH unit) for the three grain size classes investigated during the full scale thermal desorption treatment, using two different operative temperatures (500 °C and 550 °C)

The Figures from 9 to 11 describe the removal efficiency of the full-scale soil washing treatment – respectively on sandy, gravel and coarse fraction – for the six sub-areas investigated using the two different operative temperatures selected.

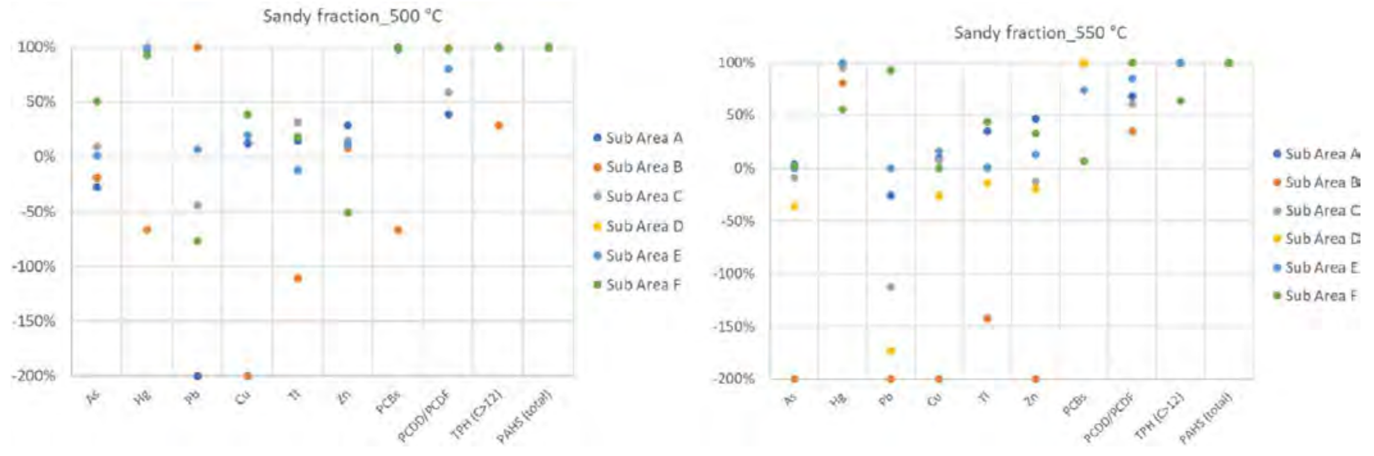


Figure 9 - Removal efficiency on sandy fraction - expressed as % w/w - of the full-scale thermal desorption treatment on the six sub-areas investigated using two different operative temperatures (500 °C and 550 °C)

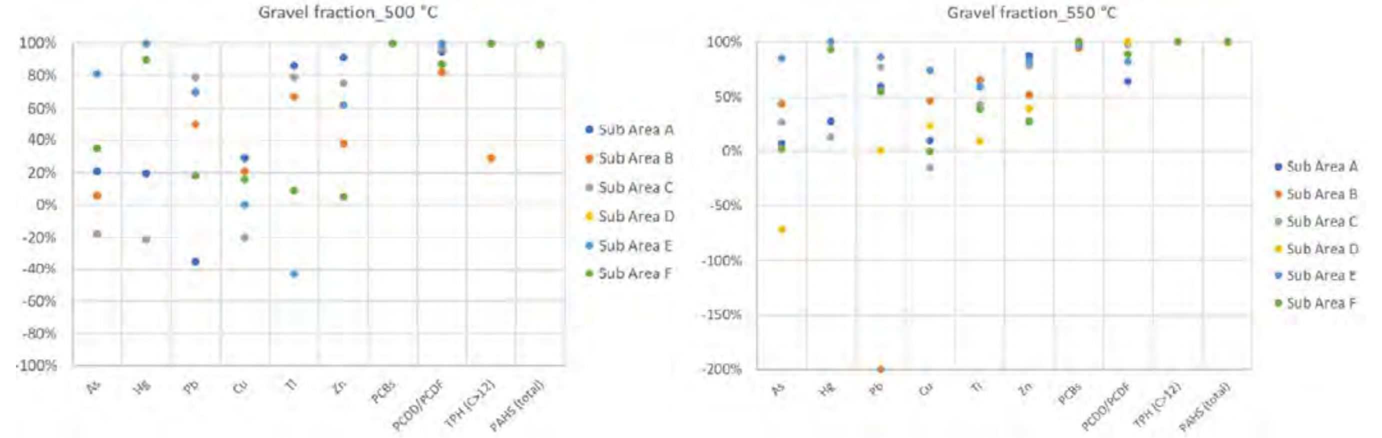


Figure 10 - Removal efficiency on gravel - expressed as % w/w - of the full-scale thermal desorption treatment on the six sub-areas investigated using two different operative temperatures (500 °C and 550 °C)

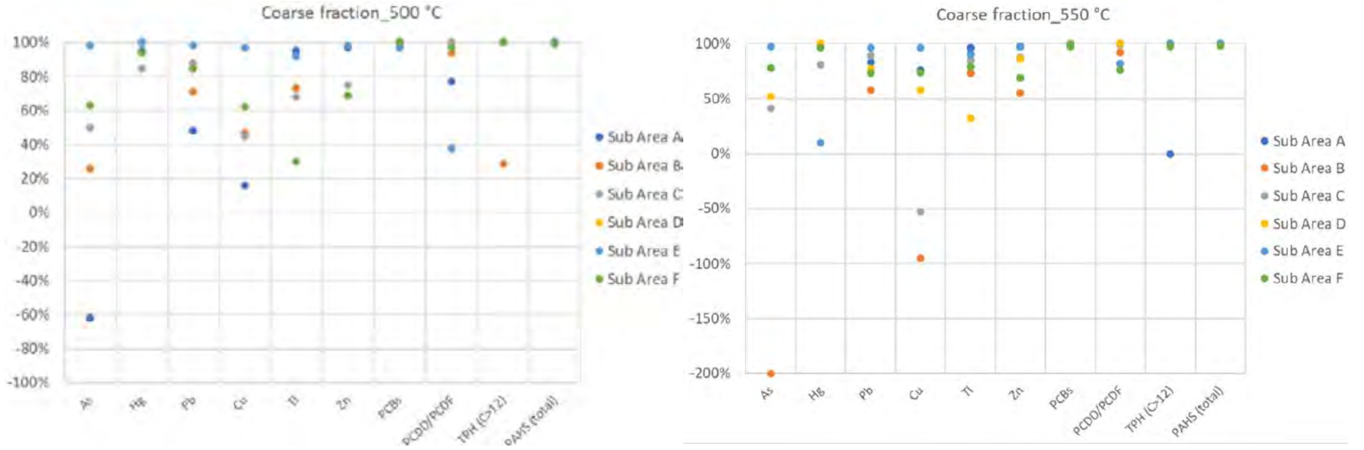


Fig. 11. Removal efficiency on coarse fraction - expressed as % w/w - of the full-scale thermal desorption treatment on the six sub-areas investigated using two different operative temperatures (500 °C and 550 °C)

Multivariate analysis of data set

Multivariate approach has been carried out using, an integrated suite of software facilities for data manipulation, calculation and graphical display. In particular the programme R has been used as open-source environment for statistical computing and visualisation, based on the S language.

Cluster package has been specifically selected for multivariate analysis of data achieved, choosing hierarchical method.

A preliminary screening on the data set has been assessed to evaluate linear relationships between couples of significant variables using Pearson's correlation coefficient (r) and to evaluate whether to keep or discard suspected critical data through an outlier's analysis based on modified Thompson parameter (τ).

Then, an exploratory statistical analysis based upon hierarchical agglomerative method has been carried out, in order to define a representative number of clusters and their trend in terms of environmental behaviour during the tests, in particular for the data set of organic and inorganic parameters investigated.

Among methods forming potentially discrete homogeneous groups, the Agglomerative Nesting Procedure for Hierarchical Clustering (AGNES) has been selected.

AGNES algorithm constructs a hierarchy of clustering. At first, each observation is a small cluster by itself. Clusters are merged until only one large cluster remains which contains all the observations. At each stage the two nearest clusters are combined to form one larger cluster.

The metric used for defining the hierarchy of clustering’s and calculating dissimilarities between observations is Euclidean-type, that is distances are root sum-of-squares of differences whereas the average method computes the distance between two clusters as the average of the dissimilarities between the points in one cluster and the points in the other cluster.

The values of main parameters achieved according to AGNES procedure for the organic compounds investigated are evaluated, combining the six areas investigated with the outcomes from all the technologies tested (soil washing, thermal desorption, wet screening, attrition scrubbing, density separation), at different operational condition and both on lab- and full-scale.

At the end of the evaluation process the following table shows for each single sub area the real applicability of the two main technologies investigated, both on lab- and full-scale, in terms of: general efficiency, the compliance with two Italian threshold and the leaching behaviour (Table 12 and 13).

In Table 14 and 15 the same evaluation has been carried out on the two main technologies investigated coupled.

		Lab-scale										Full-scale									
		Efficiency		Compliance "A" threshold		Compliance "B" threshold		Compliance site-specific targets		Leachate		Efficiency		Compliance "A" threshold		Compliance "B" threshold		Compliance site-specific targets		Leachate	
	Sub-area A	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT
Sand	Heavy metals	↑	↑	↓	↓	↑	↓	↓	↓	↓	↓	↓	↑	↓	↓	↑	↑	↓	↓	↓	↓
	Organic compounds	↑	↑	↓	↑	↑	↑	↑	↑	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Gravel	Heavy metals	↑	-	↓	-	↓	-	↓	-	↑	-	↑	↑	↓	↓	↑	↓	↓	↓	↑	↓
	Organic compounds	↑	-	↓	-	↑	-	↑	-	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Coarse	Heavy metals	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	↓	↓
	Organic compounds	-		-		-		-		-		↑	↑	↓	↑	↑	↑	↑	↑	-	
	Sub-area B	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT
Sand	Heavy metals	↑	↓	↑	↓	↑	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑	↓	↓	↑	↑
	Organic compounds	↑	↑	↓	↑	↑	↑	↑	↑	-		↑	↑	↓	↑	↓	↑	↓	↑	-	
Gravel	Heavy metals	↑	-	↑	-	↑	-	↑	-	↑	-	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Organic compounds	↑	-	↓	-	↑	-	↑	-	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Coarse	Heavy metals	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Organic compounds	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	-	
	Sub-area C	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT
Sand	Heavy metals	↑	↓	↑	↓	↑	↓	↑	↑	↓	↑	↑	↓	↓	↓	↑	↑	↓	↓	↓	↑
	Organic compounds	↑	↑	↑	↑	↑	↑	↑	↑	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Gravel	Heavy metals	↑	-	↑	-	↑	-	↑	-	↑	-	↑	↑	↓	↑	↑	↑	↓	↑	↑	↑
	Organic compounds	↑	-	↑	-	↑	-	↑	-	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Coarse	Heavy metals	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Organic compounds	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	-	
	Sub-area D	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT
Sand	Heavy metals	↑	↓	↑	↓	↑	↓	↑	↑	↑	↑	↓	↓	↓	↓	↑	↑	↓	↓	↑	↑
	Organic compounds	↑	↑	↑	↑	↑	↑	↑	↑	-		↓	↑	↓	↑	↑	↑	↓	↑	-	
Gravel	Heavy metals	↑	-	↑	-	↑	-	↑	-	↓	-	↑	↑	↑	↑	↑	↑	↑	↑	↑	↑
	Organic compounds	↑	-	↓	-	↑	-	↑	-	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Coarse	Heavy metals	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	↑	↓
	Organic compounds	-		-		-		-		-		↑	↑	↓	↑	↑	↑	↓	↑	-	
	Sub-area E	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT
Sand	Heavy metals	↑	↓	↓	↓	↑	↓	↓	↑	↓	↑	↓	↓	↓	↓	↓	↑	↓	↓	↓	↑
	Organic compounds	↑	↑	↓	↑	↑	↑	↑	↑	-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Gravel	Heavy metals	↑	-	↓	-	↑	-	↑	-	↓	-	↑	↑	↓	↑	↑	↑	↓	↑	↑	↑
	Organic compounds	↑	-	↓	-	↑	-	↓	-	-		↓	↑	↓	↑	↓	↑	↓	↑	-	
Coarse	Heavy metals	-		-		-		-		-		↑	↑	↑	↑	↑	↑	↑	↑	↑	↓
	Organic compounds	-		-		-		-		-		↓	↑	↓	↑	↓	↑	↓	↑	-	

Table 12 - the real applicability of the two main technologies investigated (subareas A,B,C,D,E)

		Lab-scale										Full-scale									
		Efficiency		Compliance "A" threshold		Compliance "B" threshold		Compliance site-specific targets		Leachate		Efficiency		Compliance "A" threshold		Compliance "B" threshold		Compliance site-specific targets		Leachate	
	Sub-area F	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT	SW	DT
Sand	Heavy metals	-		-		-		-		-		↓	↓	↓	↓	↑	↑	↓	↓	↑	↑
	Organic compounds	-		-		-		-		-		↑	↑	↓	↑	↑	↑	↓	↑	-	
Gravel	Heavy metals	-		-		-		-		-		↑	↓	↓	↓	↑	↑	↓	↓	↑	↓
	Organic compounds	-		-		-		-		-		↓	↑	↓	↑	↑	↑	↓	↑	-	
Coarse	Heavy metals	-		-		-		-		-		↑	↓	↑	↓	↑	↑	↑	↑	↑	↑
	Organic compounds	-		-		-		-		-		↓	↑	↓	↑	↑	↑	↓	↑	-	

Table 13 - the real applicability of the two main technologies investigated (subarea F)

		Soil Washing + Floatation_Lab-scale				**Soil Washing + Thermal Desorption_Full-scale**			
		Efficiency	Compliance "B" threshold	Compliance site-specific targets	Leachate	Efficiency	Compliance "B" threshold	Compliance site-specific targets	Leachate
	Sub-area A								
Sand	Heavy metals	↓	↑	↓	↓	↓	↑	↓	↓
	Organic compounds	↑	↑	↓	-	↑	↑	↓	-
Gravel	Heavy metals	↑	↑	↑	↑	↑	↑	↑	↓
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
Coarse	Heavy metals	↑	↑	↑	↑	↑	↑	↑	↓
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
	Sub-area B								
Sand	Heavy metals	↑	↑	↑	↑	↓	↑	↓	↓
	Organic compounds	↑	↑	↑	-	↑	↓	↓	-
Gravel	Heavy metals	↑	↑	↑	↑	↑	↑	↑	↓
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
Coarse	Heavy metals	-	-	-	-	↑	↑	↓	↑
	Organic compounds	-	-	-	-	↑	↑	↑	-

Table 14 - The real applicability of the two main technologies investigated coupled (subareas A, B)

		Soil Washing + Floatation_Lab-scale				Soil Washing + Thermal Desorption_Full-scale			
		Efficiency	Compliance "B" threshold	Compliance site-specific targets	Leachate	Efficiency	Compliance "B" threshold	Compliance site-specific targets	Leachate
	Sub-area C								
Sand	Heavy metals	↑	↑	↑	↓	↑	↑	↓	↑
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
Gravel	Heavy metals	↑	↑	↑	↑	↑	↑	↓	↓
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
Coarse	Heavy metals	-	-	-	-	↑	↑	↑	↓
	Organic compounds	-	-	-	-	↑	↑	↑	-
	Sub-area D								
Sand	Heavy metals	↑	↑	↑	↑	↓	↑	↓	↑
	Organic compounds	↑	↑	↑	-	↓	↑	↑	-
Gravel	Heavy metals	↑	↑	↑	↓	↑	↑	↓	↓
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
Coarse	Heavy metals	-	-	-	-	↑	↑	↑	↑
	Organic compounds	-	-	-	-	↑	↑	↑	-
	Sub-area E								
Sand	Heavy metals	↑	↑	↓	↓	↓	↓	↓	↑
	Organic compounds	↑	↑	↑	-	↑	↑	↑	-
Gravel	Heavy metals	↑	↑	↑	↓	↑	↑	↑	↓
	Organic compounds	↑	↑	↑	-	↓	↑	↑	-
Coarse	Heavy metals	-	-	-	-	↑	↑	↑	↓
	Organic compounds	-	-	-	-	↓	↑	↑	-
	Sub-area F								
Sand	Heavy metals	-	-	-	-	↓	↑	↓	↑
	Organic compounds	-	-	-	-	↑	↑	↑	-
Gravel	Heavy metals	-	-	-	-	↑	↑	↓	↓
	Organic compounds	-	-	-	-	↓	↑	↑	-
Coarse	Heavy metals	-	-	-	-	↑	↑	↑	↑
	Organic compounds	-	-	-	-	↓	↑	↑	-

Table 15 - The real applicability of the two main technologies investigated coupled (subareas C,D,E,F)

- Sustainability

Sustainability

Thermal desorption is inclined to increase bioavailability of metal pollutants, in particular the presence of cadmium, nickel and chromium, and thereby their genotoxicity.

EDTA is poorly biodegradable and quite persistent in the soil environment, which might have an adverse effect on the microorganisms and plant, and lead to secondary pollution via leaching to groundwater.

Changes of soil physical properties after EDTA-soil washing must be evaluated. It was expected that remediation process, especially intensive mixing of the soil slurry and soil compression after de-watering significantly deteriorate physical properties of soil. Furthermore, different soil additives with capacity to improve the physical characteristics of remediated soil were tested in a soil column experiment. Plant roots are integral part of soil system with significant effect on soil physical properties and water regime.

6. Post treatment and/or Long Term Monitoring

6.1 Post treatment and/or Long Term Monitoring

After a positive cross-examination of the outcomes with the Control bodies no post treatment activity is supposed to be carried out.

A long term monitoring through a groundwater detection system will be carried out after the implementation of the technology in the 80 hectares area mentioned in the chapter 7.1.

7. Additional information

7.1 Lesson learnt

In the following list the main key findings and lessons learned about the site of Bagnoli-Coroglio will be described as bullet points:

- Difficulties and weaknesses - In the field activities some stressors not encountered at laboratory affected thermal desorption: in particular an uneven distribution of contaminants and the heterogeneity of the soil structure most affected the final outcomes. The high temperatures can affect the treated soil in terms of agricultural features;
- Successes and strengths – a preliminary survey of the investigated site has been necessary to define the proper sub-areas where the thermal desorption should be applied, especially in terms of degree of contamination;
- Keystones – the laboratory must work under QA/QC procedures and possibly using Certified Reference Materials;
- Rooms for improvement – the full scale application on an approximately 80 hectares area will confirm, in full or partially, the achieved outcomes and the restoration trends.

7.2 Additional information

The main clues and evidence referable to the success of remediation are the following:

- The presence of facility corridors and other kind of interferences doesn't allow the application of an in situ thermal desorption
- The thermal desorption has been applied with the soil washing, in an integrated approach
- Scaling up is a correct procedure to define potentially predictors and indicators of the real efficiency of the treatment system

7.3 Training need

The most effective training tool from the technical, procedural, organizational point of view is a mix of different items such as workshops, training on-the job, webinars, and e-learning.
Now we have published several technical documents and papers, and we've attended important workshops and seminar. A list follows.

Scientific papers

- C. Guarino, D. Zuzolo, M. Marziano, G. Baiamonte, L. Morra; D. Benotti; D. Gresia;
- E. Robortella Stacul; D. Cicchella, R Sciarrillo 2018 Identification of native-metal tolerant plant species in situ: environmental implications and functional traits. Science of the Total Environment, Feb; 650 (2) 3156-3167.
- E. Robortella Stacul, D. Benotti, L. Morra, D. Gresia. 2019 Applicazione su scala pilota e reale di tecnologie di bonifica biologiche, chimiche e fisiche in un SIN: vantaggi di un approccio integrato – Geologia dell'Ambiente, 2/19, 258-261
- C. Guarino, D. Zuzolo, M. Marziano, B. Conte, G. Baiamonte, L. Morra; D. Benotti;
- D. Gresia; E. Robortella Stacul; D. Cicchella, D. Cicchella & R Sciarrillo 2019 Investigation and Assessment for an effective approach to the reclamation of Polycyclic Aromatic Hydrocarbon (PAHs) contaminated site: SIN Bagnoli, Italy. Scientific Reports – Nature Research, 2019 9:11522
- Teani, F. Saraceno, E. Robortella Stacul, D. Benotti, L. Morra, D. Gresia. 2020 Tecnologie di bonifica applicabili per il risanamento di siti dismessi, test di laboratorio e prove industriali per la progettazione di interventi efficaci e sostenibili: il caso del SIN di Bagnoli-Coroglio. Proceedings del Convegno HUB Tecnologica Campania – Remtech
- E. Robortella Stacul, L. Morra, D. Gresia, C. Fiore, 2021 Applicazione della norma ISO 18504 "Soil Quality – Sustainable Remediation" ad un intervento di bonifica su scala industriale mediante tecnologie di trattamento chimico-fisiche e biologiche. Monografia di Geologia Ambientale "Le bonifiche ambientali nell'ambito della transizione ecologica", 240 – 248.
- Iacobini, D. Baldi, S. Vinci, R. Mangolin, C. Fiore, E. Robortella Stacul 2021 WEB GIS per l'organizzazione, l'elaborazione e la condivisione dei dati ambientali: l'esempio del SIN di Bagnoli – Coroglio. Monografia di Geologia Ambientale "Le bonifiche ambientali nell'ambito della transizione ecologica", 263 – 268.
- D. Zuzolo, C. Guarino, A. Postiglione, M. Tartaglia, P. Scarano, A. Prigioniero, R. Terzano, C. Porfido, L. Morra, D. Benotti, D. Gresia, E. Robortella Stacul, R. Sciarrillo 2021 Overcome the limits of multi-contaminated industrial soils bioremediation: Insights from a multi-disciplinary study. J. Haz. Mat. 421(5):126762

Oral presentations

- Workshop SICON_2020 – Special Session "Aspetti e criticità emergenti nella bonifica di siti contaminati" Roma, 12–14 febbraio 2020
- Seminar "Bonifica dei siti inquinati – Analisi e soluzioni di problemi complessi." Napoli, 17 febbraio 2020 Workshop "Siti contaminati e bonifiche eco-compatibili". Napoli, 12 aprile 2022

- Workshop “Il territorio campano tra specificità geochimiche ed emergenze ambientali.” Napoli, 22 aprile 2022 Workshop “Il Programma di Risanamento Ambientale e Rigenerazione Urbana “PRARU” del Area di Rilevante Interesse Nazionale di Bagnoli Coroglio”. Napoli, 05 maggio 2022
- Workshop “Area di Rilevante Interesse Nazionale di Bagnoli Coroglio – Lo stato di attuazione degli interventi di risanamento ambientale.” Napoli, 22 maggio 2022
- Workshop SICON_2023 Plenary Session “Aspetti integrati di risanamento ambientale e rigenerazione urbana. Le linee di intervento di Invitalia Roma, 8–10 febbraio 2023
- Policy Briefing_Life Sedremed_Expert Roundtable - Classification and management of sediments in the EU “Presentation of IT legislation on management of contaminated sediments and necessary policy developments, the Bagnoli case-study,” Bruxelles, 9 febbraio 2023

7.4 Additional remarks

In the present document, the removal efficiencies of inorganic micropollutants (heavy metals, in the specific As, Sb, Cu, Hg, Pb and Zn) and organic compounds such as PCBs, PCDDs, TPHs and PAHs present in the contaminated area of a dismissed steelwork plant were evaluated using chemical-physical remediation technologies (attrition scrubbing, density separation, soil washing and thermal desorption), both on lab- and full-scale and at different operative parameters, as well as coupled in different configurations.

Considering the heterogeneity of the soil/sediment characteristic and the variety of pollutants investigated, a strong quality control on the analytical procedures and a multivariate analysis on the data set have been performed in order to support the best approach for the subsequent full-scale treatments.

The study proved that the sequential and coupled application of the different technologies tested is likely to be the more efficient remediation strategy for multi-polluted soil than the single treatment alone. This is a key-point, since cost-effectiveness and relatively low environmental impacts are required in the on-site remediation on large scale.

Further research on biophytoremediation under field conditions are in progress in the nearby areas to give more consolidated information on the most efficient remediation strategy on the whole site.

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.3

1.1 Name and Surname	Uwe Hiester
1.2 Country/Jurisdiction	Germany
1.3 Organisation	Reconsite GmbH
1.4 Position	Managing director
1.5 Duties	Contaminated land investigation, Implementation planning and realisation of: SEE (Steam Enhanced Extraction), TUBA-method (Steam-Air-Injection), P&T, SVE, explosive protection concept and application. Remediation management, environmental consulting
1.6 Email address	uwe.hiester@reconsite.com
1.7 Phone number	+49 711 410 190 0

2. Site background

2.1 History of the site

A metal works factory operated subsurface storage tanks for trichloroethene (TCE), toluene, gasoline and others with a size of 10-20 m^3. The tank farm had been removed, extended and reinstalled in the 1960th. The company is still present at the site.
In the 1980th, CHC had been monitored in groundwater and in the surface soil vapour down to 2 m.
In a first step, at the End of the 1980th, P&T and SVE had been installed to avoid further contaminant migration. SVE has been operated permanently from 2-10 m bgl and P&T down to 54 m bgl. Over the years, in total 5.4 tons of CHC and BTEX were removed from soil and groundwater and the contaminant concentration in the groundwater decreased from initially up to 1,800 µg/l (1990) to less than 6 µg/l (2011).
However, SVE operation dominated the annual mass recovery. The mass recovery remained constant in the range of 200 kg/a ± 10 %, even tons of contaminants had been already removed. A shut-down of the SVE could not be predicted.

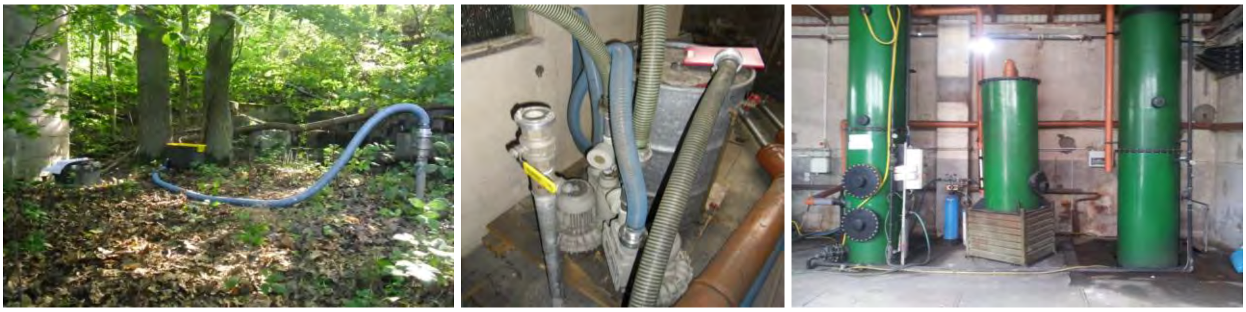


Figure 1 – Pictures from the site

Thus, restrictions from the daily business in terms of available space, time frame, logistics and others had to be taken in account for the remediation concept.

2.2 Geological setting

The soil structure at the site is almost homogenous in wide areas of the site. Beneath road surface, the unsaturated zone was mainly formed by fill material (thickness of about 3 m), underlaid by sandy clay, silt and loam. From about 13 m bgl, a weathering horizon of the shale begins, which changes to a fissured rock in about 20 m bgl.
Tensioned, water-bearing layers are present every 2-3 m from about 16 m bgl. They

have a thickness of about 0.2-1.4 m and are separated by stiff silt and clay layers.

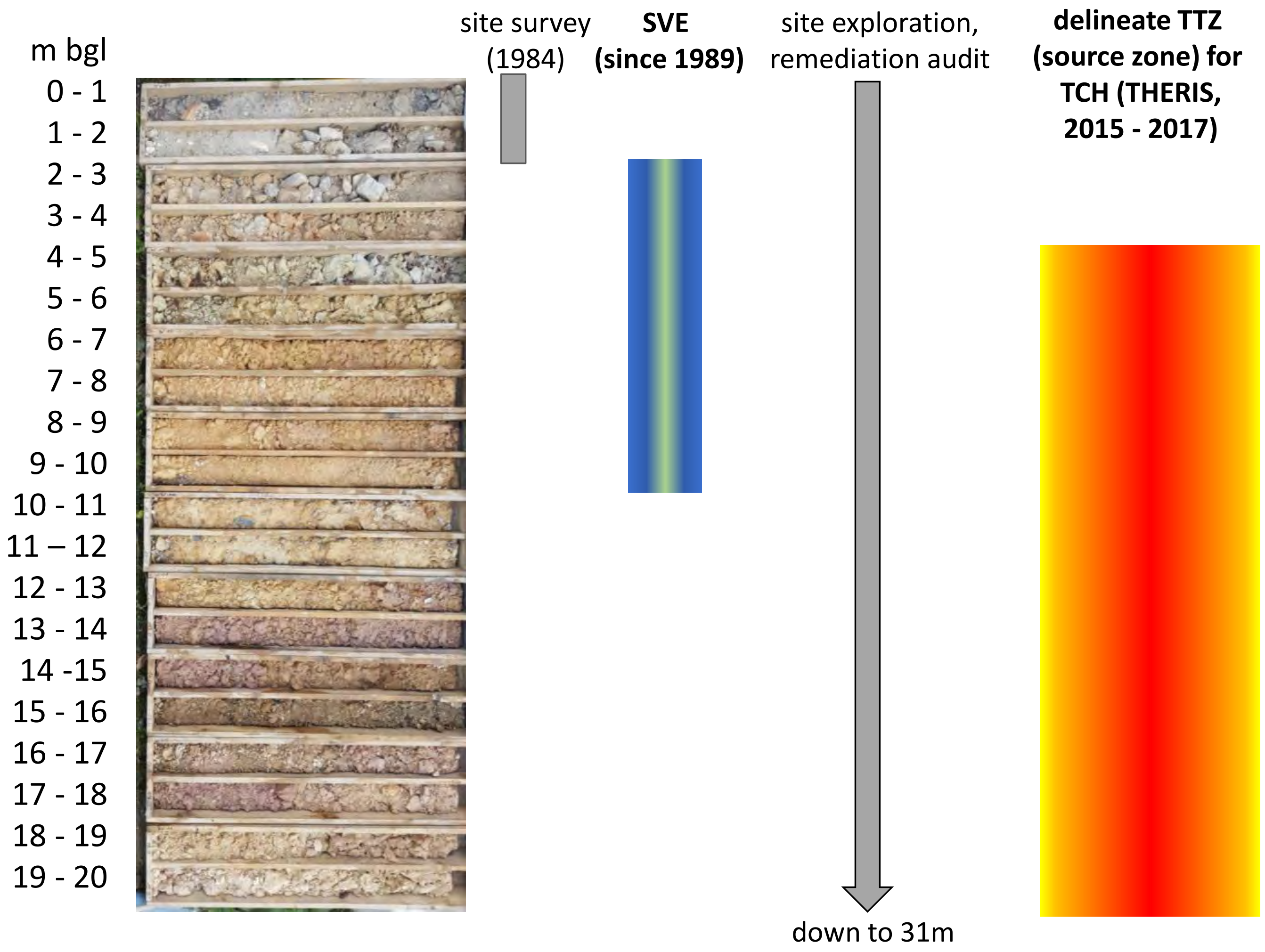


Figure 2 – Drill core exposure and remediation concept

2.3 Contaminants of concern

In 1983, groundwater contamination by CHCs (chlorinated hydrocarbons) and BTEX (benzene, toluene, ethylbenzene, xylene) was detected for the first time. Primarily trichloroethene (TCE) and toluene have been released into the soil as well as into stratum water and groundwater.

Due to the permanent contaminant mass recovery on a high value (annual recovery about 200 kg), a remediation audit was recommended by the authorities to the client to figure out the source zone. By combining various investigation methods such as Phyto-screening, soil, soil vapour and groundwater sampling, MIP (Membrane

Interphase Probe) and pumping tests, the spreading of massive CHC and BTEX contamination could be quantified. Lateral and vertical extension of the contaminated source zones were greater than assumed in the 1980th. Very high levels of contamination could be detected even next to SVE wells, operated in loamy and silty layers since decades. This indicates a low range of soil vapour extraction with the side-channel blower in the cohesive soil.

Water-bearing layers at about 16 m bgl were locally contaminated with more than 300,000 µg/l with CHCs. Local contamination in the water-bearing strata was detected down to 31 m bgl.

In individual areas above the water-bearing strata, high to very high microbiological activity was detected during CHC degradation. However, due to the high concentrations, a source zone elimination could not be expected by microbiological degradation.

2.4 Regulatory framework

Interpretation of the new site evaluation as well as remediation options had been discussed in several meetings. After technology validation considering technical, economic and environmental aspects, ISTR by TCH (THERIS method) had been selected as the most efficient method. In August 2015, the elimination of treatment target zones (TTZ) with the THERIS method was confirmed by the authority.

3. Pilot-scale application in field

3.1 Laboratory study

Due to the excellent process understanding of ISTR and TCH / THERIS as well as a wide range of application experience over the last two decades, site-specific laboratory studies or pilot tests were not required for TCH / THERIS.

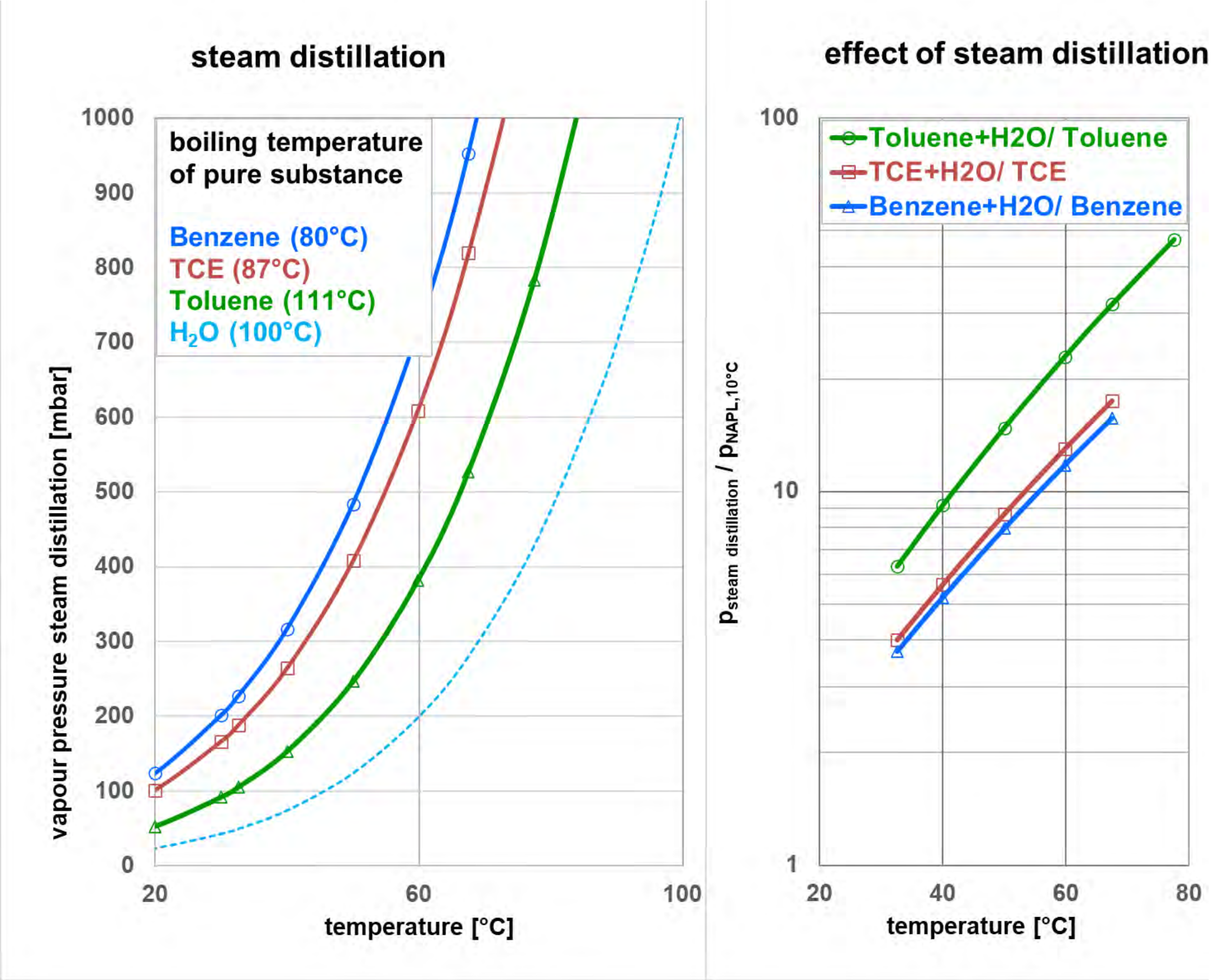


Figure 3 – Steam distillation and effect

Steam distillation, well known as co-boiling of water and contaminant, was identified as dominating remediation process in advance. This process reduces the contaminant boiling point by co-boiling with water to temperatures below 100°C (eutectic temperature). Thus, drying of soil and high temperature heating can be avoided (see graphs). Heating to a target temperature range of 75-90°C is sufficient to enable a high mass recovery.

As common for sites like these, pilot tests for in-situ thermal remediation (ISTR) are not necessary.

Additionally, the heat-pipe effect as a convective circulation process during thermal conductive heating in low permeable soil helps to speed mass recovery during MPE (multi-phase extraction).

3.2 Treatment unit (pilot scale)

For this site, ISTR feasibility study was not required (see 3.1). Treatment units were well known and state of the art.

The delineation of the sources zone characterisation demonstrated, that more than 95% of the contaminant mass was located in the TTZ. Thus, a remediation strategy had been developed to remove this high amount of contaminant mass and considering ecological and economic proportionality issue.

A technical and economic feasibility study reviewed microbiological, chemical and physical in-situ remediation methods as well as soil replacement including large boreholes. In-situ thermal remediation / treatment (ISTR / ISTT) proved to be the most economical option. Moreover, in life cycle assessments of ISTR / ISTT showed lower values for life cycle inventories and impact categories than soil replacement measures.

4. Full-scale application

4.1 Main treatment unit

The total TTZ of more than 2,500 m² was separated into four partial fields, each to be cleaned within a few months. For each field, about 100 heater wells were operated in the unsaturated as well as in the saturated zone. The cohesive soil (silt, clay) was heated by conduction to vaporize CHCs and BTEX. Multi-phase extraction (MPE) was operated at up to 40 wells simultaneously by using vacuum pumps. Stratum water and groundwater was pumped separately and cleaned with the existing stripping plant.

Figure 4 - View of the in-situ thermal remediation TTZ (field 1) using the THERIS method (electrical driven heater wells).

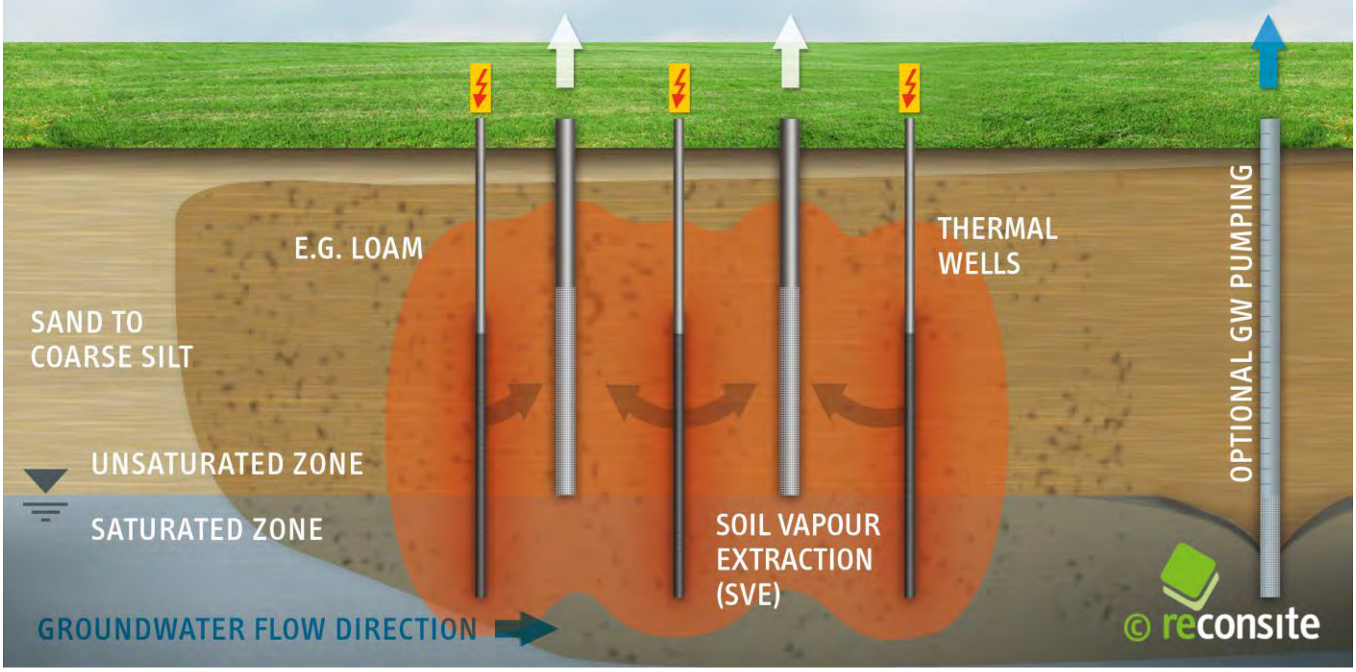


Figure 5 - Schematic sketch of THERIS method (TCH)

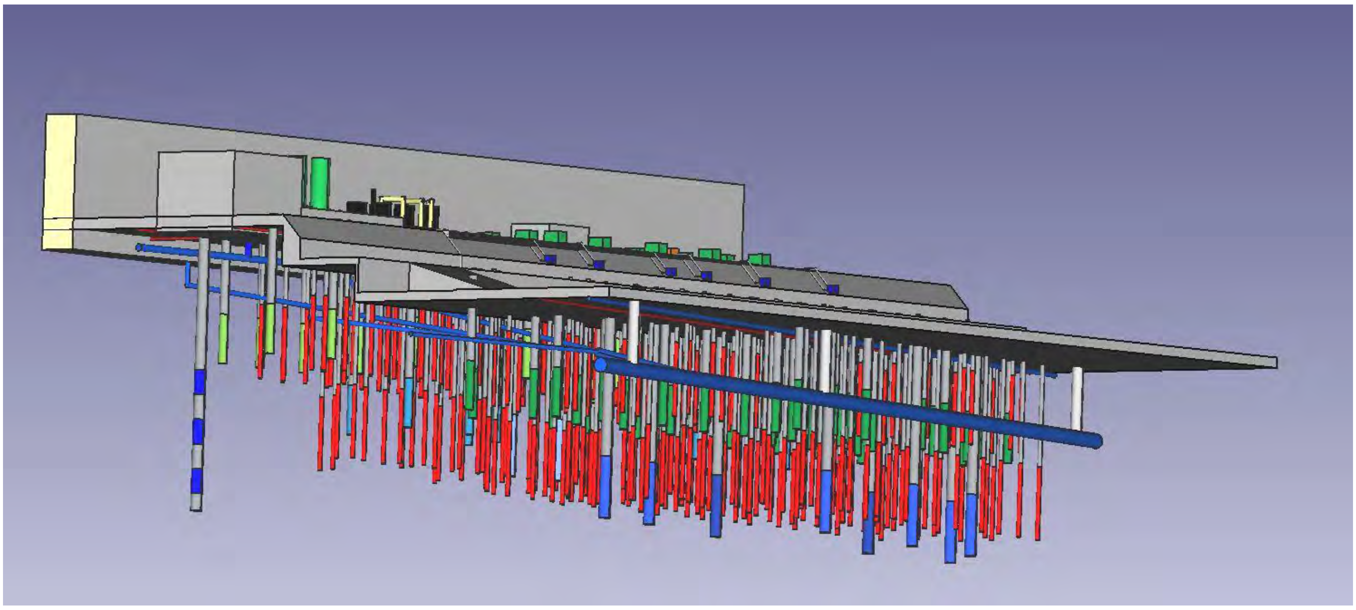


Figure 6 - 3-D model of THERIS application in TTZ at the site

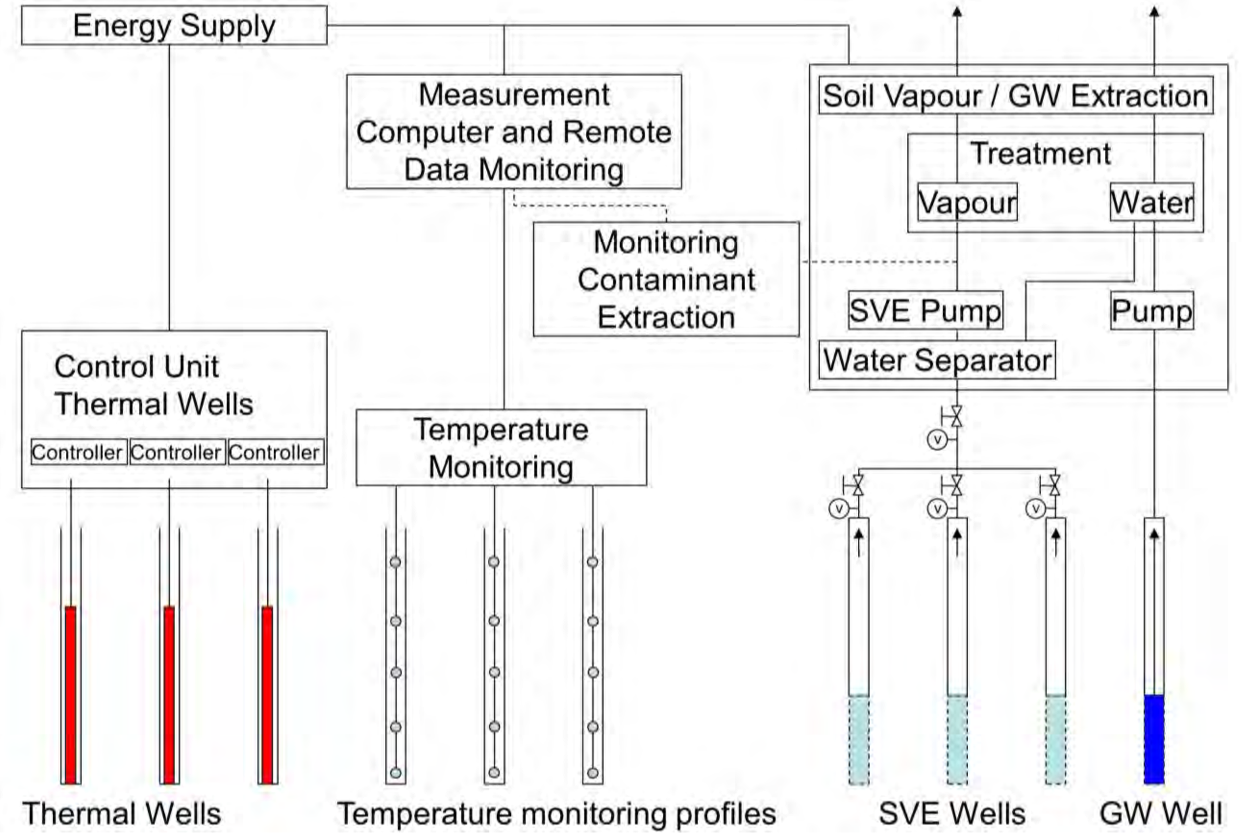


Figure 7 – Scheme of the treatment unit

Figure 8 – Heating and remote control room

4.2 Pre Treatment

To create clearing of operations for drilling equipment and plant installation, a small area of forest had to be removed next to TTZ, before starting the remediation works. Impacts from World War 2 bombing were not given at this site.

4.3 Post Treatment for effluent

The extracted soil vapour from MPE-system had been cooled down and dried. Condensate had been separated and passed on to the water treatment plant. The contaminated soil vapour was purified using granulated activated carbon.

4.4 Post Treatment for water

The operation of the established groundwater treatment system at this site continued during ISTR: conventional pumping from a groundwater well and treatment of the moderate contaminated groundwater by stripping and active carbon filters.

Condensate from the SVE was also cleaned with the existing stripping plant and activated carbon filters.

4.5 Control parameters

For an economical remediation operation, the operating parameters for thermal conductive heating (TCH), multi-phase extraction (MPE) and groundwater treatment must be coordinated. Since the processes can change very quickly during the remediation process, both the plant operation and the remediation-relevant processes in the soil and groundwater must be monitored using measurement technology.

A mobile environmental laboratory has been set up at the site to measure temperatures in the soil, contaminant concentrations in soil vapour and pumped groundwater as well as the discharge of soil vapour and pumped groundwater. The samples to be analysed from the soil vapour and groundwater were taken continuously and automatically from various measuring points and analysed on site. The data were transmitted via remote monitoring systems to the Reconsite office in Fellbach, where they were evaluated and interpreted. Especially the interpretation of the coupled thermodynamic and hydraulic processes during multiphase flow and their interaction on geotechnical and hydrogeological issues requires a detailed understanding of the process and several years of experience in data interpretation for in-situ thermal remediation.

5. Results

5.1 Removal rate

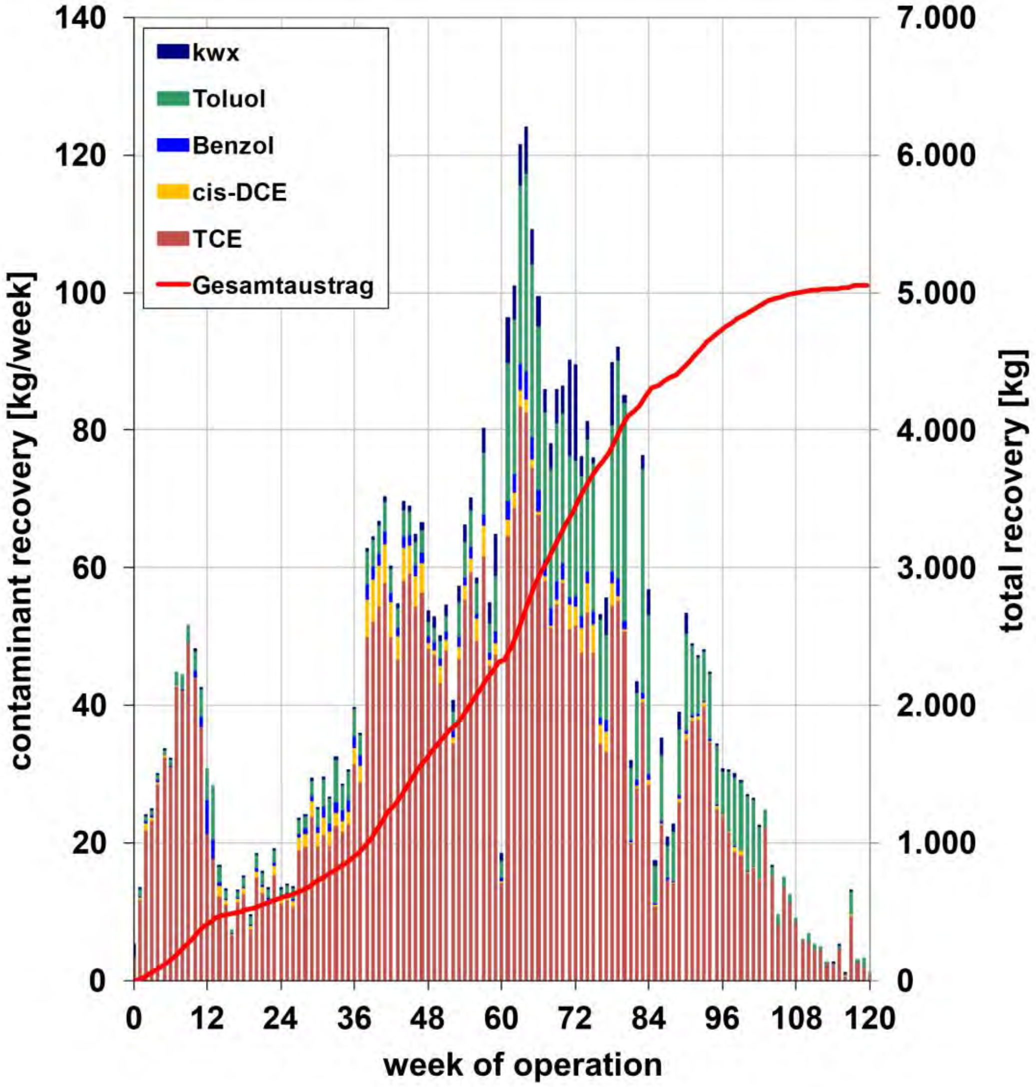


Figure 9 - Weekly contaminant mass recovery during TCH and total mass recovery

Conventional soil vapour extraction and pump and treat recovered around 5.4 tons of CHC and BTEX over 20 years of remediation. Despite this recovery, an end of the remediation could not be predicted for these methods. The contaminant would have been passed on to the next one to two generations.

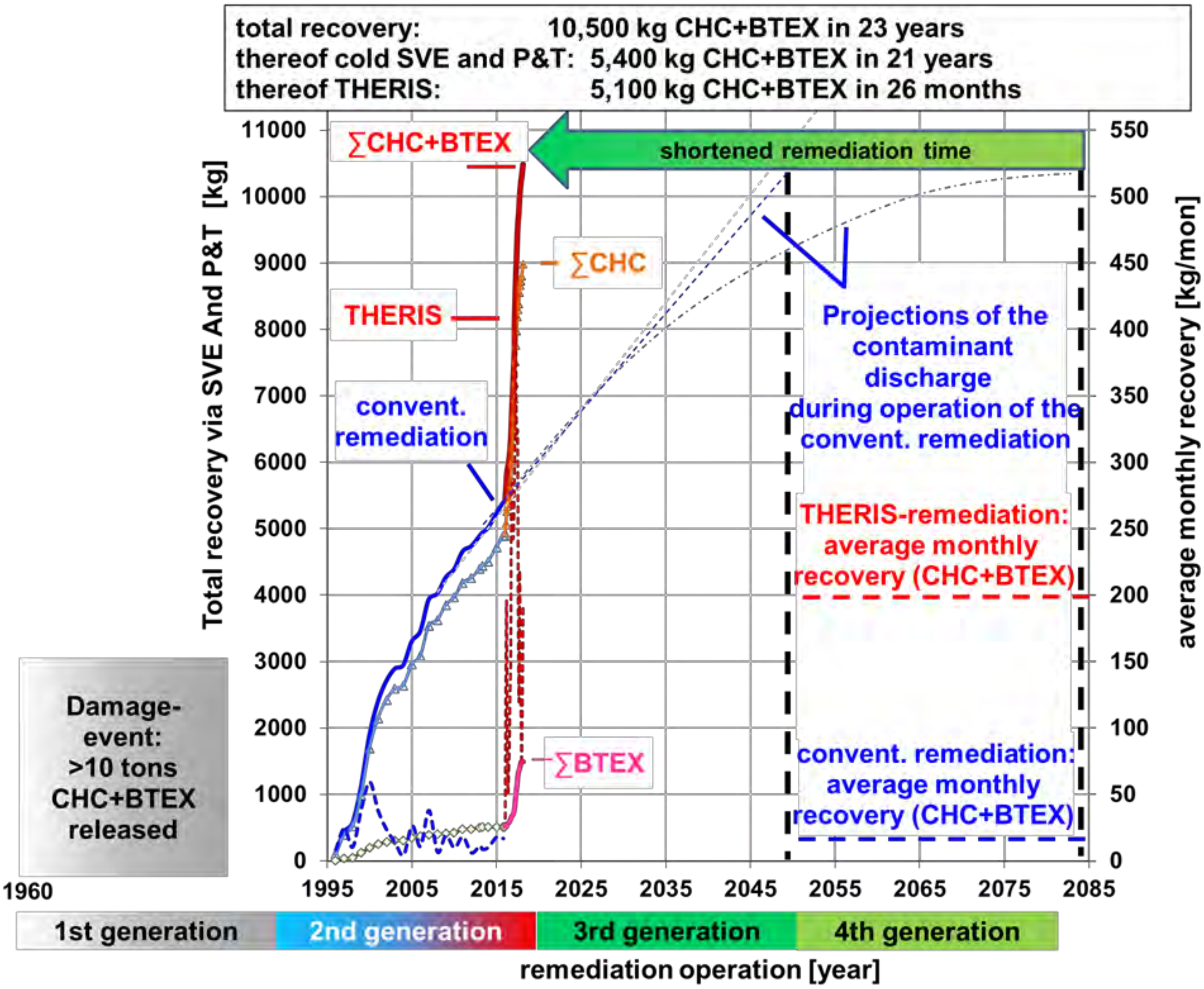


Figure 10 - Pollutant discharge with conventional and thermal remediation (THERIS method) and forecasts for further pollutant discharge with conventional remediation (linear pollutant discharge = best case).

During TCH / THERIS remediation, contaminant mass recovery was more dynamic compared with conventional SVE. This was due to the progress of heating as well as the change from one remediation field to the next. Additionally, areas of higher toluene contaminations could be identified during remediation.

In total, approximately 5,258 kg of CHCs and BTEX were removed via soil vapour extraction and approximately 42 kg of CHCs and BTEX via groundwater extraction. Together with the unspecified hydrocarbons (kwx), this results in a total discharge of nearly 5.5 tons of contaminant in 26 months of THERIS operation.

In-situ thermal remediation increased the average monthly load of CHC and BTEX (about 20 kg/month for conventional remediation) by about 10 times. This results in a shortening of the remediation time by several decades compared to the former conventional remediation.

Post treatment and/or Long Term Monitoring

6.1 Post treatment and/or Long Term Monitoring

To verify the remediation success, soil vapour extraction tests were conducted in accordance with ITVA Guideline H1-1 at various former wells in March/April 2018. The initial temperature in the particular wells were measured between 25°C and 81°C, despite shutdown of the heating system more than a year ago. The extraction was performed by connecting the well to a vacuum pump with negative pressures between 430 mbar to 210 mbar and a discharge between 125 to 175 m^3/h.

As a result, no significant contaminants could be detected. The site was removed from the list of contaminated sites by the authority.

7. Additional information

7.1 Lesson learnt

A serious source zone evaluation in combination with an efficient and economic TTZ removal concept by applying THERIS method as TCH in combination with multiphase extraction were the game changer at this site to get rid of long-lasting conventional pumping.

7.2 Additional information

ISTR by TCH in a cohesive soil had been conducted successfully in a thickness of more than 10 m close to buildings. The building usage for workshop and industrial purposes continued during ISTR without limitations. Settlements of other interactions by ISTR, relevant for the superstructure, could not be monitored.

7.3 Training need

Training guidelines are included in our quality assurance guidelines. Basic training in data evaluation and safe plant operation are combined with emergency trainings. For the project management team, basic training was obligatory incl. regular refreshments. For all site employees, health and safety instructions and explosive risk assessments were obligatory.

Glossary of Terms

Term (alphabetical order)	**Definition**
BTEX	Benzene, toluene, ethylbenzene, xylene
C	Carbon (number of carbon atoms)
CHC	Chlorinated Hydrocarbons
cis-DCE	cis-1,2-dichloroethene
COCs	Contaminants of Concern
GAC	Granular Activated Carbon
ISTD	In Situ Thermal Desorption
ISTR / ISTT	In-situ thermal remediation / treatment
kwx	(in gas chromatography) unspecified hydrocarbons
m bgl	m below ground level
MPE	Multi-Phase Extraction
PAH	Polycyclic Aromatic Hydrocarbons
PLC	Programmable Logic Controller
PCE	Tetrachloroethene
P&T	Pump and Treat for ABSTROMSICHERUNG
SV	Soil vapour
SVE	Soil Vapour Extraction
TCE	Trichloroethene
THERIS	Thermal in-situ remediation with electrical driven Heater (TCH)
TCH	Thermal Conductive Heating (in low permeable layer / soil)
TOC	Total Organic Carbon
TTZ	Treatment Target Zone
VOC	Volatile Organic Compounds are organic chemicals that have a high vapour pressure at ordinary room temperature
VTU	Vapour Treatment Unit

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.4

1.1 Name and Surname	Uwe Hiester, Laura Bieber
1.2 Country/Jurisdiction	Germany
1.3 Organisation	Reconsite GmbH
1.4 Position	Managing director
1.5 Duties	Contaminated land investigation, Implementation planning and realisation of: SEE (Steam Enhanced Extraction), TUBA-method (Steam-Air-Injection), P&T, SVE, explosive protection concept and application. Remediation management, environmental consulting
1.6 Email address	uwe.hiester@reconsite.com
1.7 Phone number	+49 711 410 190 0

2. Site background

2.1 History of the site

The petroleum port in Hamburg-Waltershof was operated since the 1920s and expanded in the following years. During World War 2, the petroleum tank farm at Hamburg port had been destroyed. As a result, hundreds of tons of gasoline, total petroleum hydrocarbons (TPH) and other pollutants were released. These hazard substances seeped into the ground and significantly polluted the soil and the tidally influenced groundwater.

Figure 1 – Hamburg Petroleum Port: Petroleum tank farm (around the year 1936), location of SEE treatment target zone (2019-2020, red marked area) (picture from: hhla.de/hamburger-fotoarchiv.de)

The area was redeveloped from the 1950s onwards. New tanks were built, and the tank farm was under operation again. To realize a container terminal expansion, restructuring of the port and conversion of the petroleum port area took place during the last two decades. The operation of the petroleum port was finished, and the tank farm was dismantled. For the land improvement, an environmental remediation of soil and groundwater had to be applied.

Figure 2 – Hamburg Petroleum Port: Petroleum tank farm (in the period 2000-2010), location of SEE treatment target zone in red (2019-2020, red marked area) and proposed project development (from 2021).

2.2 Geological setting

The soil consists of a filling with an average depth of approx. 13 m. The filling material consists mainly of grey, partly light brown medium sands. Locally, amounts of silt and varying fractions of fine and coarse sands and gravel are present. From approx. 7 m bgl higher fractions of coarse sand occur.

The filled sands are locally interspersed with low-permeability silt lenses and bands as well as peat layers, with usually only relatively small thicknesses of a few millimetres to approx. one decimetre. Occasionally also thicker silts were drilled.

The groundwater level is tidally influenced. The average groundwater level is about 5 m bgl and fluctuates by about ±0.8 m within 6 hours (groundwater level increase / decrease by about 1.5 – 1.6 m within 6 hours). Hydraulic permeability in the sand was explored to vary from 2.3 to 4.4 x $10E^{-4}$ m/s.

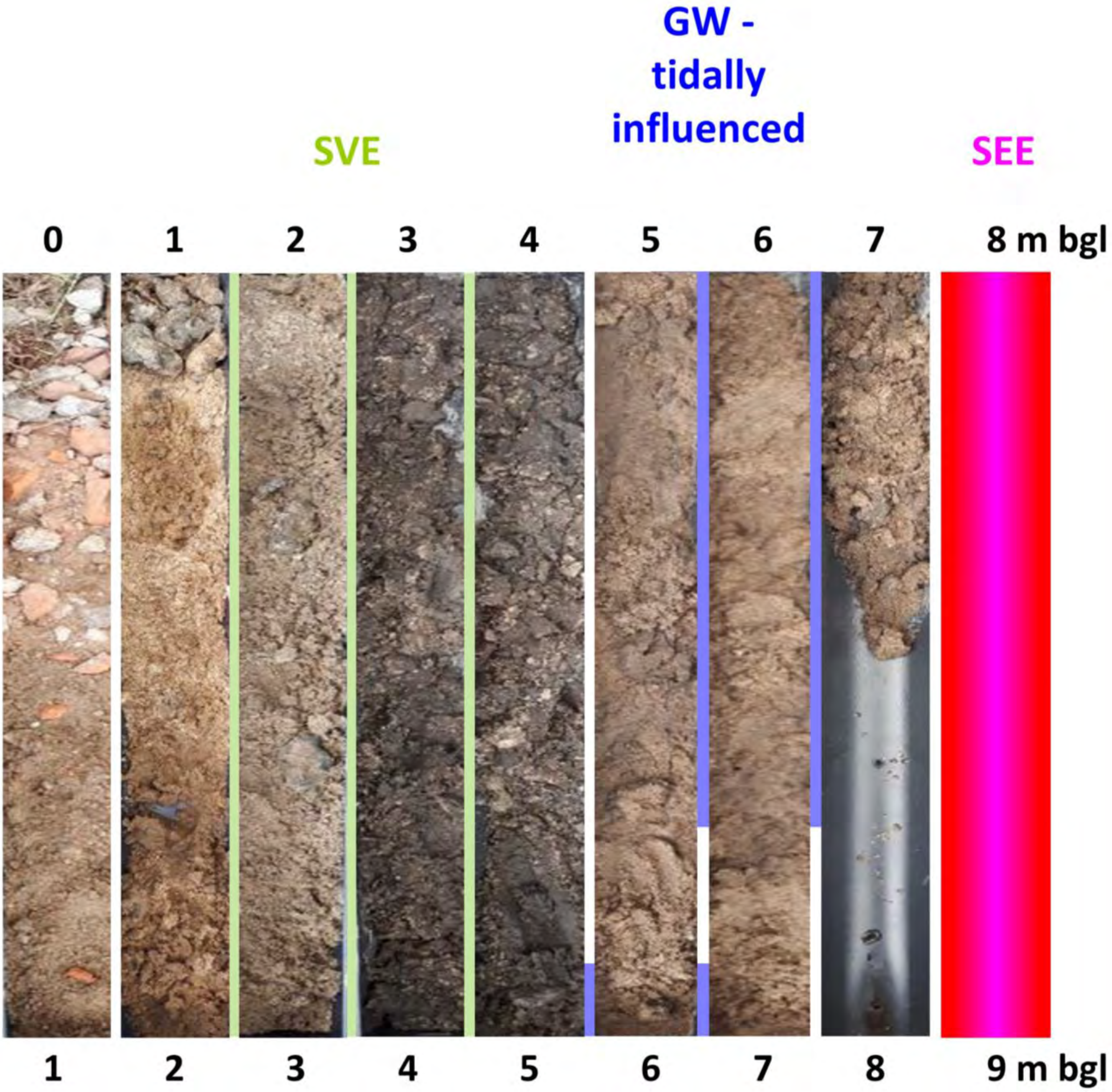


Figure 3 – Soil boring

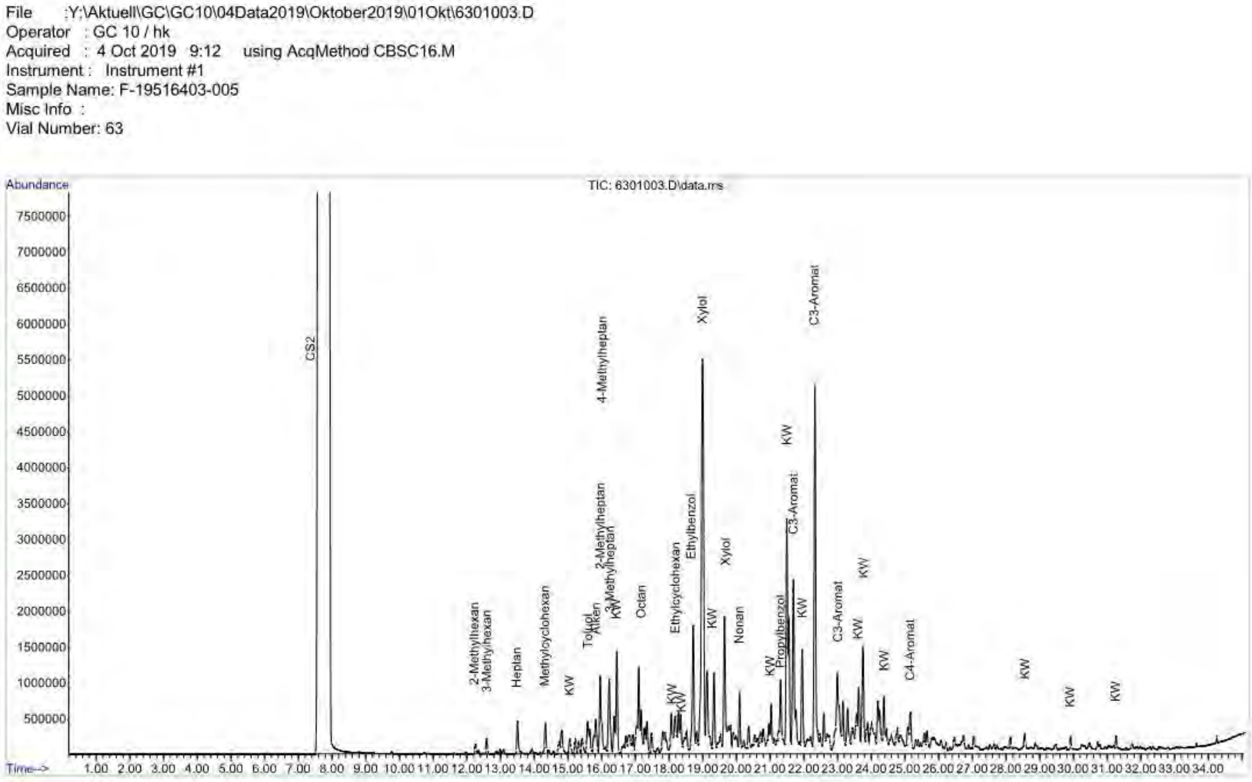
2.3 Contaminants of concern

Considerable contaminations in soil, soil vapour and groundwater were dominated by gasoline hydrocarbons (C6 - C10) (50-60%) and BTEX (benzene, toluene, ethylbenzene, xylene) (10-15%).

Initial gasoline hydrocarbon (C6 - C10) concentrations in the treatment target zone

(TTZ) reached locally up to 1,390 mg/m³ in soil vapour, up to 19,000 mg/kg in soil and more than 4,500 µg/L in groundwater. Initial BTEX concentrations in the TTZ reached locally up to 275 mg/m³ in soil vapour, more than 7,000 mg/kg in soil and more than 45,000 µg/L in groundwater. BTEX were dominated by Xylene by 70% (boiling point at about 140°C at atmospheric pressure).

Additionally, total petroleum hydrocarbons (TPH) (C10 – C40) (>4,500 µg/L), polyaromatic hydrocarbons (PAH, >2,300 µg/L, naphthalene >2,000 µg/L), C3-aromatics (trimethylbenzene, propyl benzene, ethyltoluene, styrene (boiling point between 145-170°C)) and other pollutants were present. The chromatogram illustrates the wide range of contaminants.



```
File        :Y:\Aktuell\GC\GC10\04Data2019\Oktober2019\01Okt\6301003.D
Operator    : GC 10 / hk
Acquired    :  4 Oct 2019   9:12     using AcqMethod CBSC16.M
Instrument :   Instrument #1
Sample Name: F-19516403-005
Misc Info  :
Vial Number: 63
```

Figure 4 – Typical chromatogram

Locally, floating LNAPL-phase was present on the groundwater surface (TPH >80,000 µg/L, BTEX >38,000 µg/L, C3-aromatics > 65,000 µg/L, PAH >2,300 µg/L). A total of about 200 tons of contaminants were suspected in the ground in 2018.

2.4 Regulatory framework

The project timeframe for the soil and groundwater remediation was strict to fit to the time frame of the port development strategy. The primarily remediation goal was to recover a huge number of contaminants to prevent spreading of mobile substances in future.

Site specific remediation strategy has been designed by considering e.g. “Bundes-Bodenschutz- und Altlastenverordnung (BBodSchV) vom 12. Juli 1999 (BGBl. I S. 1554), letzte Änderung Artikel 5 Absatz 31 des Gesetzes vom 24. Februar 2012 (BGBl. I S. 212)“ and “Ableitung von Geringfügigkeitsschwellenwerten für das Grundwasser, Ländergemeinschaft Wasser (LAWA), 2016“.

Steam enhanced extraction (SEE, TUBA-method (steam-air-injection)) has been selected to be the most efficient and economical method to recover a tremendous number of contaminants from the TTZ.

3. Pilot-scale

3.1 Laboratory Study

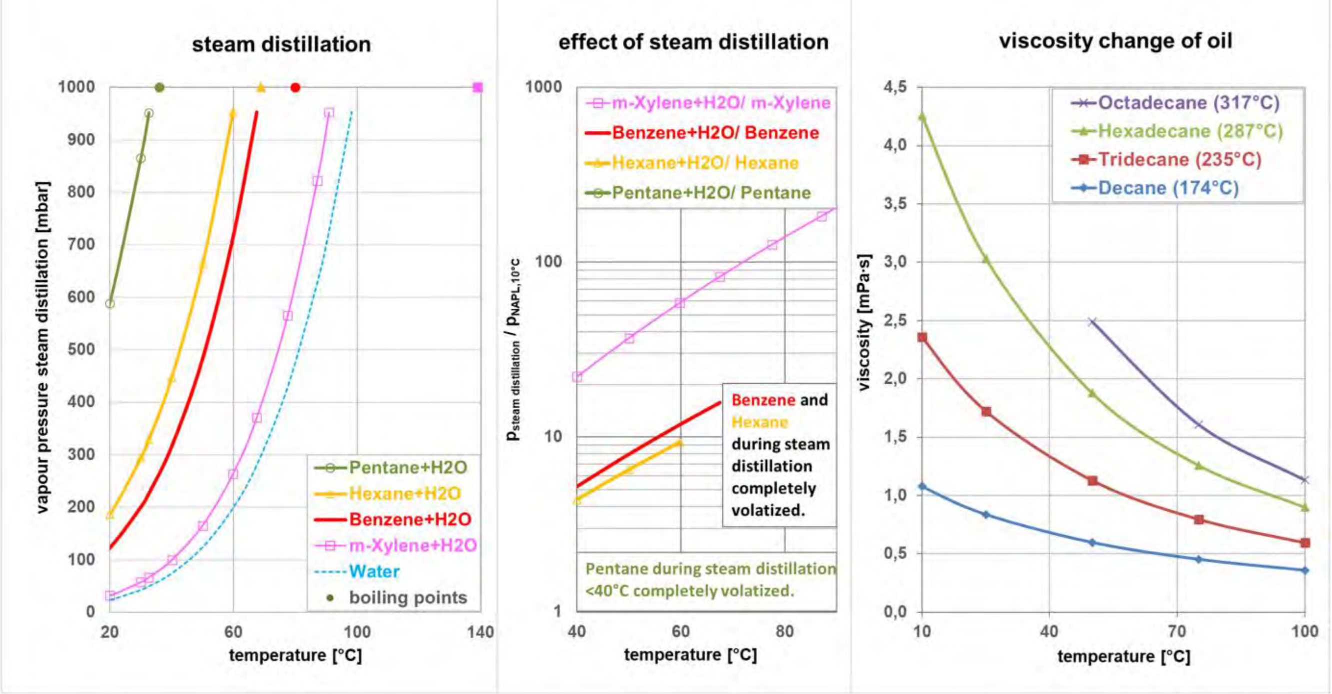


Figure 5 – Steam distillation and its effect

Due to the excellent process understanding of ISTD and SEE / TUBA as well as a wide range of application experience over the last two decades, site-specific laboratory studies or pilot tests were not required for SEE / TUBA.

The key remediation process at this site was steam distillation (co-boiling of water and contaminant). This process reduces the contaminant boiling point by co-boiling with water to temperatures below 100°C (eutectic temperature). Thus, drying of soil and high temperature heating can be avoided (see graphs). Heating to 60-90°C is sufficient to enable a high mass recovery.

As common for sites like these, pilot tests for in-situ thermal destruction (ISTD) are therefore usually not necessary.

3.3 Pre Treatment (pilot scale)

At this site conducted feasibility studies for BioBat-method, in-situ soil washing with surfactants and microbiological in-situ destruction failed in terms of technical and economic criteria for in-situ source zone remediation.

Due to the good understanding of ISTD-processes, an ISTD pilot test was not required for this site. While combining hydraulic and thermodynamic processes, ISTD enables remediation success even under complex boundary conditions (see 3.1).

Furthermore, the different storage tanks in the past (see 2.1) caused a site-specific strong variation of contaminant spreading at different locations. Additionally, the artificial filling in that area caused hydrogeological heterogeneities.

Therefore, a conclusion transfer from local pilot test results to other areas at this site would only have been possible with a wide range of uncertainties. Thus, a site specific ISTD / SEE pilot test would not have improved the design for the full scale ISTD.

4. Full-scale application

4.1 Main treatment unit

To enable brownfield redevelopment of this highly contaminated area, roughly 10,000 m² of soil and groundwater were remediated to a depth of up to 12 m below the ground level (bgl). To remove TPH from the tidally influenced groundwater in a sustainable manner, the largest steam enhanced extraction (SEE) with additional air-co-injection (TUBA method) in Europe had been applied.

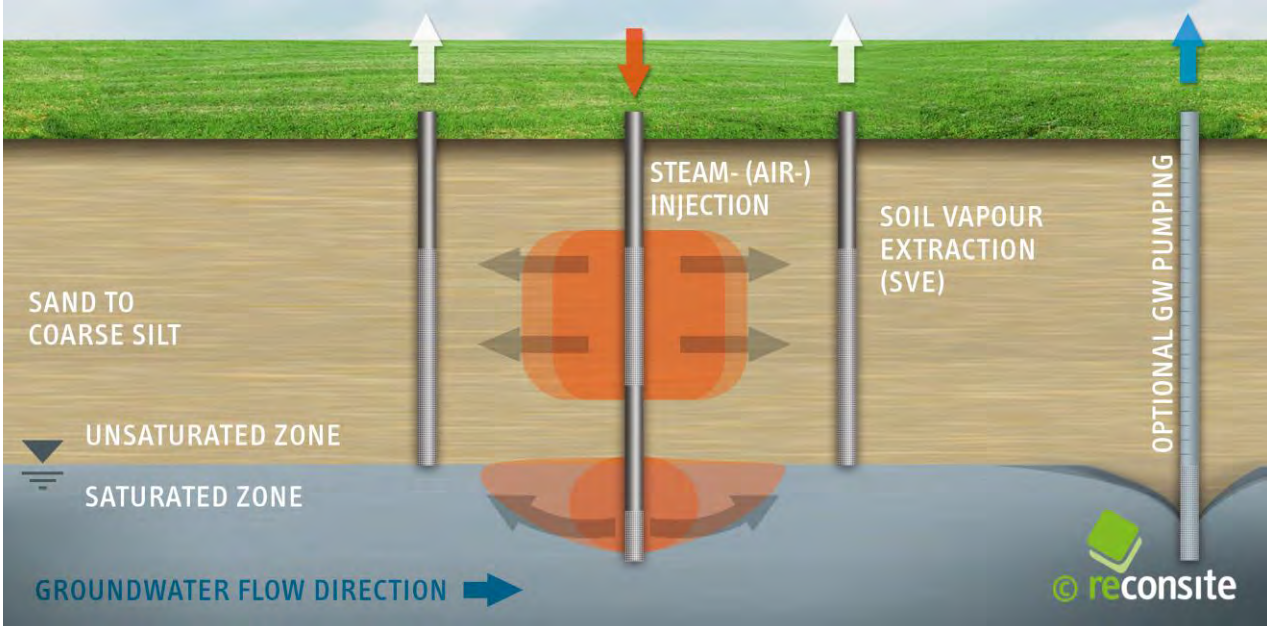


Figure 6 – General scheme of the technology

To realise the remediation, a steam generator with a steam capacity of up to 10,000 kg steam/h, a soil vapour extraction and treatment unit with a performance of up to 7,500 m³ soil vapour/h and a groundwater treatment plant for the treatment of up to 16 m³ contaminated groundwater/h were installed on site within a few weeks.

The mixture of steam and air had been injected into the tidally influenced groundwater (saturated zone). More than 120 injections wells (2”) were drilled with filter screens from mainly 8-9 m bgl and locally 11-12 m bgl.

Through injection of steam in the saturated zone, the unsaturated zone was heated as well. Contaminants were vaporized and transferred from groundwater into soil vapour.

The evaporated pollutants were captured via 150 soil vapor extraction (SVE) wells in total. A surface sealing had been implemented to improve the lateral SVE flux toward the soil vapour extraction wells.

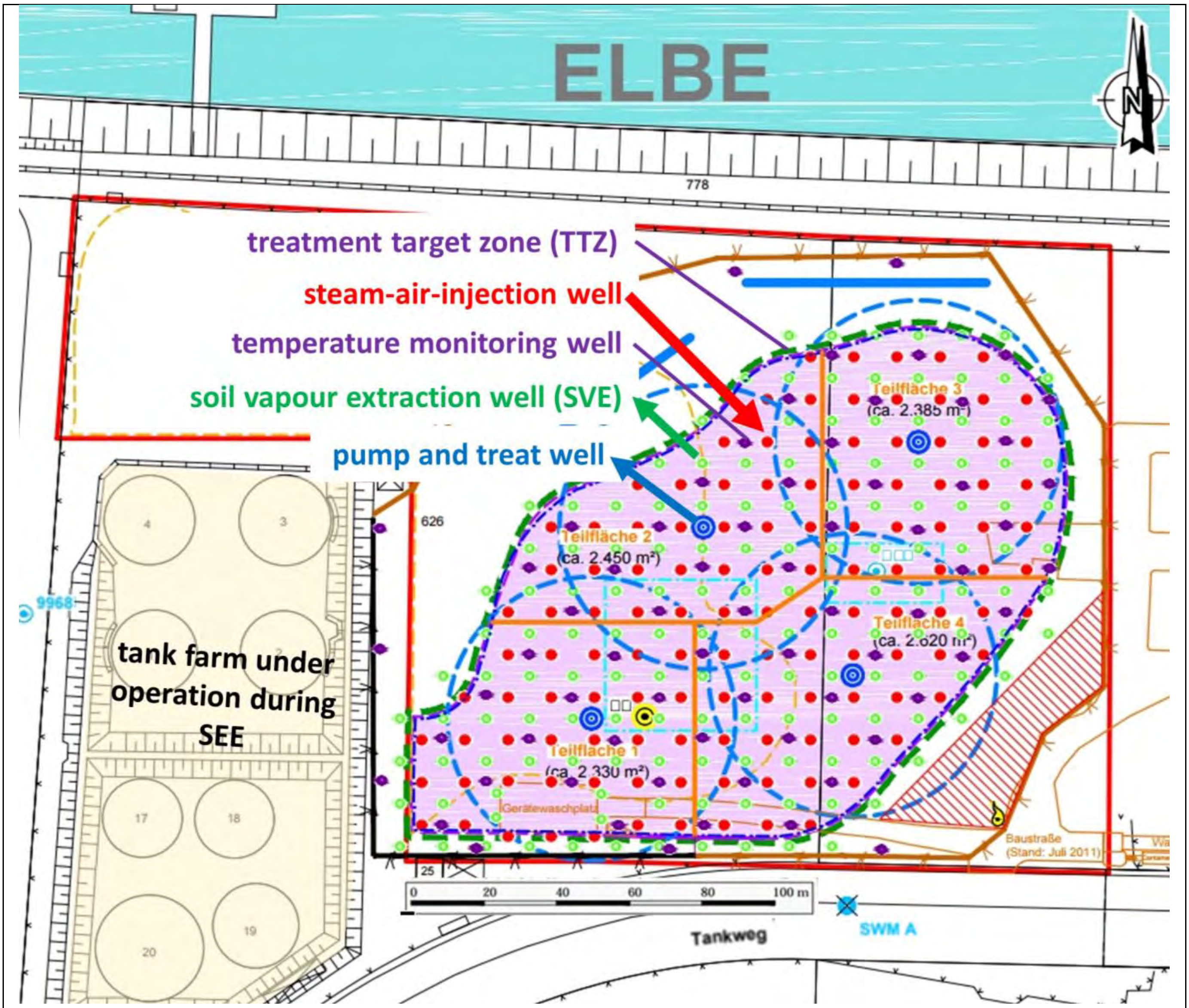


Figure 7 – Plan of the treatment target zone (TTZ)

A strict risk assessment and explosion protection enabled a serious and relaxed plant operation. The extracted soil vapour had been cooled down and dried. The contaminated soil vapour had been treated in the off-gas treatment before being released to the atmosphere.

Accumulated condensate from the cooling process of the SVE had been passed on to the wastewater treatment plant of the pump and treat system (P&T). P&T was installed at four groundwater wells. These wells were also equipped with belt skimmers to extract floating contaminant phase. During the operation of the groundwater wells, the influence of the tide had to be considered.

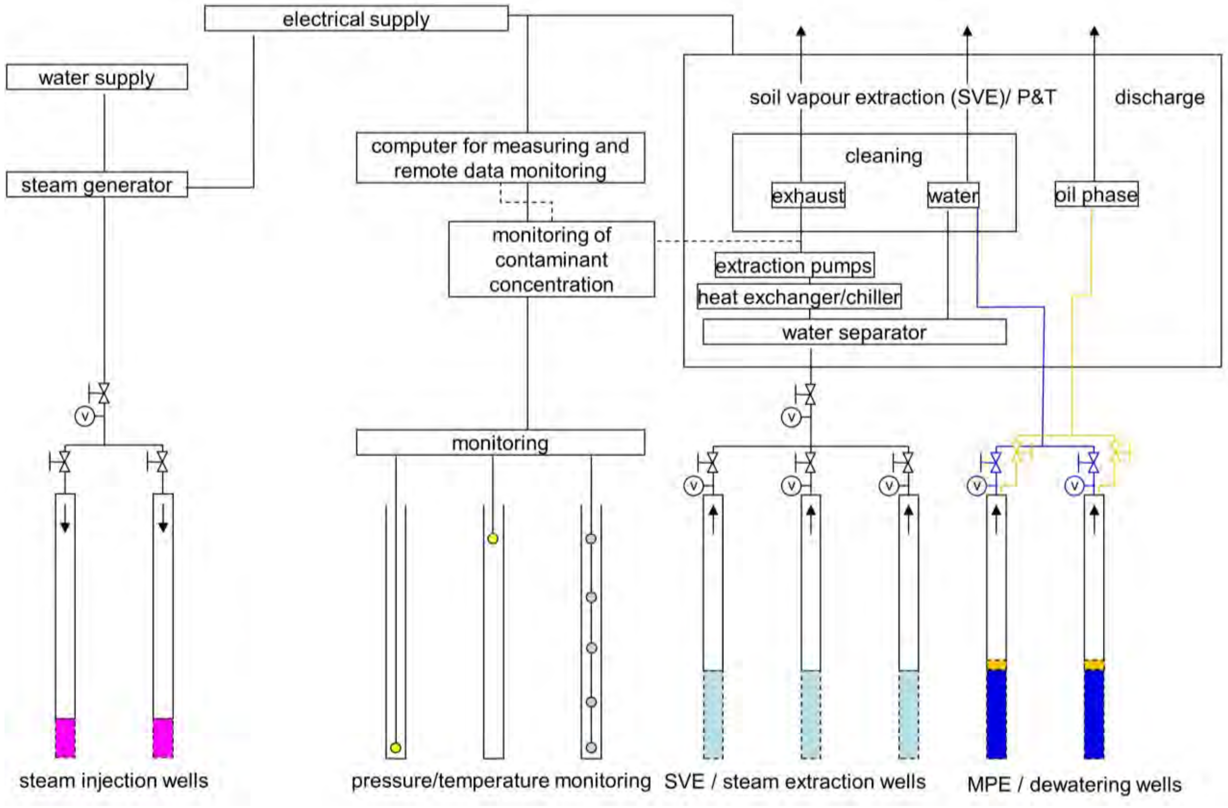


Figure 8 – Plant scheme

Figure 9 – SVE-pipes from the field

To monitor and optimize the SEE / TUBA remediation progress, heating of soil and groundwater, concentrations in soil vapour, plant operation of the steam boiler and SVE-system as well as the off-gas and water treatment system had been measured remote controlled and automated. Data post-processing and evaluation were automized. Data interpretation in terms of ISTD processes had been conducted daily. Remediation optimization followed strict quality assurance guidelines. Health and safety procedure (H&S) were considered. The impact of tidally effects on the groundwater temperature had been observed. The groundwater tide wave was thereby quantified in time and height by temperature data.

Figure 10 – SVE-pipes from the field to the treatment plant

Figure 11 – Oil phase from different areas of the TTZ, operated at the same time

Figure 12 – Water treatment (left), RTO (right)

Figure 13 – Steam boiler (left), RTO (right), remediation field

4.2 Pre Treatment

Due to the fact that the site was bombed in World War 2, explosive ordnance in parts of the TTZ had to be cleared for health and safety reasons prior to the remediation. Thus, surface soil had been removed and replaced locally up to a depth of 3 m bgl in parts of the TTZ.

4.3 Post Treatment for effluent

The extracted contaminated soil vapour was purified using a recuperative thermal oxidation system (RTO). In this process, gasoline, TPH and other pollutants were converted autothermal into H_2O and CO_2 at temperatures of up to 900°C before being released into the atmosphere.

The RTO cleaned the contaminated air from three independently operating SVE plants, each with a capacity of 2,500 m^3/h. To ensure a safe remediation process, contaminant concentrations in the extracted soil vapour were redundant permanently monitored in each SVE unit. SVE units and measured data had been remote accessed and controlled. Regarding explosive risks, the plc-controlled plant enabled an immediate optimisation of the soil vapour conditioning for the off-gas treatment. In terms contaminant concentrations reached a safety relevant share of the lower explosive limit (LEL), soil vapour was diluted with atmospheric air to match explosive risk restrictions.

4.4 Post Treatment for water

Figure 14 – Water treatment

The extracted groundwater as well as the condensate from the soil vapour extraction system were collected in an oil-water separator. Due to the different densities, oil phase was separated from groundwater. The oil phase was pumped, collected separately and properly disposed by a specialist disposal company. The remaining water was treated as follows:

- Iron removal through dosage of several chemicals in multiple reactor tanks
- Separation of floatable solids through a crossflow filter
- Stripping unit
- Treatment of stripped air from wastewater treatment plant by GAC
- And additional treatment of water from water treatment plant by GAC

The treated groundwater was discharged into two infiltration ditches.

4.5 Control parameters

During the remediation, contaminant concentration in soil vapour, discharges of soil vapour and groundwater as well as temperatures in the soil and programming logic controller (PLC)-data from the plants were continuously measured, saved and automatically evaluated.

In addition, groundwater samples were taken weekly to biweekly and analysed from a certified laboratory.

5. Results

5.1 Removal rate

The total contaminant mass recovery (>280 tons) exceeded the initially proposed mass (200 tons) by more than 40%. Around 1.8 tons of oil phase (LNAPL) were separated and disposed externally. The groundwater treatment plant treated 0.4 tons of contaminants. Thus, the soil vapour extraction (SVE) dominated the total mass recovery by >99%. Due to the detailed monitoring during SEE / TUBA operation, mass recovery (%) per partial TTZ was calculated in the project back analysis (see below).

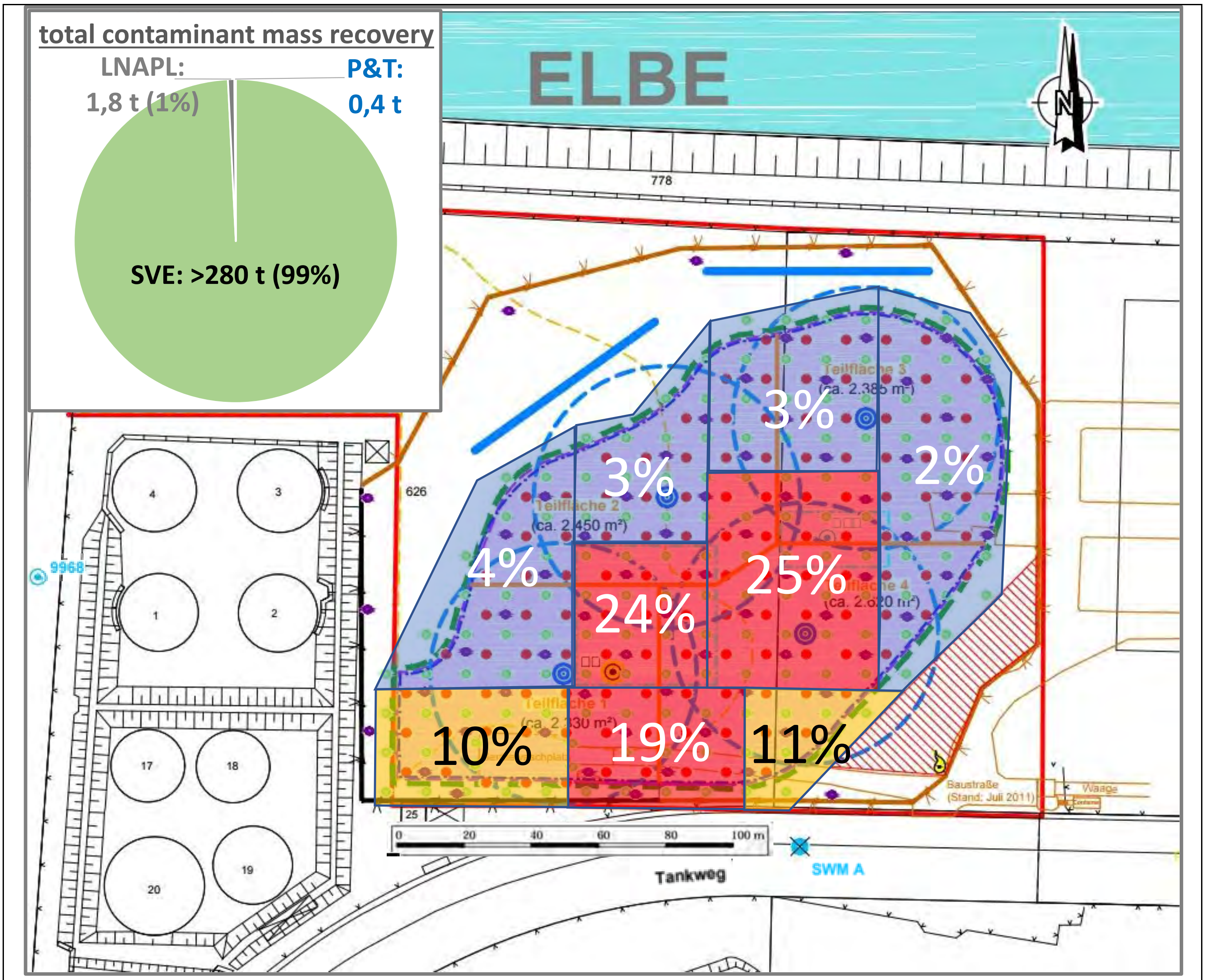


Figure 15 – Mass recovery (%) per partial Target Treatment Zone

During the dismantling of the wells, the soil vapour around the well location has been monitored with a photo ionization detector (PID). The recovered well pipes were still warm, but no contaminants were detected during the complete dismantling stage.

6. Post treatment and/or Long Term Monitoring

6.1 Post treatment and/or Long Term Monitoring

After final SEE / TUBA shutdown at the site, control drillings were conducted in soil and groundwater. Measured groundwater temperature varied from approx. 37°C (15 months after SEE shutdown) to approx. 29°C (23 months after SEE shutdown).

To evaluate SEE remediation success, soil concentration (mg/kg) were defined by the environmental authority. Action threshold was set to 500 mg/kg for gasoline hydrocarbon and 30 mg/kg for BTEX (see diagram). Evaluation criteria was the correlation of initial soil concentrations to past ISTD soil concentrations. Initial soil concentrations exceeding remediation targets (action thresholds) were reduced by a factor of almost 1,000 by SEE / TUBA. This relates to an average remediation success of 99.7%. After SEE / TUBA, several soil concentrations were below detection limit.

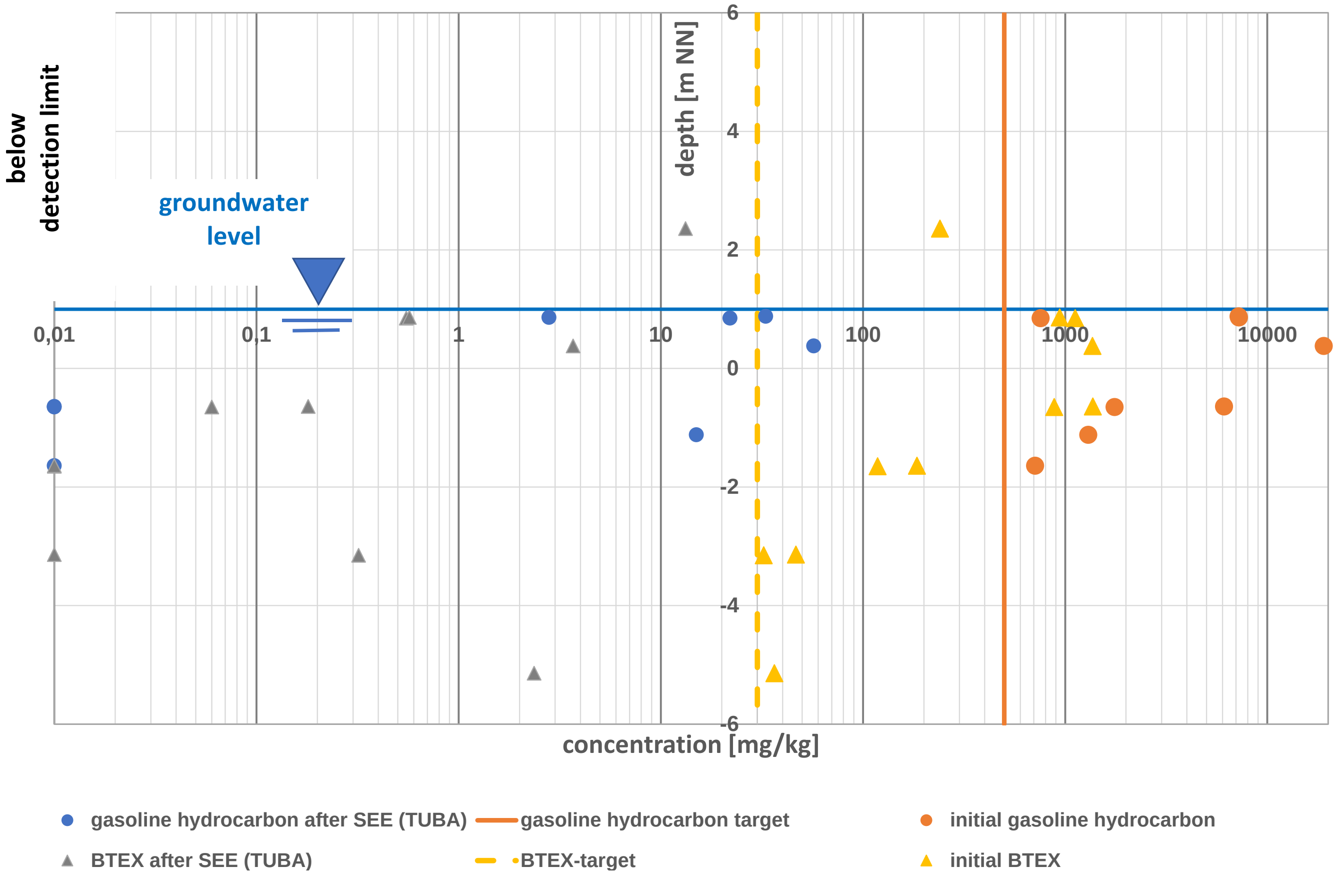


Figure 16 – Initial and target concentrations

The ISTD has been certified being successful. No further monitoring e.g. of groundwater concentrations is required. The TTZ is permanently released for reuse (brownfield redevelopment).

7. Additional information

7.1 Lesson learnt

This SEE / TUBA remediation of a former tank farm was the largest project of this technology at least in Europe. Due to the excellent engineering, data evaluation and SEE/TUBA operation and optimisation, this project has been honoured with the Brownfield24 Award 2022.

Contaminant distribution and hydrogeological conditions changed throughout the TTZ. Similar conditions were found for an average of about 500 m², which was usually about or less than half of one partial TTZ (see 5.1).

Detailed process planning including consideration of accident scenarios (unexpected rapid increase of soil vapour concentrations, which can lead to an explosive air-TPH-mixture). To implement health and safety guidelines in the SEE plant operation, the following issues were essential:

- implementation planning under respect of emergency scenarios like shut down of single components or gasoline blow outs in the SVE (effecting a sudden change of gasoline - soil vapour mixture by rising the LEL quote),
- a high degree of automated sensor and remote-controlled system (PLC),
- automated measurement devices incl. automated data post-processing to monitor environmental data like subsurface temperature, concentrations, discharge and more,
- trained staff for data evaluation, process interpretation and remediation progress extrapolation in terms of optimisation of ISTD,
- continuous documentation of measured data, interpretations, discussions and decisions,
- coordination with client on a weekly base, additionally as well with authorities and other involved parties in terms of needs.

The specific price per ton of soil (approx. 30 €/t) is the total remediation cost (approx. 6 Mio. €) divided by the soil mass of the TTZ (200,000 t). The energy input per ton of treated soil (approx. 55 kWh/t) is calculated from the total energy consumption of 10.080 MWh (energy consumption) and the soil mass of the TTZ (200,000 t). With this energy input, excavated soil could be transported about 20 km by truck, e.g. in terms of dig and dump.

The specific cost per kg of gasoline hydrocarbon (approx. 21 €/kg) is derived of the total remediation cost (approx. 6 Mio. €) and the gasoline hydrocarbon removed (280,000 kg).

The energy consumption per kg gasoline hydrocarbon (approx. 36 kWh/kg) results from the total energy consumption (approx. 10.080 MWh) and the tons of gasoline hydrocarbon removed (280,000 kg). The average energy consumption for pump and treat, found in literature for other sites, is in the range of 800 – 850 kWh/kg. Thus, ISTD with SEE / TUBA is about 20 time less energy consuming than P&T.

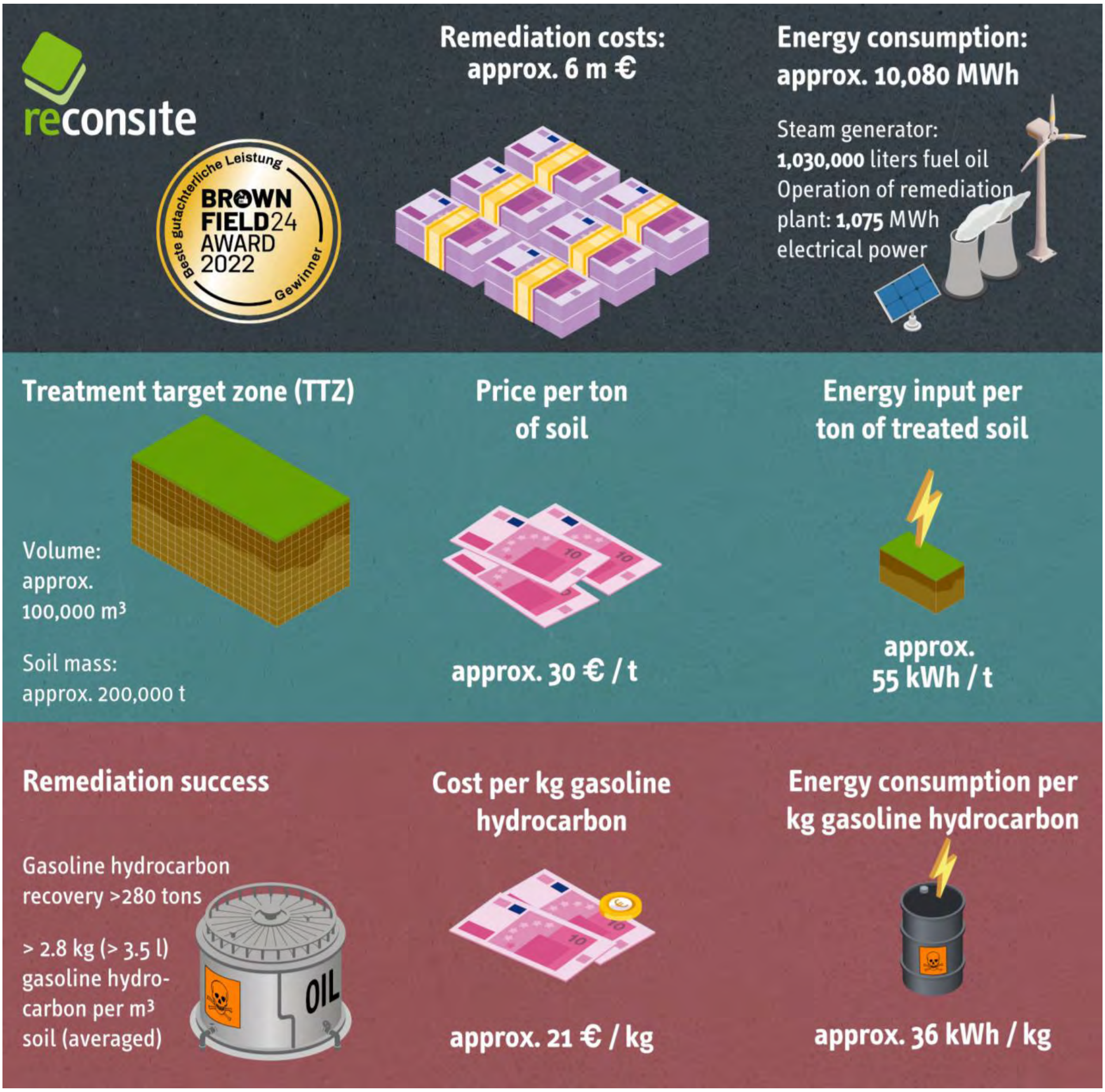


Figure 17 – Technology cost breakdown

7.2 Additional information

At the neighbouring tank farm, pipeline routes were installed on pillars. Settlement monitoring was made for the foundations of these pillars. During the entire remediation process, no effects of the SEE / TUBA in terms of settlements or stability of these pillars were detected.

Steam distribution in the groundwater was affected by the tidal influence, e.g. due to changing hydrostatic pressure in the aquifer. These hydrostatic fluctuations could be overcompensated by keeping the injection pressure on a higher value.

The contaminant recovery through the operation of the P&T system contributes only insignificantly to the total contaminant removal. The total mass of contaminants by P&T (400 kg) within 17 months was almost equal to 18 hours operation of SVE (average daily recovery >520 kg/d).

7.3 Training need

Training guidelines are included in our quality assurance guidelines. Basic training in data evaluation and safe plant operation are combined with emergency trainings.

For the project management team, basic training was obligatory incl. regular refreshments. For all site employees, health and safety instructions and explosive risk assessments were obligatory.

7.4 Additional remarks

Natural Attenuation processes (NA) by microbiological degradation were present at the site before ISTD at locations with low concentrations. Even next to the TTZ, contaminants were present but not of interest for an ISTD.

During and after SEE / TUBA, spreading heat from TTZ to the surrounding subsurface provoke an increase of microbiological activities in terms of contaminant destruction. Thus, this thermal energy spread can be entitled as (thermally) enhanced natural attenuation (ENA).

Even this process was present at the site, no detailed monitoring was conducted. Thus, the mass of additional contaminant removal, effected by this thermal enhancement, cannot be quantified by calculations.

Glossary of Terms

Term **(alphabetical order)**	**Definition**
C	Carbon (number of carbon atoms)
COCs	Contaminants of Concern
GAC	Granular Activated Carbon
ISTD	In Situ Thermal Desorption
ISTR	In Situ Thermal Remediation
ISTT	In Situ Thermal Treatment
LEL	Lower Explosive Limit
LNAPL	Lighter than water Non-Aqueous Phase Liquid
m bgl	m below ground level
SEE	Steam Enhanced Extraction
PAH	Polycyclic Aromatic Hydrocarbons
PLC	Programmable Logic Controller
PID	photo ionization detector
RTO	Recuperative Thermal Oxidation
SVE	Soil vapour extraction
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbon
TTZ	Treatment Target Zone
TUBA-method	Steam Enhanced Extraction (SEE) with additional air co-injection (steam stripping)
VOC	Volatile Organic Compounds are organic chemicals that have a high vapour pressure at ordinary room temperature
VTU	Vapour Treatment Unit

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.5

1.1 Name and Surname	Alessandro Teani Christian Gambelli
1.2 Country/Jurisdiction	Italy
1.3 Organisation	Greenthesis S.p.A.
1.4 Position	CTO Project Manager
1.5 Duties	
1.6 Email address	alessandro.teani@greenthesisgroup.com christian.gambelli@greenthesisgroup.com
1.7 Phone number	+39 335.6201002 +39 347.2172210

2. Site background

2.1 History of the site

The concerned area is placed in the locality called "Tre Monti" in the Municipality of Bussi sul Tirino near the industrial centre of Bussi Officine. The Area is located along the valley floor of the Pescara River, near the confluence with the Tirino River, between the left bank of the river and the pillars of the A25 “Autostrada dei Parchi” (Rome – Pescara). The site occupies an area of approx. 30,000 m^2. The site is characterized by the presence of buried waste of various origins, in particular industrial production waste mixed with demolition waste and various landfills.

Figure 1 – Satellite image of the affected area

The area has been affected by various investigative phases of characterization:

- an initial investigation was conducted in 2007, under the supervision of the State Forestry Corps, on behalf of the Pescara Public Prosecutor's Office;
- a second aimed at outlining the conceptual model of the site in anticipation of a reclamation and safety intervention was carried out in 2014 by the Deputy

Commissioner;

a third and final investigative phase, in chronological order, was carried out starting from May 2017 and had the aim of integrating the information made available from the previous characterization phases in order to fill some interpretative gaps, allowing to outline the conceptual model of the area.

2.2 Geological setting

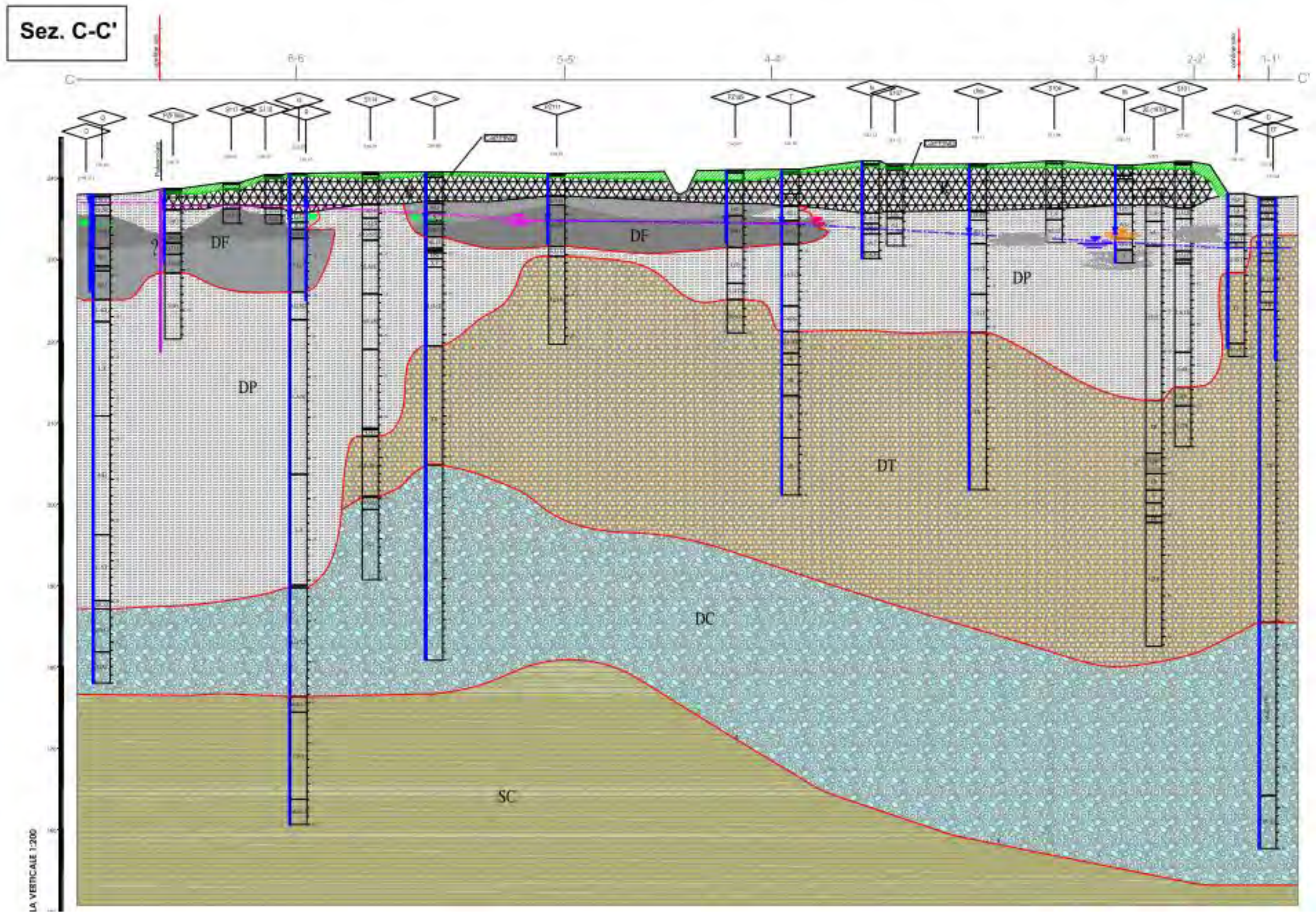


Figure 2 – Section C-C' of underground strata

The site is characterized by the presence of a surface layer made up of landfill/human waste. The lithostratigraphic succession of the natural soils underlying the anthropic materials is rather articulated and complex, diversifying in the southern, central and northern portions of the site.

Southern sector: below the anthropic materials are the fluvial deposits (DF), consisting of gravels and sands with a variable sandy-silty matrix and interspersed with finer clayey silty lenses. This is followed by the marsh deposits (DP), consisting of silts, clayey silts, peaty silts and peats and subordinate sandy silts with local sandy silty, silty peaty intercalations. This formation reaches a maximum thickness of over 40 m. Below this we find fan deposits (DC) of slope debris and landslides, consisting of pebbles and heterometric and angular polygenic blocks in a silty sandy matrix and finally the carbonate substrate consisting of detrital limestones, calcarenites and calcilutites of Monte Morrone fractured to intensely fractured places.

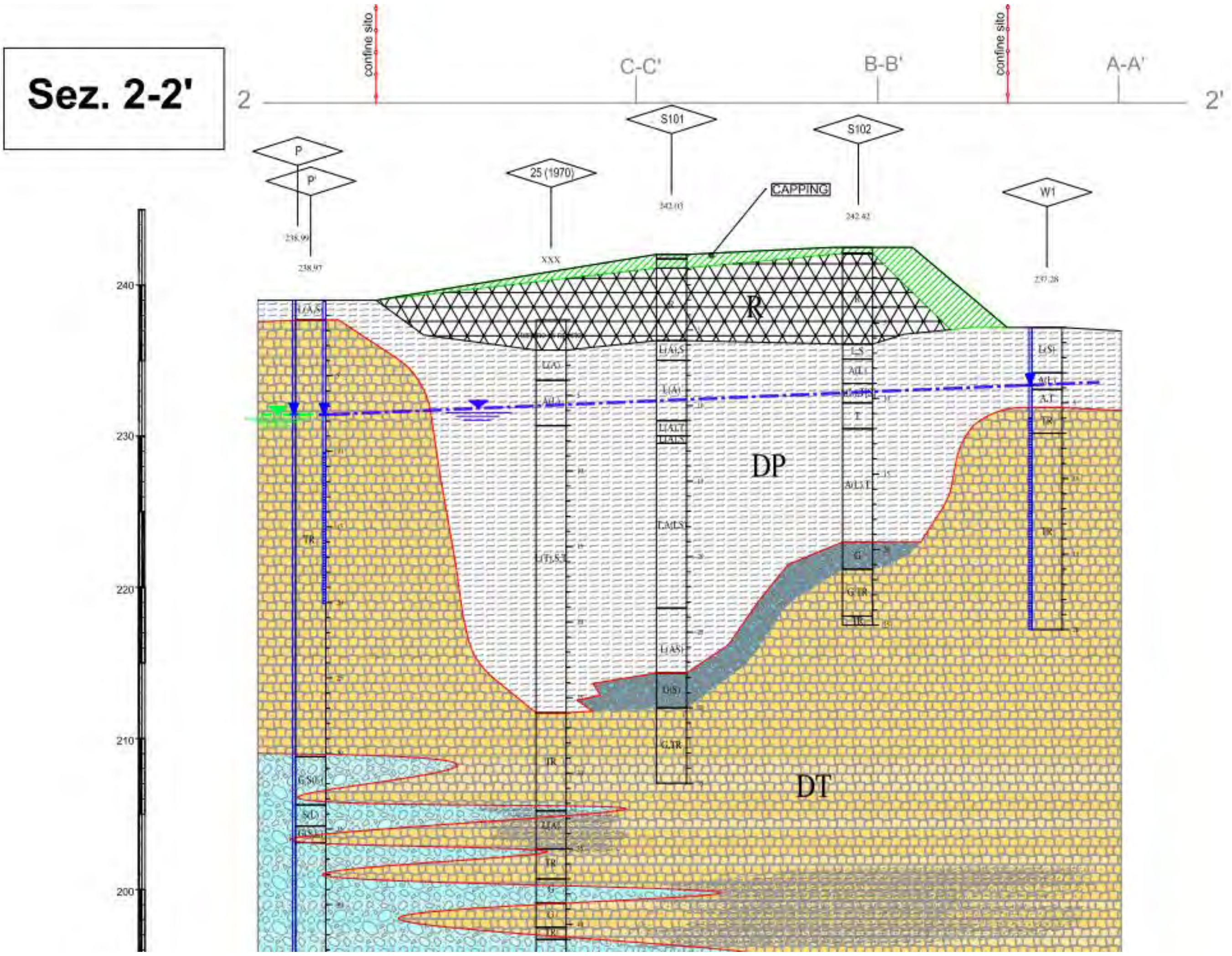


Figure 3 – Section 2-2' of underground strata

Central sector: the anthropic materials still rest on the fluvial deposits (DF). The thickness of the marsh deposits (DP) is considerably thinner due to the effect of the travertine deposits roof rising (DT). In this area, direct contact between the fluvial deposits and the travertines is locally observed; below the travertines the deposits of conide are still found followed by the carbonate substrate.

Northern sector (see Sez. 2-2') in this sector the anthropic materials rest directly on the marsh deposits (DP) consisting of silts, clayey silts, peaty silts and peats and subordinate sandy silts with local sandy or silty sandy interbedded areas, the thickness of which can reach a maximum value of over 20 m. River deposits (DF) are completely absent. Towards the northern border of the site, the thickness of the marsh deposits (DP) becomes thinner, and the travertine roof (DT) is found a few meters from the ground level. Below these are found fan deposits (DC) of slope debris and landslides, consisting of pebbles and heterometric and angular polygenic blocks in silty sandy matrix, followed by the calcareous substrate (SC).

In this area the installation of the in situ thermal desorption system is foreseen.

The lithologies surveyed on site identify hydrogeological complexes with their own characteristics and host an aquifer. The marsh deposits (DP) are an exception, which constitute an aquitard/aquiclude, with sometimes limited levels of silty sands which host impregnation waters.

2.3 Contaminants of concern

The Area is characterized by the presence of a superficial blanket made up of anthropic material which were, in all probability, the original source of contamination. Below these are found natural soils which currently constitute the most contaminated matrix. The complex of investigations carried out over the years at the site has made it possible to outline the physical and qualitative characteristics of the different environmental matrices found (superficial man-made cover, unsaturated soils, groundwater).

<u>Superficial anthropic blanket</u>: the thickness of the waste body varies from north to south, going from maximum values between 5 and 6 m in the northern portion of the site to values between 3 and 4 m in the southern portion. The product analysis of the materials found indicates a diversified origin, ranging from processing waste to demolition aggregates to backfill and it has also identified concentrations of chlorinated solvents of the order of a few tens of mg/kg in the samples of material taken from the body of waste.

<u>Soil and subsoil</u>: the complex of investigations carried out on natural soils below the anthropic blanket has identified some contaminants in concentrations higher than the limit values defined by Legislative Decree 152/06 (CSC of Tab1 Column A of Legislative Decree 152/06). The contaminants mainly detected in concentrations exceeding these limits belonged to the Chlorinated Aliphatic family; less significant surpluses in terms of size and frequency were also found for chlorobenzenes. In addition to the excesses already illustrated for the parameters of the families indicated above, local excesses also for the Inorganic elements (Selenium, Cadmium, Beryllium), Aromatic hydrocarbons

(Benzene, Ethylbenzene, Xylene), Light C≤12 and heavy C>12 hydrocarbons. However, the entity of the exceedances is reduced compared to that found for the chlorinated aliphatic compounds.

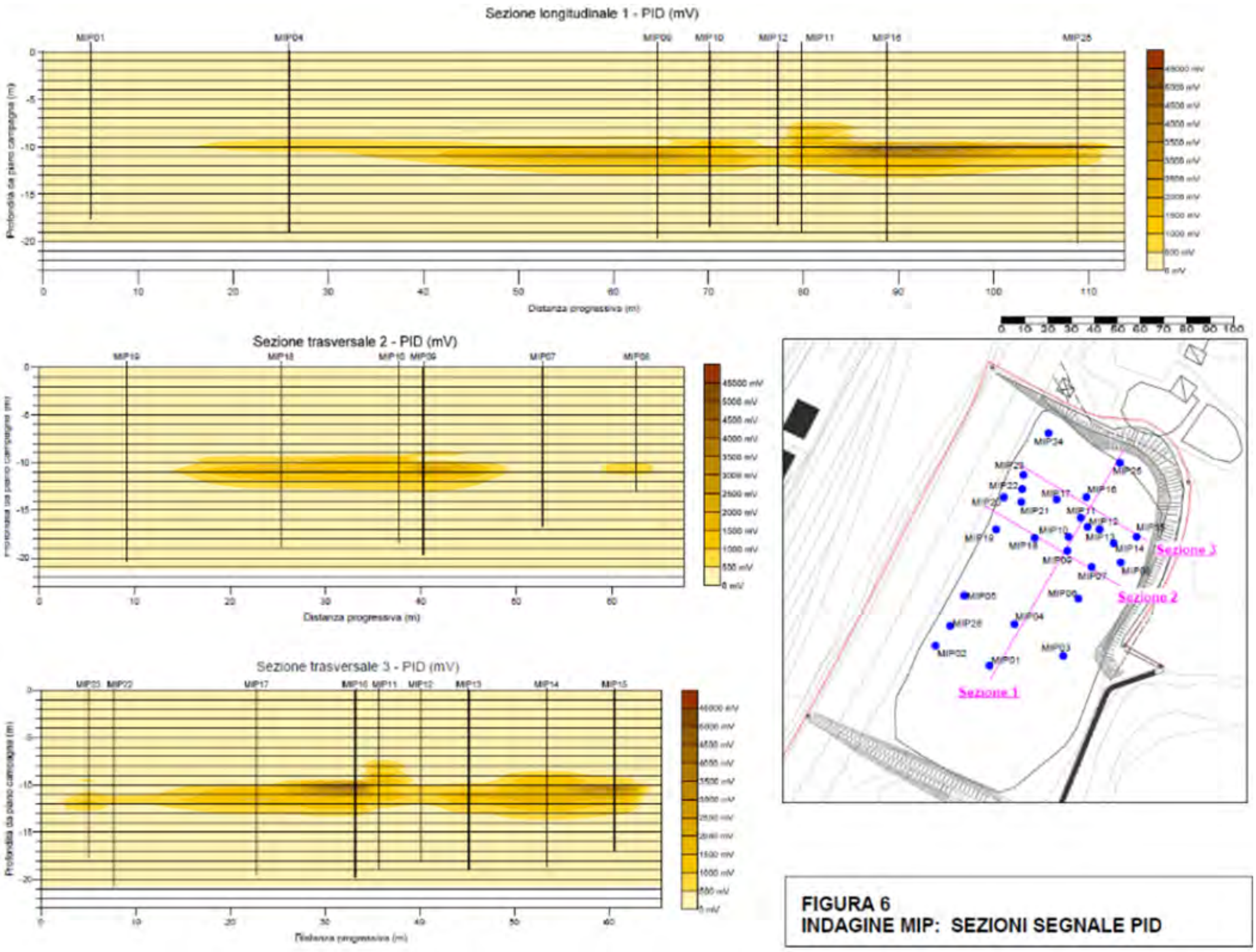


Figure 4 – MIP investigation with PID signal

In the Northern sector, where the installation of the in situ thermal desorption system is planned, the contamination situation is illustrated to the side. The main contaminants are:

- 1,1-dichloroethylene
- Trichloroethylene; Tetrachloroethylene; Dichloromethane
- 1,1,2,2 Tetrachloroethane
- 1,1,1,2 Tetrachloroethane

Groundwater: groundwater is mainly impacted by compounds belonging to family of chlorinated aliphatics.

2.4 Regulatory framework

The intervention on the site is developed according to the project approved by the Italian Ministry of the Environment by Decree n. prot. 0000403 of 6 August 2018. In this decree, the Ministry approves (Art.1):

- the removal of waste located in the southern sector of the site;
- the application of the in situ thermal desorption pilot module in a portion of the northern area of the construction site.

If the pilot test should provide satisfactory data, the final design of the full-scale plant will be carried out for its installation in the northern area of the site. The approval of the full-scale project is in the hands of the Ministry of the Environment (MASE).

At the conclusion of the full-scale in situ thermal desorption intervention, the waste volume above the soil layer treated using ISTT technology will be removed.

3. Pilot-scale

3.1 Laboratory Study

No laboratory studies have been conducted regarding the applicability of in situ thermal desorption technology for the type of contaminants.

To study the applicability of this technology to site-specific reality, it was decided to carry out a pilot test.

3.2 Treatment unit (pilot scale)

To verify the applicability of the technology to the contamination present and to the type of soil to be reclaimed, an ISTT pilot test was installed in the northern area. On the bases of:

1. Type of contaminants present (mainly chlorinated solvents)
2. restrictive remediation objectives
3. presence of saturated horizons in low permeability insulated lenses
4. articulated stratigraphy (locally sandy clay silts)

the electrically conductive type (TCH) has been identified as the best technology for in situ desorption is, as it does not present depth and system efficiency limitations such as for conductive heating a gas whose main limitation is the depth of treatment. The maximum concentration of contaminants is found in correspondence with the peaty and clayey levels detectable at a depth of 8-9 m and 13-14 m from the pc.

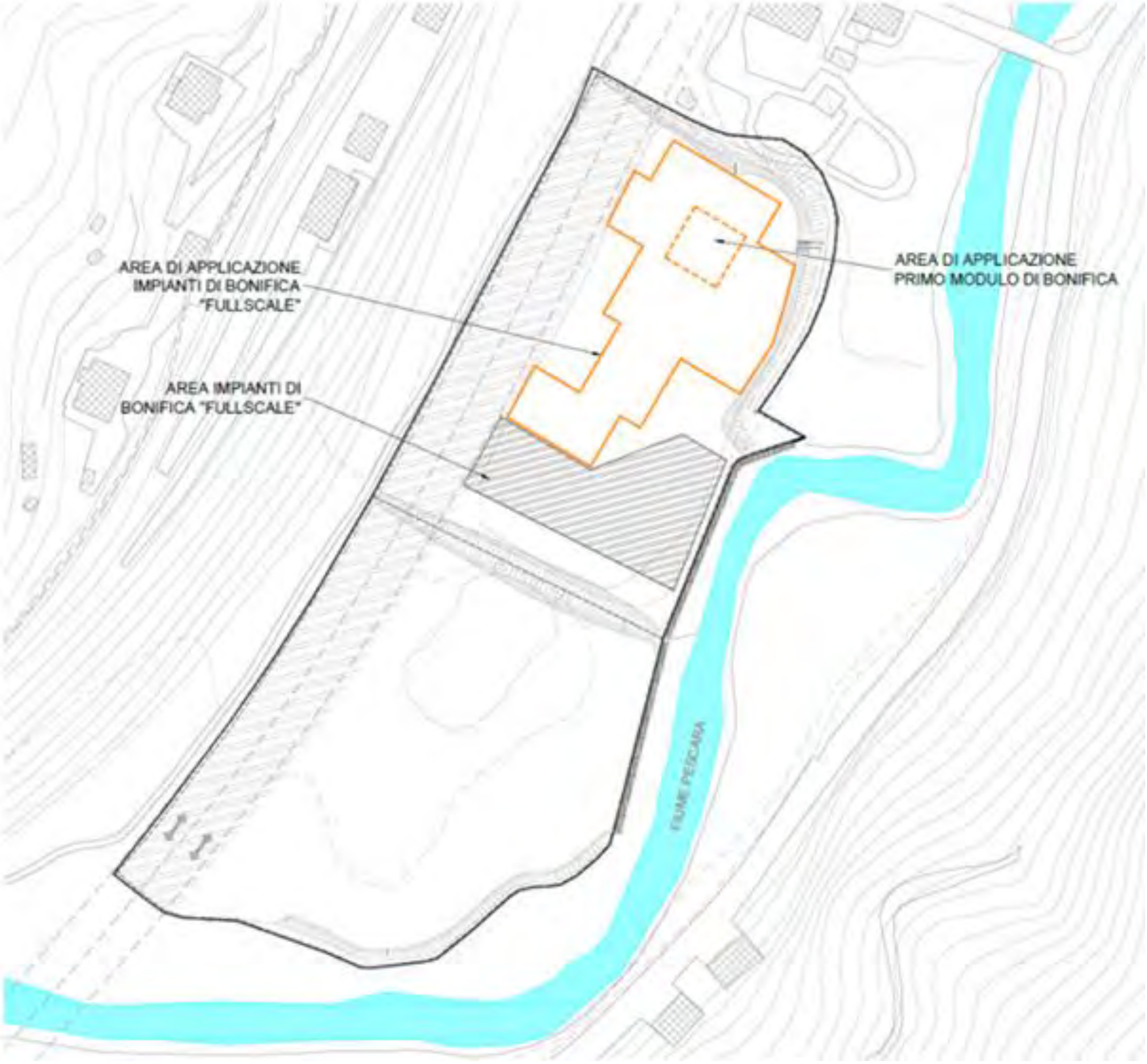


Figure 5 – Application of different technologies

Contaminant removal mechanism:

- Heating of the soil up to the boiling point of the water contained in the soil pores;
- Contaminants become volatile and are transferred to the vapor phase;
- The contaminants in gaseous and liquid form are then captured and aspirated by a series of extraction wells installed in intermediate points to then be treated through various processes based on their nature and their initial concentration.

Treatment area features:

- Treatment area surface: 300 m^2;

- TTZ treatment area roof: 9.00 m from ground floor;
- TTZ treatment area bed: 13.00 m from pc;
- Volume of contaminated soil: 1,200 m^3;
- Groundwater subsidence: 10.00 m from ground floor;
- Hydraulic conductivity: 7.0 x 10^{-8} m/s

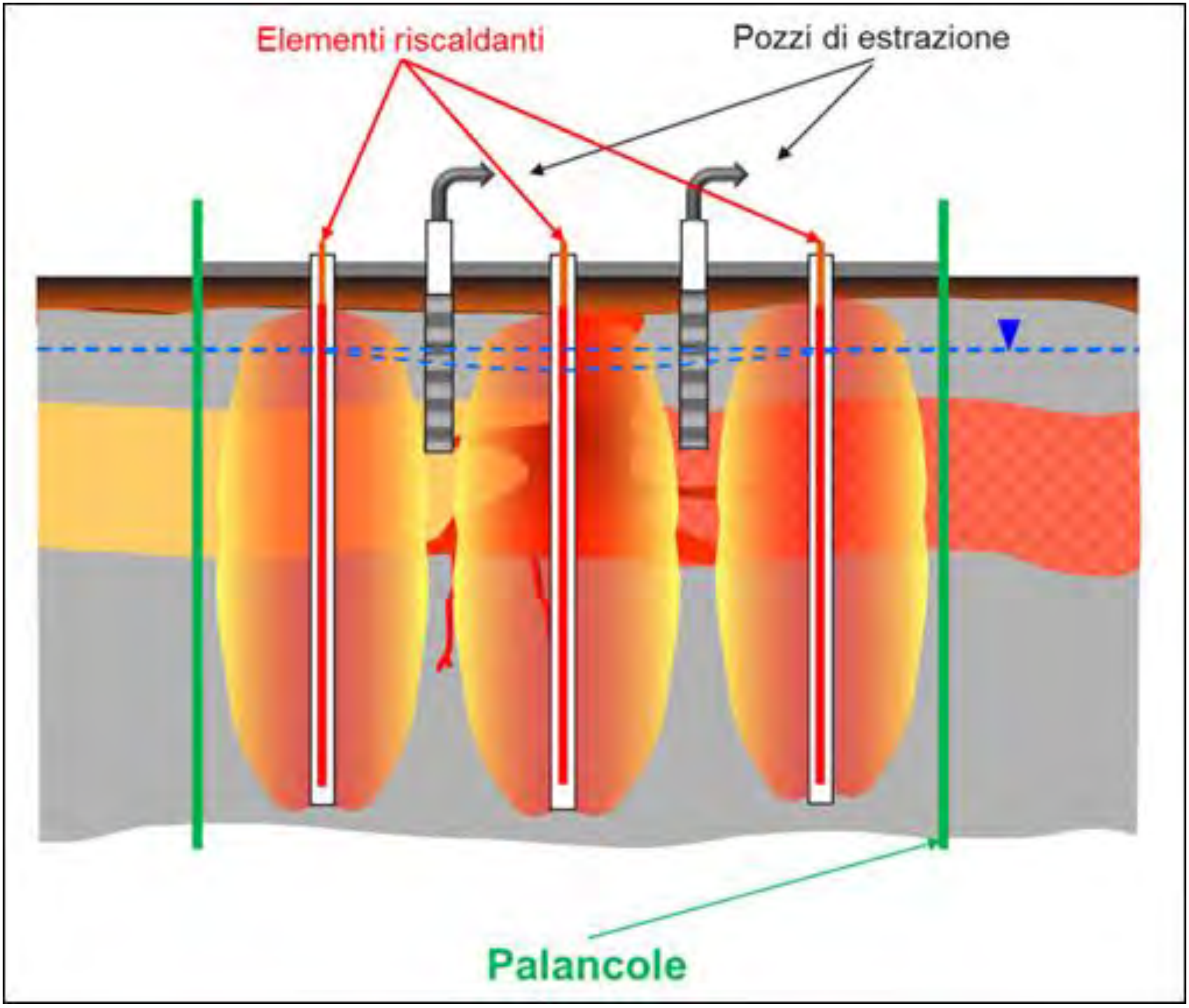


Figure 6 – Heating system and extraction wells

__Well field__:

- No. 39 heating wells (TCHh): 3" H-1 ÷ H-39;
- N. 4 extraction wells (VEW): V-1 ÷ V-4 of 2";
- N. 3 multiphase extraction wells (MPE): M-1 ÷ M-3 of 2";
- N. 4 monitoring wells: M-a ÷ M-d of 2";
- N. 5 temperature monitoring wells (TMP): T-1 ÷ T-5 of 1"1/2.

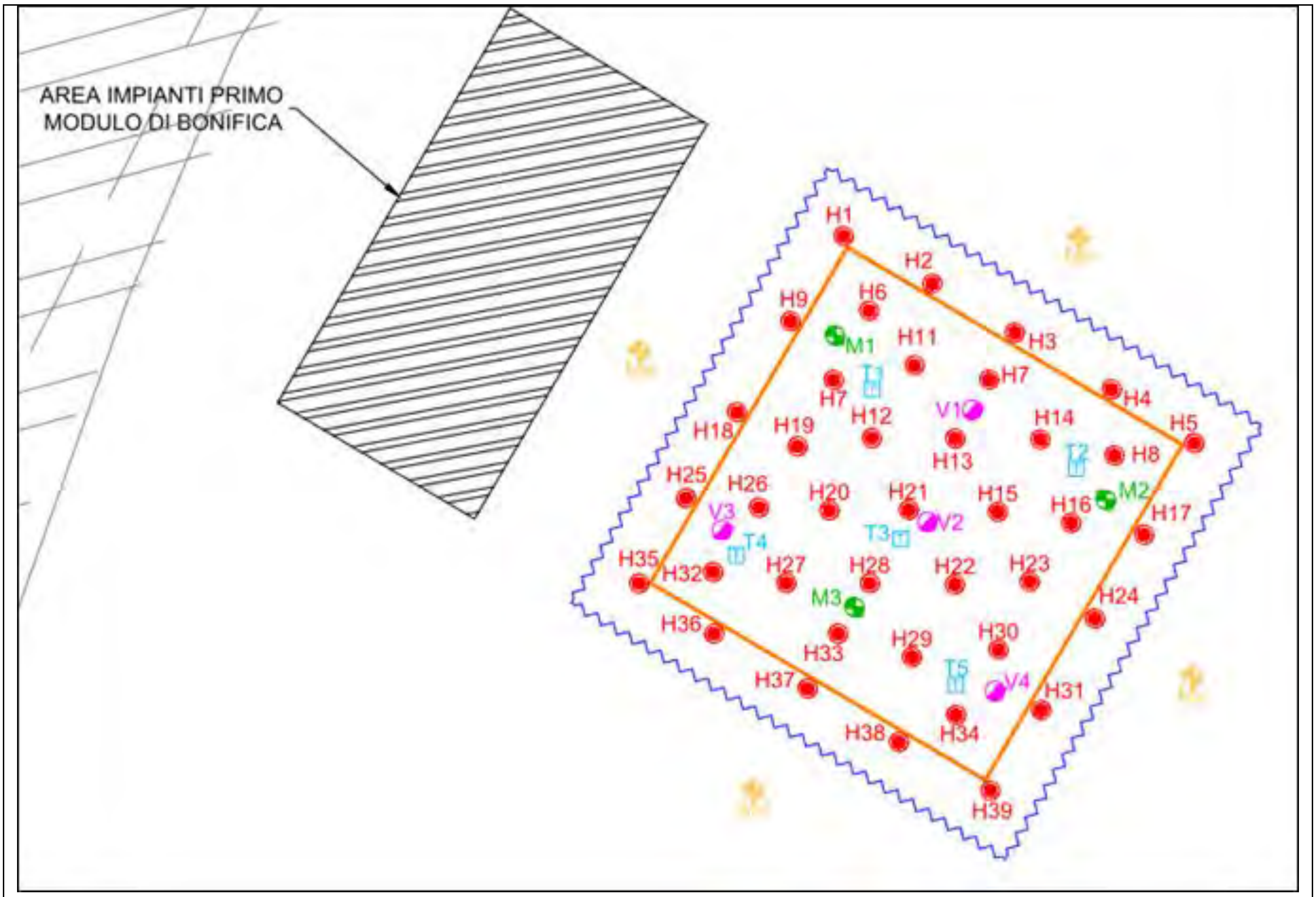


Figure 7 – Scheme of the well field

Figure 8 – Picture of the well field

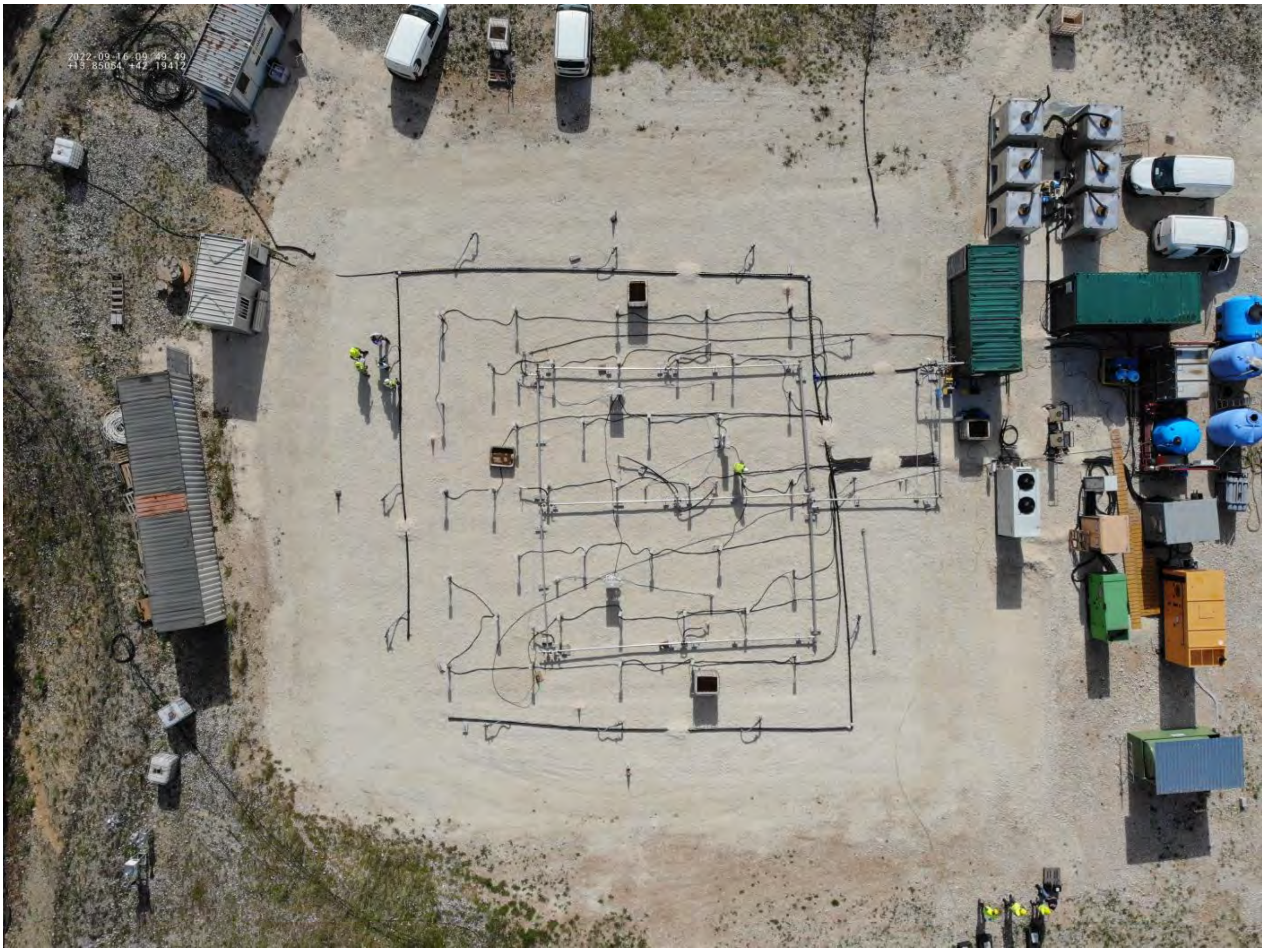


Figure 9 – Picture of the well field from above

Design parameters:

- maximum depression applied to the well field: 100 mbar;
- minimum soil temperature in cold spots to ensure desorption of contaminants: 100°C;
- maximum flow rate of the extracted steam: 408 Nm^3/h.

Energy Balance:

- Energy input into the treatment volume: 248 kW;
- Soil Volume: 780 m^3;
- Pore volume: 420 m^3;
- Temperature at T0: 10°C;
- Target Temperature: 100°C.

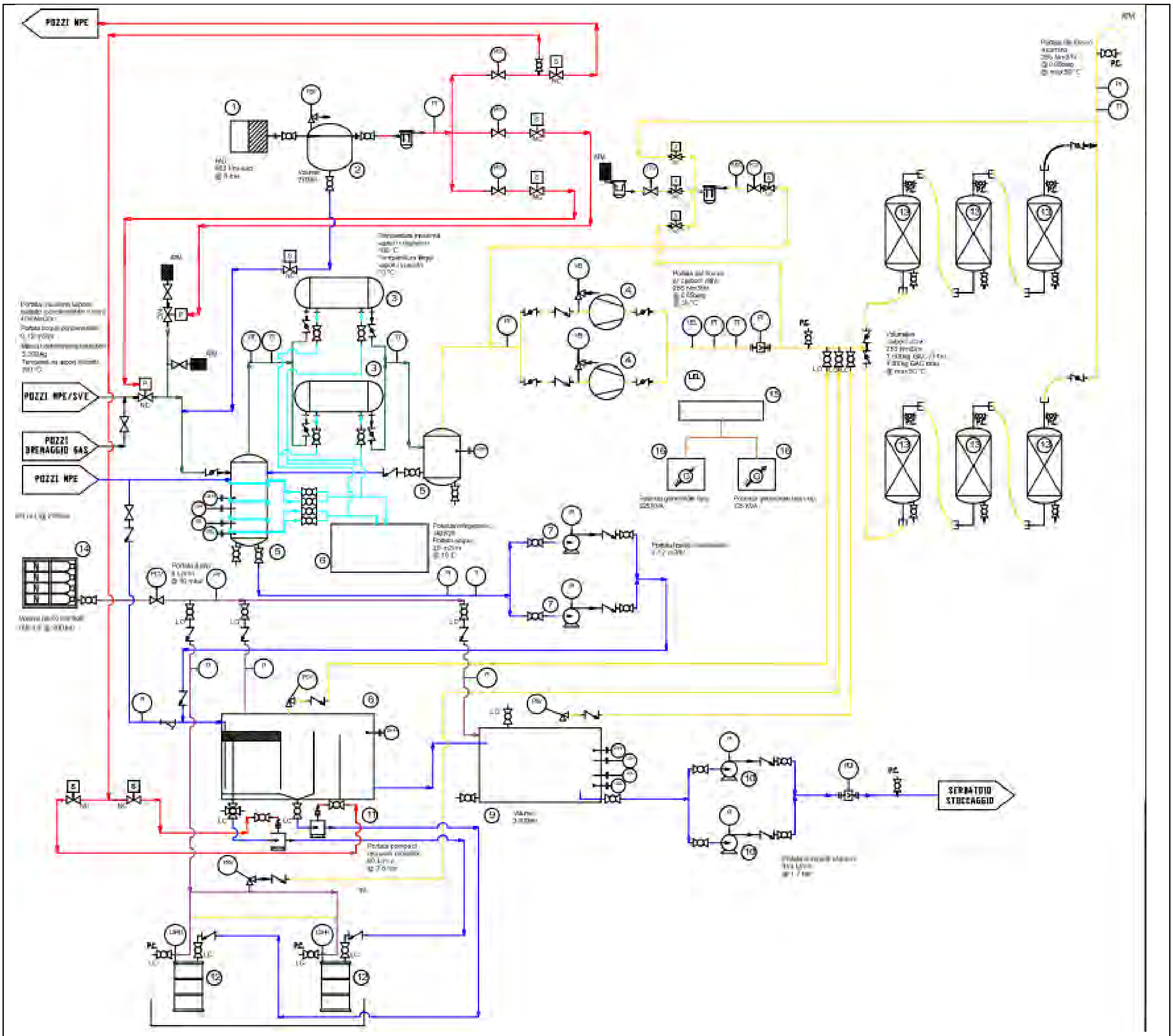


Figure 10 – Detailed scheme of the Thermal Desorption Plant

Stages of installation and heat treatment

A. Preparation of the treatment area: Pile driving, Vapor Cap creation and Well field installation;
B. Dewatering;
C. Start-up: Inspection and testing of wiring and grounding; Inspection of piping and collection containers; hydrostatic pressure tests e Tyres; Inspection, calibration and testing of measuring instruments; Control of the regulation loops; Check and test the interlocks; Inspection and testing of security systems; Operational tests; Operational tests and start-up procedures of the heating system;
D. Heat treatment stages: Heating up to the operating temperature of 100°C;

Treatment at constant temperature and maximization of the removal of pollutants; Cooling of the reclamation area

E. Intervention testing to achieve remediation objectives: execution of 3 surveys in the contaminated area and collection of 3 probing samples; compliance of the results with the remediation objectives (CSR identified in the site specific risk assessment Review).

3.3 Control parameters and verification of the applicability (pilot scale)

Depending on the type of flow (liquid and gaseous), the following pre-treatment sections are installed in the thermal desorption pilot plant:

A. Liquid phase:

- No. 1 OWS-201 oil / water separator capable of separating, by gravity and through the use of filters coalescence, the water from the contaminants present in the free phase;
- N. 1 buffer tank S-201 with the function of accumulating the water separated from the product in the free phase and at the outlet of the OWS-201 separator, and favour its re-launch to the local storage tank;
- N. 2 P-202 A/B booster pumps capable of transferring the water from the S-201 buffer tank to the of local storage;
- N. 2 free phase product storage tanks, respectively S-202 for LNAPL storage (Light Non-Aqueous Phase Liquids) and S-203 for storage DNAPL (dense Non-Aqueous Phase liquids);
- N. 2 P-203 A/B product recovery pumps capable of transferring the product in the free phase, accumulated in the separator OWS-201, to the storage tanks S-202 and S-203;

B. Vapour phase:

- N. 1 compressor able to supply compressed air to the pneumatic pumps of the wells, to the pumps P-203 A/B product recovery pneumatics, and XV-101 & XV-102 pneumatic actuators;
- N. 1 condensate separator KOT-101 able to Favor the inertial precipitation of the condensate present in the aspirated interstitial gas stream;
- N. 2 shell and tube air-water heat exchangers with stainless steel pipes and shell (n.1 operational and 1 reserve) E-101 A/B, capable of reducing the temperature of the extracted effluent;

- N. 1 Chiller capable of supplying the chilled water necessary for the heat exchangers;
- N. 1 KOT-102 condensate separator capable of separating the residual condensate downstream of the E-101 A/B heat exchangers;
- N. 2 side channel blowers BL-101 A/B (n.1 operational and n.1 reserve) connected in parallel, which they will generate the depression inside the wellheads of the interstitial gas extraction wells e in multiphase extraction wells.

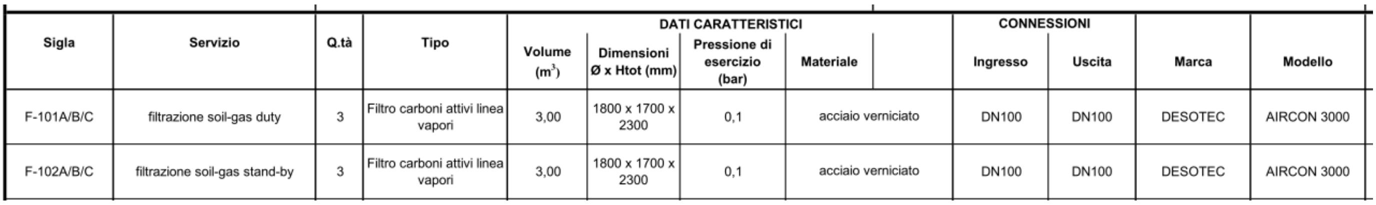
3.4 Post Treatment for effluent (pilot scale)

The treatment present in the pilot system concerns exclusively the flow of extracted steam. The liquid flow, after a pre-treatment, will be managed as waste and transported to a suitable final treatment plant.

The vapours extracted from the subsoil, once separated from the liquid phase, will be sent for treatment through a battery of N. 6 activated carbon filters divided into n. 2 sets of no. 3 filters each, installed in parallel with each other they.

Each filter will be equipped with a sampling socket to evaluate the saturation level of the activated carbons. The individual filters will be connected to each other by means of hoses and quick couplings, to allow modifications rapid composition of the series and in particular allowing the inversion of the order of use of the various filters in order to obtain the complete saturation of the entire volume of activated carbon available.

The gaseous effluent emitted into the atmosphere will be automatically sampled cyclically via the TVOC-101 fixed photo ionizer and the EV-101÷103 solenoid valve system. The vapor treatment module will be equipped with a single chimney for both 2 series of filters in order to provide a single sampling point from which to monitor emissions into the atmosphere.



Sigla	Servizio	Q.tà	Tipo	DATI CARATTERISTICI				CONNESSIONI		Marca	Modello
				Volume (m^3)	Dimensioni Ø x Htot (mm)	Pressione di esercizio (bar)	Materiale	Ingresso	Uscita		
F-101A/B/C	filtrazione soil-gas duty	3	Filtro carboni attivi linea vapori	3,00	1800 x 1700 x 2300	0,1	acciaio verniciato	DN100	DN100	DESOTEC	AIRCON 3000
F-102A/B/C	filtrazione soil-gas stand-by	3	Filtro carboni attivi linea vapori	3,00	1800 x 1700 x 2300	0,1	acciaio verniciato	DN100	DN100	DESOTEC	AIRCON 3000

Table 1 – Filtering system

3.6 Control parameters (pilot scale)

Parameters	
Temperature:	Soil heating probes extraction wells before and after automatic condensation Condensed stream Before and after a.c. filter (vapour stream)
Pressure:	Main collector Between Blower and carbon filter Condensate separator inlet Inlet first carbon filter Soil
Stream flow	Extract air (non-condensable) Extracted steam (depending on the condensation) Extracted water
Masses (Quantity)	Extracted solvents Samples on CA vials for laboratory analysis
Energy	Underground power supply Energy released into the subsoil Energy treatment plant Total energy consumption Calculation of energy extracted with steam Calculation of energy extracted with water
Other measurements	Piezometric levels DNAPL level in separation tank

Table 2: Main control parameters

The management of the operating logics of the system will be performed via PLC installed on all local control panels. All local PLCs will be connected to the PLC master via Modbus network or similar, for master logging of system data.

In the event of an alarm, the local PLC where the problem occurred will process the data and report the alarm to the main PLC, which in turn will initiate the necessary actions on the panels local control. The operating data of the system will be memorized through a system of framework data logging.

During operation, operational data is constantly collected and the processing of which will be used to monitor the progress of the reclamation and to evaluate the system's performance. These surveys will also have the function of intervening on the functioning of the system, through adjustments.

The recording / processing of the following data is expected:

- energy consumption;
- mass and energy balances for the subsoil volume being treated;
- subsoil temperatures;
- laboratory data;
- measurement of depressions;
- cumulative mass removal rates of contaminant.

Portable PID instrumentation can be used to monitor concentrations in vapours at numerous points in the system daily:

- inlet of treatment system;
- inlet gaseous effluent adsorption section;
- gaseous effluent adsorption system outlet (emission to atmosphere).

Effluent monitoring

The monitoring protocol for the remediation of the saturated matrix is given below:

- Vapour effluent monitoring protocol;
- Liquid effluent monitoring protocol.

Vapour effluent			
Parameter	*Monitoring Point*	*Measurement method*	*Frequency*
Temperature	strategic point	Thermocouples installed	Continuous measurement
Pressure	strategic point	Instrumentation installed	Continuous measurement
CO, CO_2, O_2, SO_2	IN/OUT Vapour treatment plant	Instrumentation installed	Day to day
VOCs/SVOC	IN/OUT Vapour treatment plant	Laboratory	Day to day / twice a week

Table 3: Main vapour effluent parameters

With regard to emissions into the atmosphere, compliance with the provisions of Legislative Decree 152/06 and subsequent amendments, in the Annexes to Part V (Annex I-X)

Liquid effluent			
Parameter	*Monitoring Point*	*Measurement method*	*Frequency*
Temperature	strategic point	Thermocouples installed	Continuous measurement
VOCs/SVOC	OUT pre-treatment unit	Laboratory	Day to day / twice a week

Table 4: Main liquid effluent parameters

4. Full-scale application

4.1 Main treatment unit

The full-scale system will be designed on the basis of the results of the pilot plant

installed and described above.
Based on some preliminary considerations related to the degree, extent and type of contamination present in the northern area of the site, the full-scale system will have the following preliminary characteristics:

- Total area of the treatment area: 5,200 m^2;
- Roof of the TTZ: 9.0 m;
- TTZ bed: 13.0 m;
- Volume of contaminated soil: 20,800 m^3;

Well field:

- No. 300-350 heating wells (TCHh);
- N. 50-80 extraction wells (VEW);
- N. 20-40 multiphase extraction wells (MPE);
- N. 30-40 temperature monitoring wells (TMP).

Preliminary Design parameters:

- maximum depression applied to the well field: 100 mbar;
- minimum soil temperature in cold spots to ensure desorption of contaminants: 105°C;
- maximum flow rate of the extracted steam: 4,000 Nm^3/h.

Preliminary Energy Balance:

- Energy input into the treatment volume: 2,100 kW;
- Soil Volume: 13,520 m^3;
- Pore volume: 7,280 m^3;
- Temperature at T0: 10°C;
- Target Temperature: 105°C;
- Total electricity consumption (heating + effluent treatment): 9,800,000 – 12,900,000 kWh

Schedule:
start of full-scale system installation: first month of 2024

5. Post treatment and/or Long Term Monitoring

5.1 Post treatment and/or Long Term Monitoring

The management of the pilot system is underway; the results of the treatment, by means of in situ thermal desorption, on the volume contaminated by chlorinated solvents will be made public as soon as the test is completed (expected for July 2023)

7. Additional information

7.1 Lesson learnt

Based on the findings from the first months of management of the in situ thermal desorption pilot system, i.e.:

- a «careful» management of the first thermal desorption pilot module;
- proper regulation and monitoring of heating element temperatures;
- a continuous monitoring of temperatures in the subsoil;
- effective control and monitoring of gaseous and liquid effluent flows;

will allow

- the plant engineering and technological optimization of the future full-scale remediation plant;
- adequate regulation of the process operating parameters;
- a reduction in execution times;
- a reduction in electricity consumption;

greater overall sustainability

7.3 Lesson learnt

Running a ISTT plant requires experience in the geological, chemical and mechanical fields. The management of the process is completely automatic and can be carried out, even remotely, by a process engineer. A supervisor must be present on site.

7.4 Additional remarks

The application of heat treatments is very complex, and its management must be carried out by technical personnel with extensive experience. It is important to guarantee organization and document availability such as to allow the best capacity linked to the monitoring of flows and plant parameters.

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.6

1.1 Name and Surname	Klopp, Daniel 1) Trötschler, Oliver 2) Horstmann, Malte 3) Edel, Hans-Georg 4)
1.2 Country/Jurisdiction	Germany
1.3 Organisation	1), 4) Züblin Umwelttechnik GmbH 2) VEGAS Universität Stuttgart 3) Hanseatisches Umweltkontor GmbH
1.4 Position	1) Project Manager 2) Technology Engineer 3) Project Manager 4) Manager R&D
1.5 Duties	1), 4) In-situ thermal remediation 2) Scientific support for thermal in-situ processing 3) Consultant remediation
1.6 Email address	1) daniel.klopp@zueblin.de 2) oliver.troetschler@iws.uni-stuttgart.de 3) m.horstmann@haukon.de 4) hans-georg.edel@zueblin.de
1.7 Phone number	1) +49 40 238818714 2) +49 711 68567021 3) +49 451 7025411 4) +49 7145 9324-249

2. Site background

2.1 History of the site

In the city of Neumünster, a hvCHC contamination in need of remediation was found on the old site of a former mineral oil and chemical wholesaler (operating period 1978 - 2008). Since 1991, the Soil Protection Authority (Untere Bodenschutzbehörde) has been aware of groundwater contamination caused by volatile chlorinated hydrocarbons (hvCHCs) on the property in question. In the following years, damage assessment measures were carried out, but initially did not provide a conclusive explanation for the cause of the contamination.

Only during the later questioning of contemporary witnesses, it turned out that around 2,000 L of solvents (tetrachloroethene) had been released from a storage tank in the northwest of the property in an accident. Based on eyewitness reports, further handling losses during the operating period are also considered as a fact.

So far, the following main investigations and measures for groundwater protection have been carried out:

- 1994: First indicative investigation of contaminated sites
- 1995-2002: Operation of a P&T measure by the polluter and various successor companies until 2002, hvCHC discharge approx. 1,200 kg
- 2008-2010: In the course of cessation of operations and land sale, detailed investigations at the site with considerable hvCHC results in the northwest of the property (former storage tank and transfer station for tetrachloroethene)
- 2012-2019: Remediation investigations and planning, including in-situ remediation, honeycomb processes, large-hole drillings
- 2012-2021: Continuation of the P&T measure by the city of Neumünster, hvCHC discharge approx. 200 kg

2.2 Geological setting

The town of Neumünster is located in the area of the Schleswig-Holstein geest ridge on a Weichselian glacial outwash plain, which is upstream of the end moraine lines running a few kilometres to the north and east. The glaciofluvial sands form a first near-surface uncovered aquifer at the site, which can be described as well permeable and only slightly protected against penetrating pollutants. A Weichselian glacial basin silt forms at a depth of 16-17 m bgl of the first aquifer. The groundwater table is at approx. 2.2 to 3.2

m and the general groundwater flow direction is oriented to the southwest. This is followed by further groundwater levels of Pleistocene meltwater deposits, partly interrupted by boulder clay and basin silts. The glacial sands, which are up to 85 m thick, merge directly into the Miocene lignite sands below. These are underlain by mica clays. The up to 60 m thick lignite sands form the main aquifer, which is mainly used in Neumünster for drinking water production.

In the groundwater fluctuation area, the subsoil exhibits partially thin silt layers. From a depth of 2.5 m in the north and 5.0 m in the south, organic admixtures occur in the sands, which were described as charcoal or "lignite". Usually these occur finely distributed in the sands, in certain areas, layers of 1-2 dm are encountered. Due to the high adsorption capacity of the organic components and the affinity of the hvCHCs to the organic matter, an accumulation of hvCHC takes place in coal-bearing sands.

The hydraulic permeability of the first aquifer varies within a range of 1.1 x 10-4 to 1.7 x 10-3 m/s. The average groundwater gradient I is 0.0005. The resulting flow velocities are 15-80 m/a.

2.3 Contaminants of concern

In the run-up to the remediation planning, extensive investigations were carried out by ECOS Umwelt Nord GmbH, Kiel, to record and evaluate the contamination situation. A plume of contaminants with hvCHC levels above 100 µg/L was located over a length of more than 300 m. While almost 100% PCE occurred in the contamination centre (area A and B), mainly degradation products (TCE, cDCE) were detected further downstream (Fig. 1).

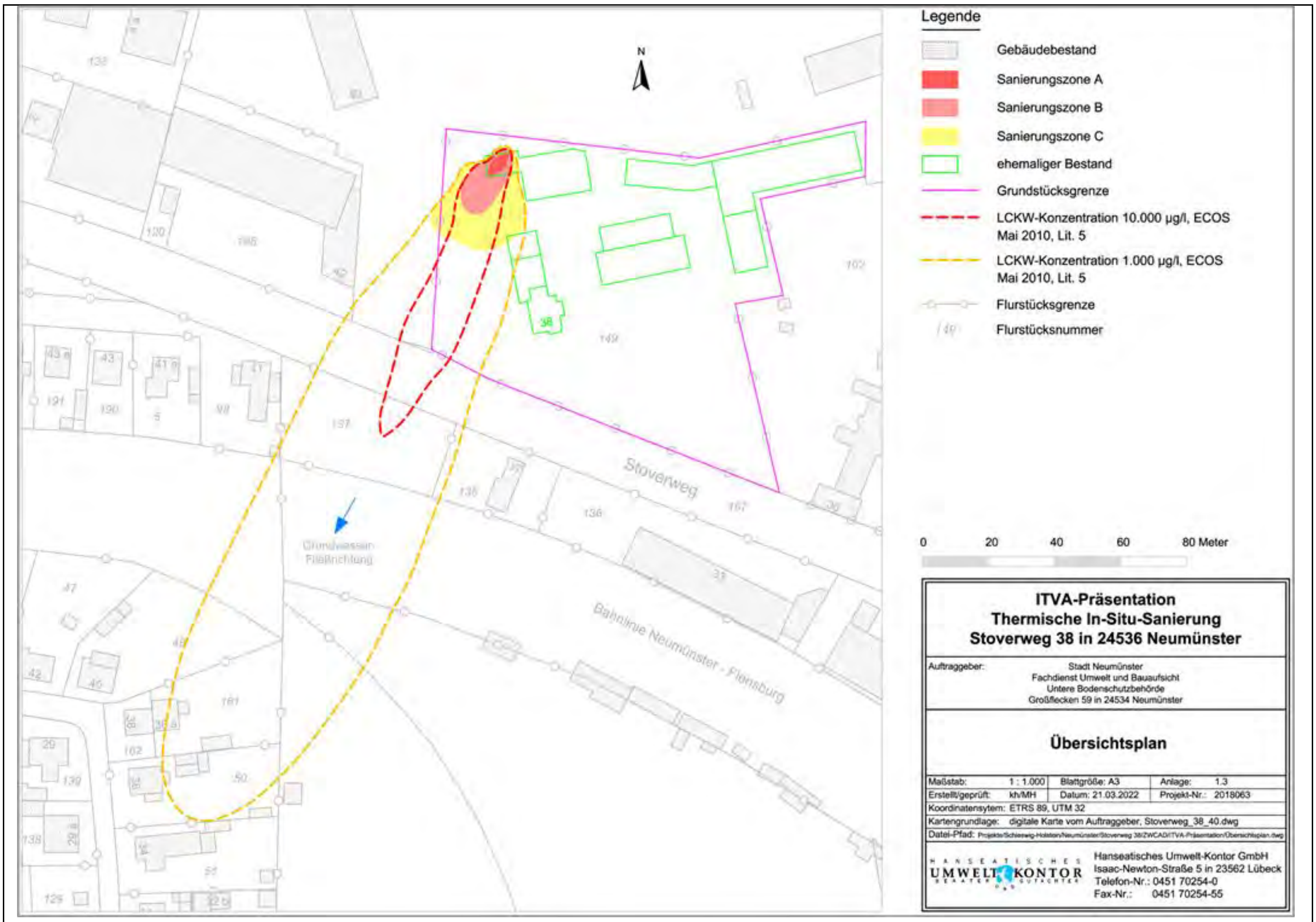


Figure 1: Site plan with groundwater contamination by hvCHCs (2020). Legend here reported

German	**English**
Gebäudebestand	Existing buildings
Sanierungszone	Remediation zone
Ehemaliger Bestand	Former buildings
Grundstücksgrenze	Site boundary
LCKW-Konzentration	hvCHC concentration
Flurstücksgrenze	Parcel boundary
Flurstücksnummer	Parcel number

The results of the investigation showed that the hvCHCs were present in the saturated zone in form of a finely divided incoherent organic phase, sorbed on the soil and in dissolved form in the groundwater. Phases occurred especially above or within the coal-bearing layers (**Fig. 2**). The maximum hvCHC levels were 8,100 mg/kg in soil and 49,000 µg/L in groundwater (DP probing). In the unsaturated soil zone, up to 8,400 mg/m³ were measured in the soil vapour at the contamination centre.

Based on the detailed investigations carried out in 2008-2010, the masses of pollutants in the area of remediation zones A to C were roughly estimated on an area of 650 m² with approx. 800 kg of hvCHCs, primarily tetrachloroethene (PCE) (**Fig. 2**).

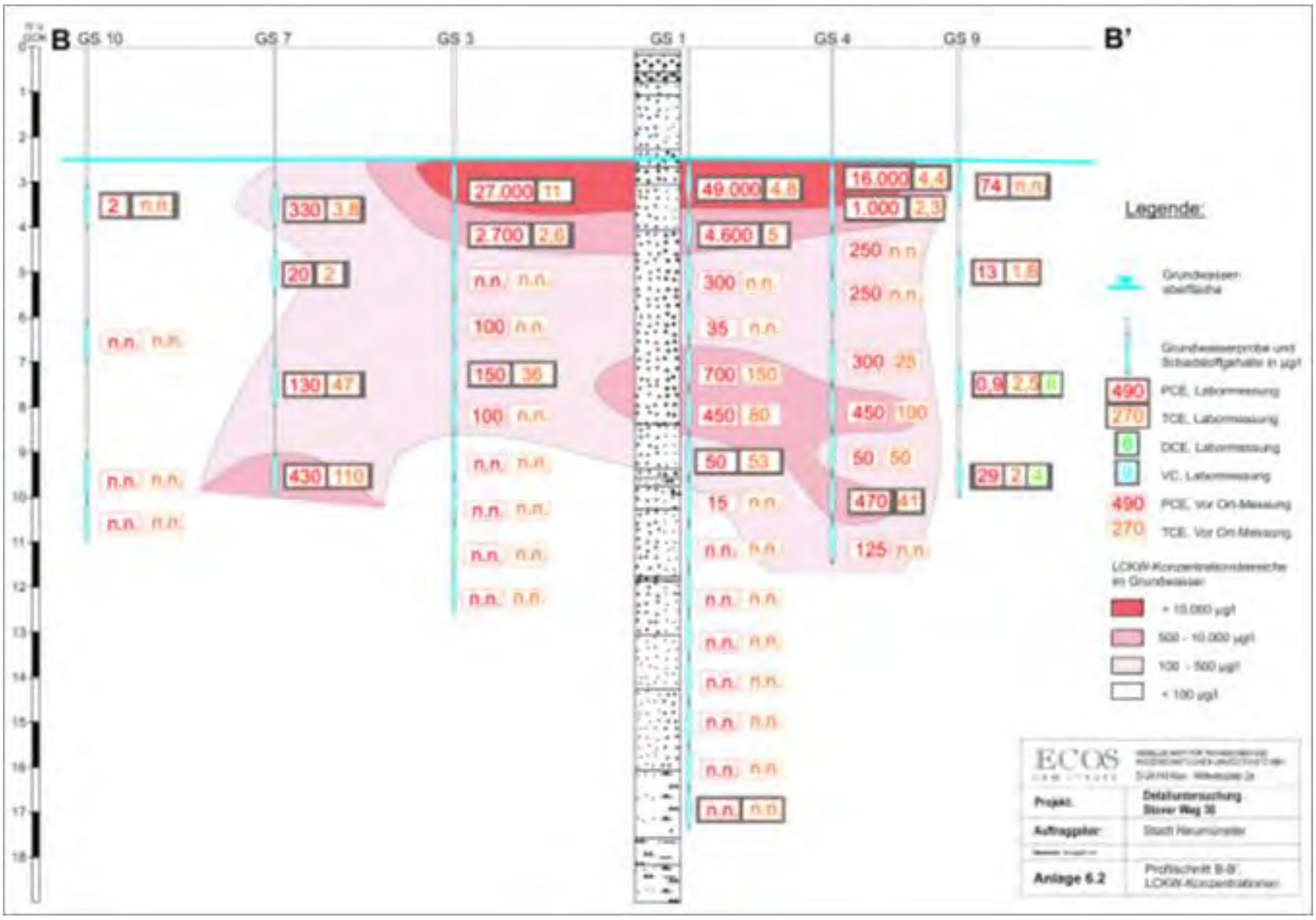


Figure 2: Vertical distribution of pollutants in the contamination centre, source: ECOS Umwelt Nord GmbH

German	**English**
Grundwasseroberfläche	Groundwater surface
Grundwasserprobe und Schadstoffgehalte	Groundwater sample and pollutant content
Labormessung	Laboratory measurement
Vor-Ort-Messung	Site measurement
LCKW Konzentrationsbereiche im Grundwasser	hvCHC concentration areas in groundwater

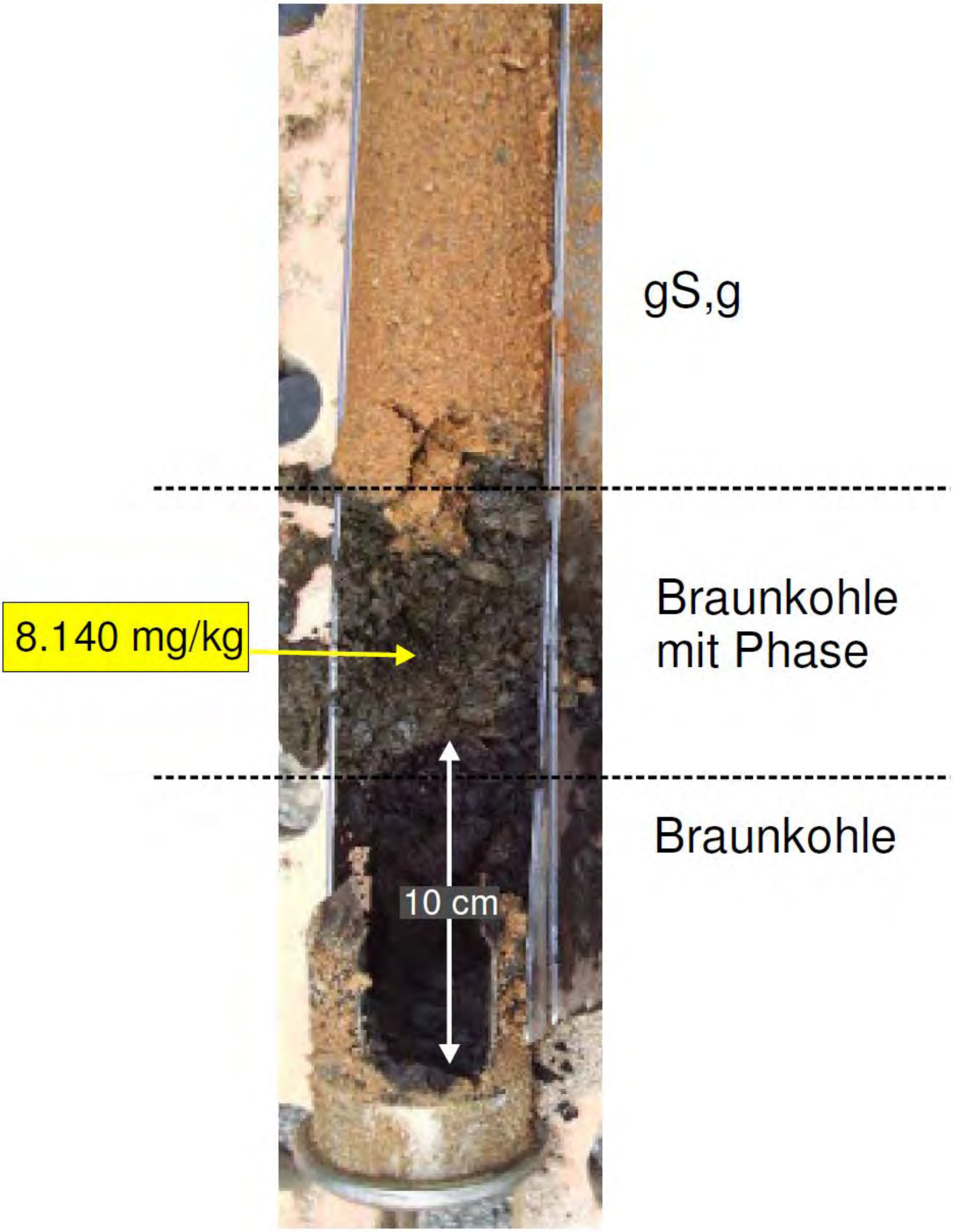


Figure 3: Core of liner bore LB 3 (2.5-3.0 m bgl, source: ECOS Umwelt Nord GmbH)

2.4 Regulatory framework

The primary remediation goal was to remediate the primary source of pollutants in order to prevent further significant pollutant discharge. Remediation was therefore targeted at the input area (remediation zone A) and the immediate surroundings (remediation zones B and C), where the main mass of pollutants is found at depths up to max. 6 m bgl.

The following indicative remediation target values were agreed upon:

- Compliance with an hvCHC concentration of 100 to 140 µg/L in groundwater in the near effluent at the downstream property boundary in the upper portion of the aquifer (up to 6 m bgl).
- Reduction of the pollutant load (emission of hvCHC total) emanating from the remediation site by at least 75%.
- Compliance with a concentration of hvCHC solids.

Lignite	(TOC approx. 10.0%)	100 mg/kg
Silt	(TOC approx. 1.0%)	2 mg/kg
Sands	(TOC approx. 0.1%)	1 mg/kg

3. Pilot-scale

3.1 Laboratory Study

No laboratory study has been conducted. At the request of the Soil Protection Authority of the City of Neumünster, a feasibility study with a cost estimate for the use of steam-air injection (SAI) at the site was prepared in 2018 [1].

Remediation Technology

The in-situ thermal remediation (ISTR) technology appropriate for the site is based on the injection of a water steam-air mixture below or at the level of the contamination centre for heating to a mixture boiling temperature and subsequent contaminant evaporation (Fig. 4).

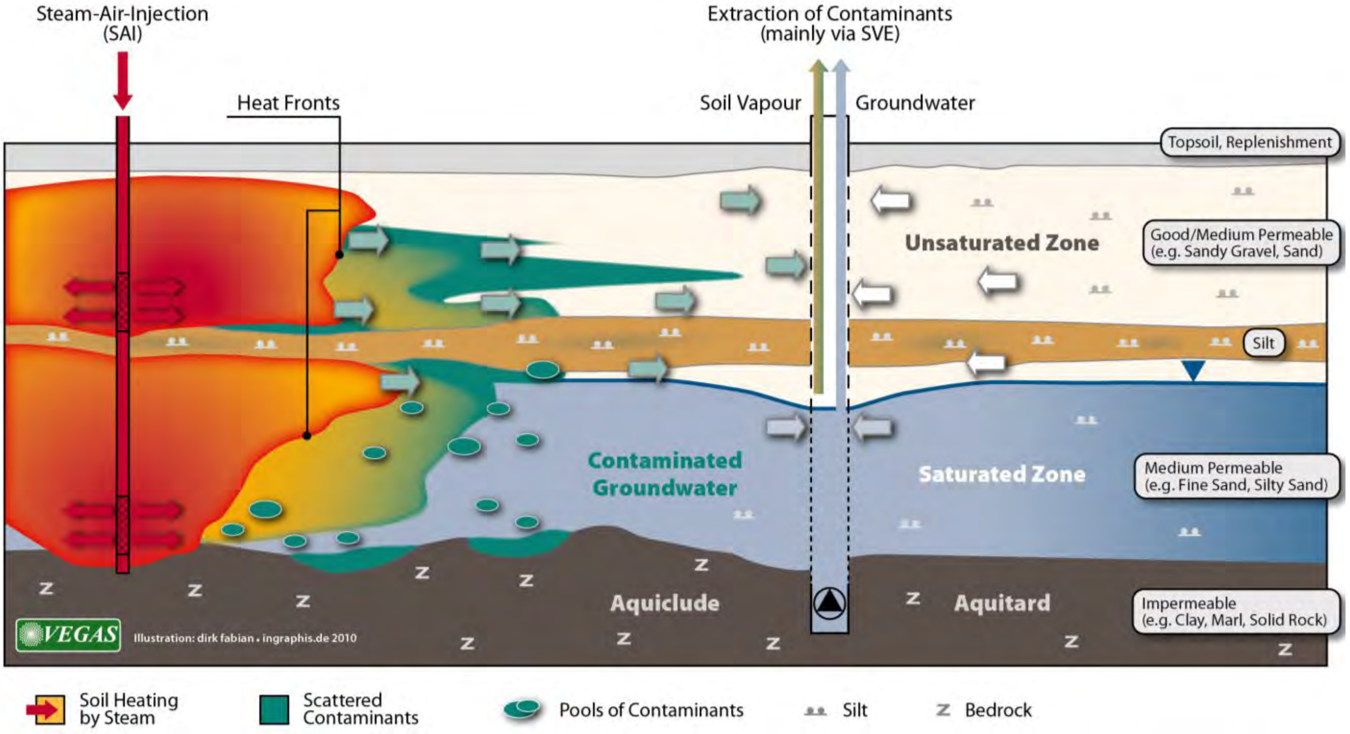


Figure 4: steam-air injection (SAI) and extraction of contaminants, principal diagram

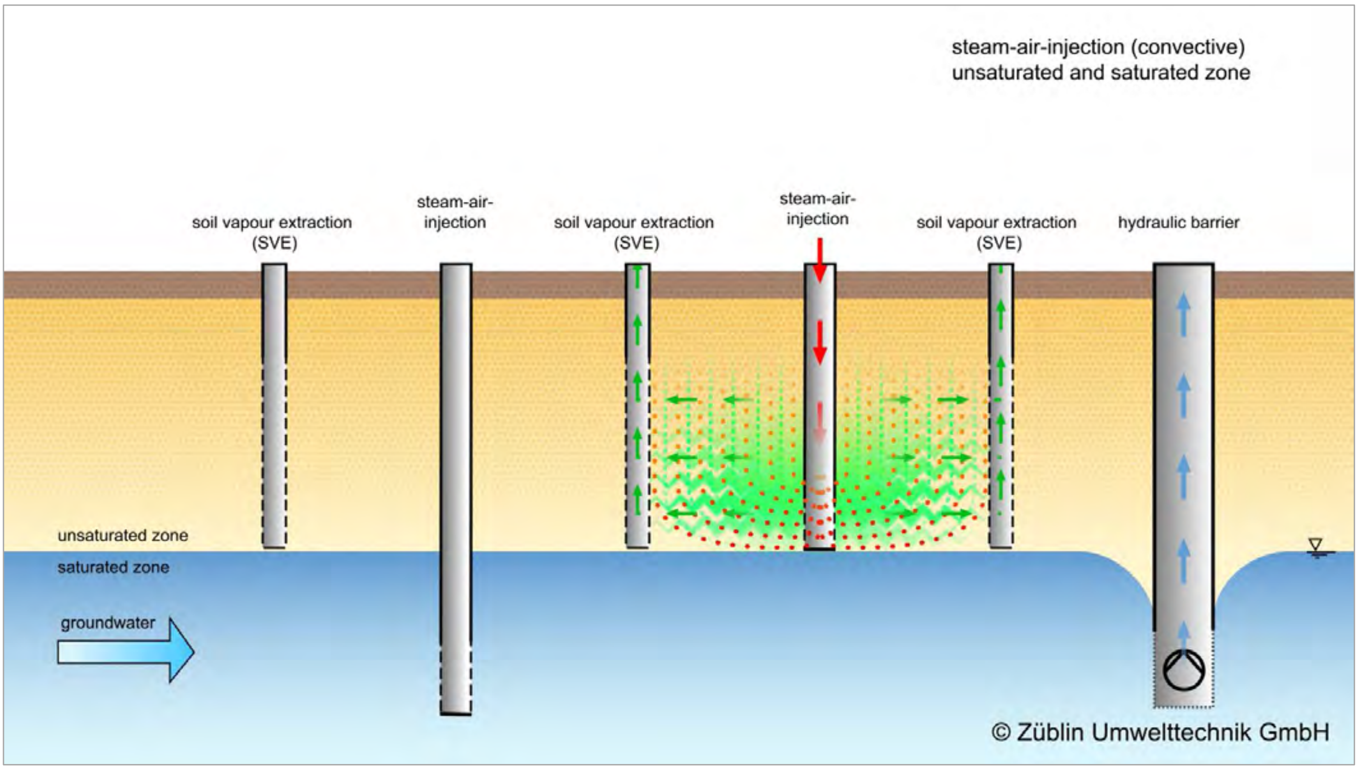


Figure 5: In-situ thermal remediation (ISTR) by means of steam-air injection (SAI), principal diagram

According to the contaminant location, the saturated soil zone shall be injected by a deep steam-air injection (SAI) between 6-8 m bgl, in order to clean the areas above 5-6 m bgl. The plan was to support evaporation by an additional shallow injection plane in the upper part of the aquifer and the unsaturated soil zone at 4 m depth.

The vapour and heat fronts spread radially symmetrically around the injection wells, vaporising the contaminants. In this case, the pollutant-water (vapour) mixture of the PCE contamination boils at a mixture boiling temperature of 95 °C or 92 °C for the present pollutant mixture with approx. 82% PCE and 15% TCE content. This temperature must be maintained in the subsurface until the pollutants are completely extracted (evaporation phase). The air injected with the steam subsequently carries out the contaminants in gaseous form, toward the unsaturated zone, where they are removed by soil vapour extraction (SVE). As a result of the buoyancy forces, the vapour front also opens up the unsaturated soil zone during the initial propagation phase. The soil vapour as well as pore water and condensate can be extracted or pumped out of combination wells and cleaned via air and water activated carbon filters, and the hvCHCs can be removed. In the downstream, an existing hydraulic groundwater protection system removes the hvCHCs that are increasingly dissolved in the groundwater at high temperatures. The pumped waters (groundwater, condensate) are cleaned by activated carbon filters and used to cool the hot soil vapour. The heated cooling water is discharged into the storm sewer at a temperature of 25 °C - 32 °C.

Dimensioning of the steam-air injection (SAI)

The parameters relevant for dimensioning could be taken from the reports of the detailed investigation (DI) and remedial investigation (RI). Essentially, the hydraulic permeabilities in the remediation field, groundwater levels, contaminant type and quantity, and their location are needed to plan a SAI using the computer-based SAI Tool 2.0 [2].

Due to the lignite-bearing sands and lignite inclusions present, the mass transfer coefficient for the desorption of the hvCHCs was halved in the calculation with the SAI tool. As a result, the expected rehabilitation period was extended by approx. 30%.

The range of steam-air injection was calculated for a steam capacity of 500 kg/h, reaching a radius of 2.7 m (zone A+B), resp. 3.0 m (Zone C) at a depth of approx. 5-6 m bgl per injection well [3]. The range of the soil vapour extraction reached a radius of approx. 10 m for a negative pressure of 140 mbar. According to these ranges, the development of the remediation field was planned (Fig. 4).

The remediation field was divided into 10 treatment sections, with 3-4 injection wells each, in order to reduce the amount of steam required. As a rule, twice the number of extraction wells as injection wells are operated. Combination wells are used for hydraulic control.

So-called temperature measuring lances (measuring bundles with Pt-100) at different radial distances from the injection wells are required to monitor the soil temperature.

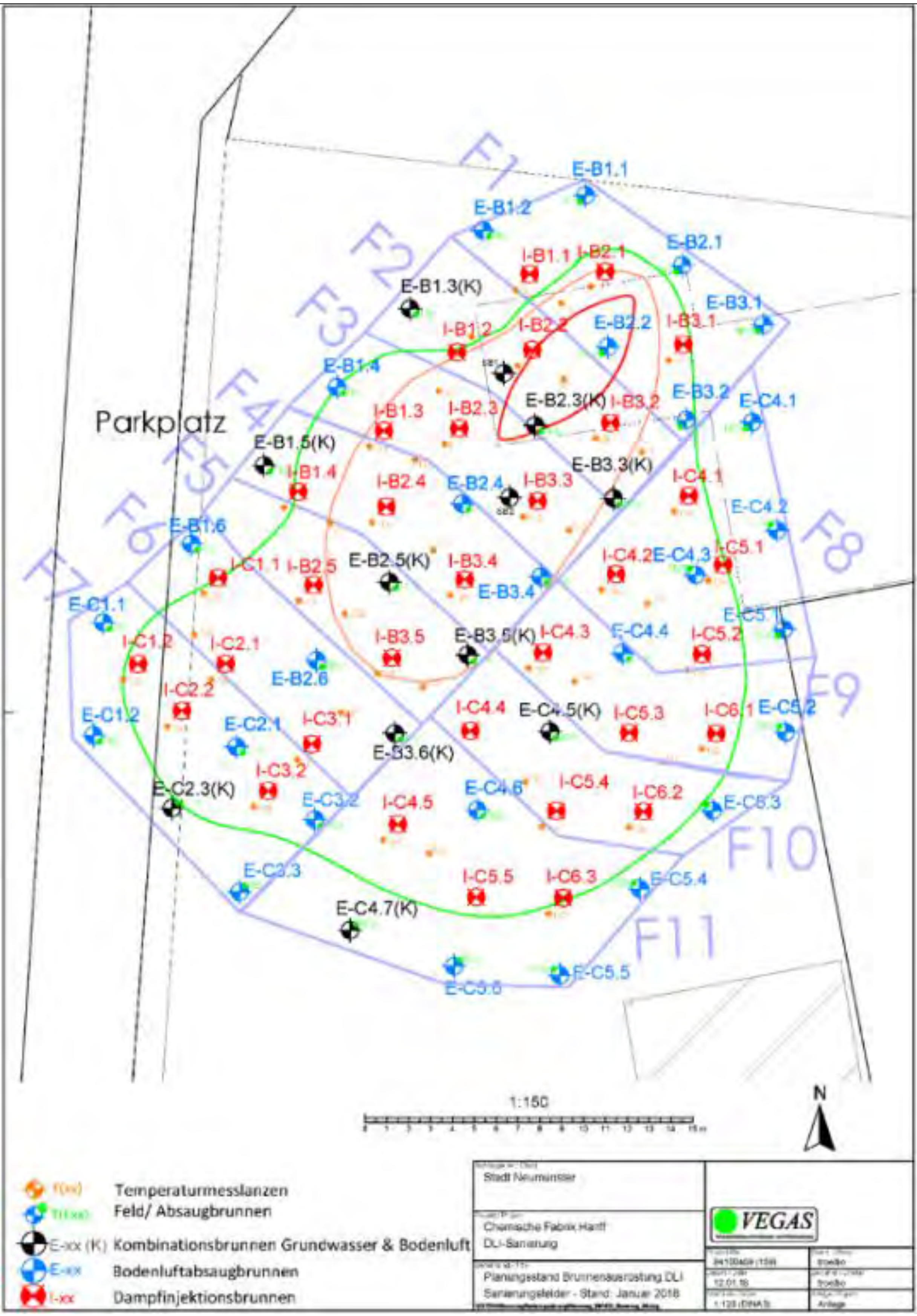


Figure 6: Remediation sequence areas A+B (F1 - F5) and C (F6 - F11)

Legend Fig. 6

German	**English**
Parkplatz	Parking area
Temperaturmesslanzen	Temperature measuring lances
Feld/Absaugbrunnen	Field/extraction well
Kombinationsbrunnen Grundwasser & Bodenluft	Combination well groundwater & soil vapour
Bodenluftabsaugbrunnen	Soil vapour extraction well
Dampfinjektionsbrunnen	Steam injection well
Frischluft	Fresh air
Stripkolonne	Stripping column
Reinluft	Clean air
Luftaktivkohlefilter	Air activated carbon filter
Wasseraktivkohlefilter	Water activated carbon filter
Reinwasserbecken	Clean water tank
Ableitung	Discharge
Kühlwasser BLA-Anlage	Cooling water SVE plant
Einzelstränge BLA	Single lines SVE
Injektionsrate	Injection rate

Dimensioning design

Equipment of the remediation field, subsurface	
• 33 injection wells, SAI in two levels • 11 combination wells	• 29 soil vapour extraction wells • 84 temperature measuring lances
Performance variables of the plant and remediation technology	
• 1,000-1,500 kW steam capacity, regular operation: 1,100 - 1,250 kW • 100-180 m^3/h air injection, regular operation: 120 m^3/h	• 1,800-3,200 Nm^3/h soil vapour extraction, regular operation: 2,500 Nm^3/h, 140 mbar • 15-30 m^3/h groundwater extraction, regular operation: 25 m^3/h
Duration of SAI per field section	
• Heat and vapour passage: 3-4 days • Heat-up phase to mixture boiling temperature: 3-5 days hvCHC discharge phase: min. 6-10 days	• Time required for pollutant discharge: 90 days for max. 2,000 kg hvCHC, 75 days (heat front) + 15 days (evaporation) • Cooling phase min. 28 days (up to 45°C), 50 days (up to 30 – 35°C)
Duration of SAI	
• Discharge phase: 90 days • Remediation time: 205 days in total	146 days of remediation: 28 days start-up(s) + 90 days discharge time + 28 days cooling time + 31 days cooling for final sampling + 28 days conversion time

Table 1: Dimensioning design SAI Stoverweg

The dimensioning of the remediation, with indication of field equipment, plant technology as well as remediation times, is presented in Table 1.

The cost estimate, which was based on market prices, resulted in a total volume of about EUR 1.4 million for the remediation of the contaminated area (zones A+B) and about EUR 2.25 million for the total remediation (zones A+B+C) for a depth of 8 m with specific costs of EUR 231/ton (A+B) and EUR 236 per ton of soil.

This planning was revised in 2020. The total volume was reduced to 3,700 m³, with an average depth of the remediation area of 5.7 m. The cost estimate in 2020 was 1.2 million EUR net = 180 EUR/t of soil.

4. Full-scale application

4.1 Main treatment unit

4.1.1 Contract award and scope

The award of the services for the in-situ thermal remediation of the groundwater contamination at Stoverweg 38, Neumünster, was made by the City of Neumünster as contracting authority within the framework of a public invitation to tender to Züblin Umwelttechnik GmbH, which had submitted the most economical bid concept. The contract initially included a plausibility check of the bid concept in comparison to the remediation concept and a re-dimensioning of the in-situ thermal remediation with all remediation components. This involved finalising the heat requirements, steam injection and extraction rates, injection and extraction wells, and their placement in the remediation area. A schedule presented the time sequence of the entire remediation with heating, discharge, cooling, and conversion phases. The subsequent project execution included the construction of the wells and the installation of the technical equipment, the execution of the thermal remediation and the complete dismantling of all remediation components after the successful completion of the remediation.

4.1.2 Development of the remediation field

The remediation area for in-situ thermal remediation (ISTR) covered an area of about 650 m². The three rehabilitation zones A, B (source of contamination) and C (downstream area) were divided into ten fields (F1 - F10, Fig. 5). The core contamination area (remediation zone A) was remediated in an overlapping manner to allow a longer discharge phase for the contaminants. Overlapping means that injection and extraction wells were gradually integrated into the subsequent fields (Fig. 6, Fig. 7).

For the injection of the steam-air mixture, a total of 31 wells were drilled to a depth of 7.0 m to 8.0 m bgl. In the highly loaded area of remediation zones A and B, these were positioned at a distance of 4.0 m, and in remediation zone C at a distance of 5.0 m.

Three to four injection wells were operated per field. The steam propagation was calculated according to the steam quantity (400 kg/h) with a radial range of approx. 2.5 m at a depth of 6.0 m bgl. To collect the pollutants, a total of 50 extraction wells were initially built to a depth of 3.0 m bgl. The design was based on a predicted extraction range of up to 15 m, and with the extraction wells arranged at a distance of approx. 3.0 to 6.0 m, pneumatic control was ensured. Up to 16 extraction wells were in operation for the remediation of a subfield.

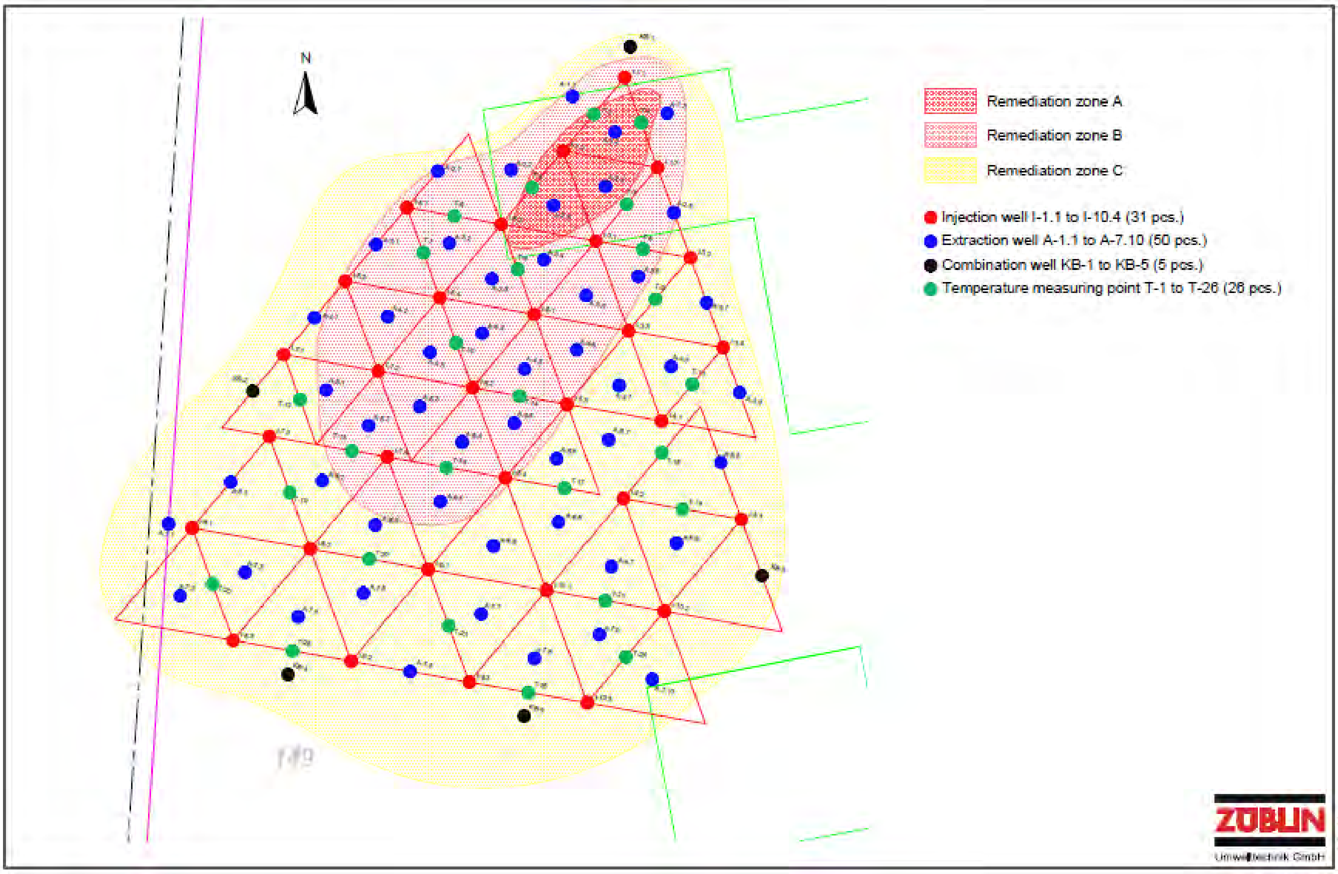


Figure 7: Site plan with injection and extraction wells and remediation subfields.

At the borders of the remediation area, five combination wells were built to a depth of 11.0 m bgl. The wells were designed for combined groundwater and soil vapour extraction and served as hydraulic control, in addition to the existing groundwater wells. It was not necessary to operate the groundwater control via the combination wells, as a remediation well was available.

Within the remediation area, 26 temperature measuring points were established in order to control and monitor the soil heating to the required target temperature of 92 °C for the encountered PCE-TCE pollutant mixture. The temperature measurement was carried out, differentiated by height at intervals of 1.0 m. Each measuring point continuously provided the current temperatures (1-6 m bgl) at six depths for a three-dimensional evaluation of the heat propagation and the resulting adjustment of steam quantities to maintain the 92°C limit with minimum energy input.

Fig. 8: Development of remediation area (red = injection well, blue = extraction well)

In order to prevent atmospheric air from being aspirated and outgassing, the entire remediation area was sealed with a PE film. The wells and the field measurement equipment were connected via temperature-resistant lines installed above ground. These were laid with a continuous slope in the direction of the soil vapour extraction system, so that the removal of the generated condensate was always guaranteed.

4.1.3 Plant engineering

Three to four steam-air injection wells and up to 16 associated extraction wells were assigned to each remediation field. The dimensioning specified a required steam rate of up to 1,600 kg/h, a compressed air rate of up to 100 Nm^3/h and an extraction rate of up to 2,000 Nm^3/h. The hydrogeology in conjunction with the injection depth resulted in a required injection pressure of 1.5 to 1.7 bar absolute at an injection temperature of approx. 115 °C.

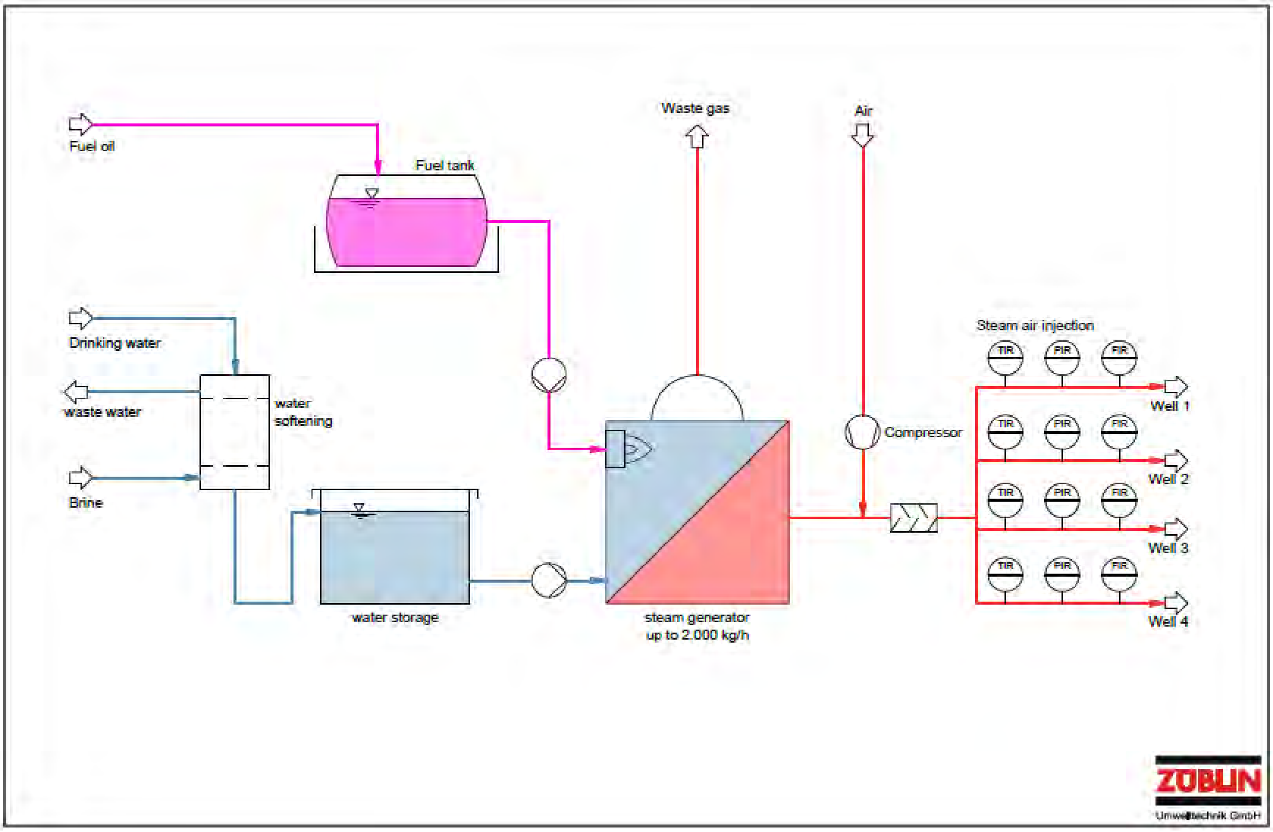


Fig. 9: Basic flow diagram of the steam-air injection system

Fig. 10: Container with steam generator unit and fuel oil tank

The installed plant technology for steam-air injection consisted of the following components: Feed water treatment with softening plant, steam generator with a steam output of up to 2,000 kg/h, compressor for the provision of compressed air and measurement and control technology for the control of the steam-air injection rates (Fig. 9, Fig. 10).

Fuel oil served as the primary energy source for water heating and steam generation. Softened drinking water was used for steam generation.

The system for soil vapour extraction and purification consisted of the following components: raw air measuring points with pressure, flow and temperature measurement, condensate separator, heat exchanger for cooling the hot soil vapour, three extraction compressors with frequency control, two air activated carbon filters for adsorption of the pollutants (Fig. 11, Fig. 12).

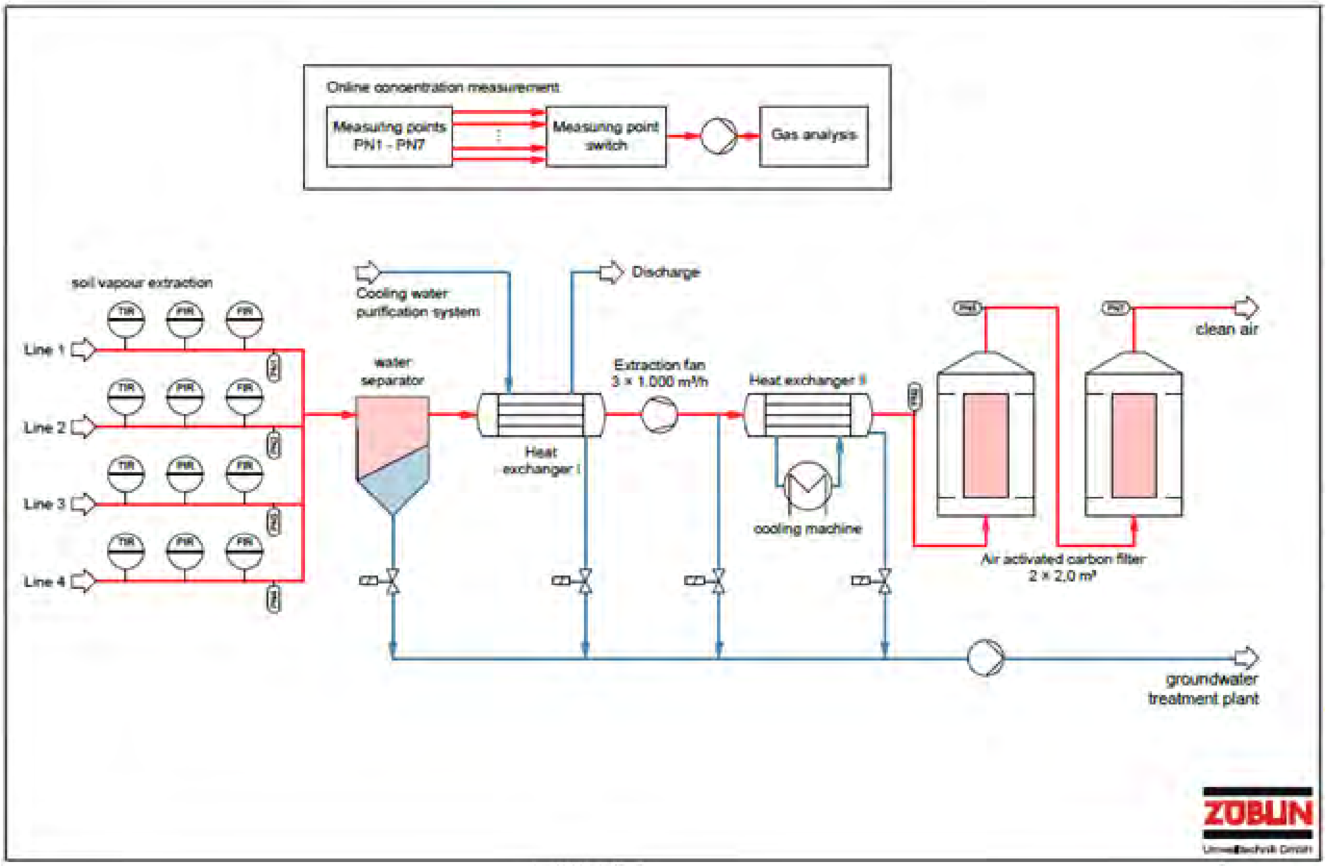


Fig. 11: Process diagram (simplified) of the soil vapour extraction system

The hvCHC concentrations were analysed by an online gas analyser (GC-FID) with measuring point switch. The pollutant discharge via soil vapour extraction and the efficiency of exhaust air purification were continuously determined and evaluated.

Fig. 12: Raw air measuring sections and condensate separator of the soil vapour extraction system

The vapour mass fraction in the air puts a particular strain on the suction compressors. To address this concern, three compressors were installed in parallel, whereby only two were allocated to the extraction operation, and the third was available as failure reserve. An air/liquid heat exchanger was installed to cool the hot soil vapour and to condense the water vapour conveyed along with it, it was operated with the cooling water from the groundwater purification plant. A second heat exchanger cooled the soil vapour to approx. 25 °C for optimal pollutant adsorption on the air activated carbon. The condensate produced was treated in the groundwater purification plant (Fig. 11, Fig. 12). The purification of the cooled soil vapour took place in two air activated carbon filters connected in series.

As possible downstream control and for the provision of cooling water, a groundwater purification plant for a water flow of up to 30 m^3/h was built on site. The plant comprised the process stages of groundwater deferrization, sand filtration for the removal of particulate substances, stripping for the removal of volatile chlorinated hydrocarbons, exhaust air purification via air activated carbon and a water activated carbon filter in its function as a safety and police filter.

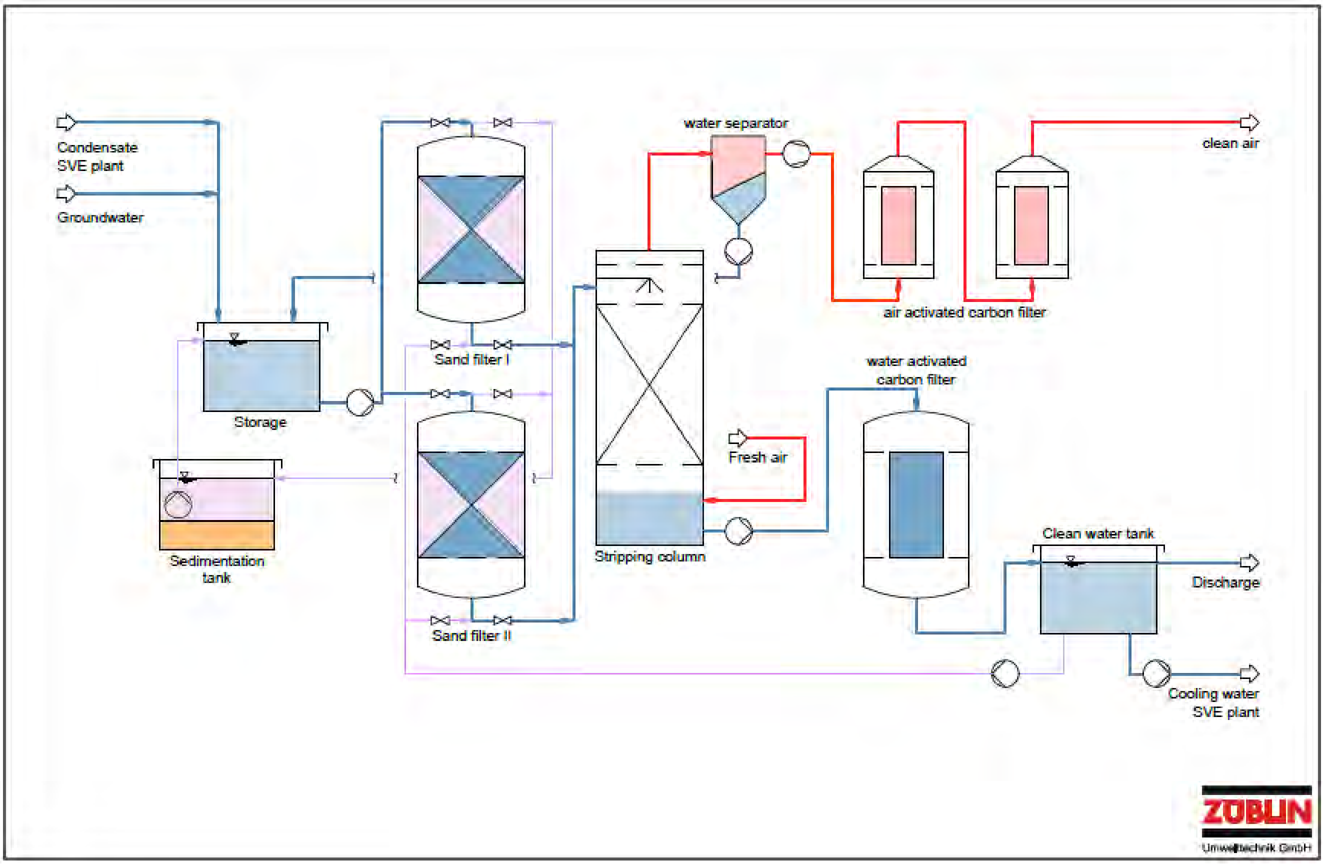


Fig. 12: Process diagram (simplified) of the groundwater purification plant

Fig. 13: Remediation system with groundwater purification plant (left side)

The area for the remediation technology and the construction site equipment was located directly next to the remediation area. An electricity connection, a drinking water connection, a wastewater connection and a fuel oil tank system were built for the operation.

4.1.4 Project schedule

The coordination with all project participants and the detailed planning of the thermal in-situ remediation began in February 2021. Subsequently, the production of the technical equipment was started at the Züblin Umwelttechnik GmbH plant. At the same time, the necessary approval documents, and notifications according to building, occupational health and safety, product safety and emission control laws were submitted. The first on-site work, such as well construction, started in March 2021. All construction and assembly work could be completed as expected towards the end of July, after final submission of all permits and official approvals.

Thermal remediation started on 16.08.2021 on subfield 1 in the northern remediation area after a successful test phase. Subsequently, the subfields were treated southwards in sections. The remediation time for individual subfields was forecast at two to three weeks, with one to two weeks of evaporation phase projected for each subfield. The treatment started with maximum steam rate to heat up the soil and the groundwater to pass the co-boiling temperature of 92°C within 3 days.

The first remediation field was operated for the longest period of time, because here, the initial operating experience was gained, and the pollutant discharge was greatest due to the proximity to the suspected discharge point. The western area of subfield 8 was repeatedly put into steam operation, as it was suspected here that the yield-related remediation target had not yet been fully achieved.

4.1.5 Disruptions

In subfields 1 and 2, a significant decrease in the extraction rate over the course of the remediation was recorded. An investigation of the extraction wells revealed considerable wetting of the unsaturated pore space and silting as well as clogging of the filter sections of the extraction wells.

By switching to surrounding extraction wells, the remediation in the two fields could be conducted successfully. A later probing and analytical examination confirmed the remediation success. Since preliminary tests for in-situ chemical and biological remediation methods as well as a partial soil exchange had been conducted in the areas of subfields 1 and 2 in the past, it was suspected that these fields would react much more sensitively to condensate formation than the other subfields. As no water logging occurred in the subsequent subfields, this assumption could be verified.

As suspected, the suction compressors posed the greatest risk of failure. A high steam output was required to heat the remediation area up to the required 92°C and maintain it for the duration of the hvCHC discharge. This led to the accumulation of condensate in the pipelines on the remediation field and in the plant. By using the third extraction compressor installed as a reserve, it was possible to maintain the extraction operation even with significant droplet formation.

Nevertheless, technical modifications also had to be made to the extraction system in order to minimise the damaging influence and to be able to drain the water from the system more effectively. This work was planned for the conversion phase between two partial fields, so that the thermal remediation operations did not have to be interrupted for this purpose.

Due to the high plant availability, the in-situ thermal remediation (ISTR) was successfully completed within the set time frame. The pollutant discharge took slightly longer than originally planned, so minor adjustments to the schedule were necessary.

4.4 Post treatment of water

Over a period of 6 months, the groundwater control was continued after the end of the steam-air injection (SAI). The results show that the total outflow load of hvCHCs is less than 6 g/d, and thus groundwater extraction can be stopped.

4.5 Control parameters (full scale)

During the in-situ thermal remediation, essentially the following parameters were measured in order to control the injection and extraction operation and to ensure the efficiency of the pollutant removal:

- hvCHC concentrations by means of gas chromatography in the raw air and clean air as well as within the exhaust system
- Flow rate of soil vapour extraction from the remediation fields
- Flow rate of steam-air injection into the injection wells
- Steam mass part of the steam-air injection
- Air content of the steam-air injection
- Steam injection pressure per injection well
- Temperatures in the remediation fields, differentiated by height at 1 m intervals
- Temperatures in the raw air and clean air as well as within the exhaust system

5. Results

5.1 Removal rate

5.1.1 Results of the steam-air injection (SAI)

VEGAS accompanied the SAI on behalf of Züblin Umwelttechnik with the representation of the heat propagation and the assessment and/or advice to the remediation operation by means of weekly reports. The operating data of the plant technology were evaluated in order to be able to adjust the plant operation mode in terms of reaching target temperature, pollutant discharge and steam dispersion. The main focus was to forecast or determine the completion of the respective remediation field as well as the control of exhaust air and steam quantities for an economic plant operation. Attention was paid to the typical pollutant discharge behaviour, a clear increase in pollutant discharge after steam passed through the extraction wells, an increase in discharge after reaching the mixture boiling temperature and a radial steam dispersion of at least 2.5 m. Maintaining the mixture boiling temperature, is the basis of almost complete pollutant removal from the contaminated soil body. During the evaporation phase, the discharge of pollutants decreases continuously. After the hvCHC concentration in the hot soil vapour has fallen below approx. 20 mg/m³, a release or dissolution of hvCHCs from the cooled soil by leachate or groundwater in the range of 10-20 µg/m³ can be expected [4].

As a result of a plant availability >97%, this remediation target was achieved in all remediation fields within 10-16 days of SAI, except for field 1 which was operated for 28 days.

Originally, 126 operating days of the remediation plant with 28 days of cooling time with two injection levels per injection filter were planned. In real terms, the SAI took place on 145 operating days, the cooling period on 50 operating days. During the review of the remediation concept, SAI operation was calculated for 147 days and a cooling period of approximately 40 days. Thus, with 195 operating days in real terms, the remediation period was only slightly longer than the 187 days projected before the start of the remediation.

5.1.2 Plant operation

The operation of the steam injection and soil vapour extraction systems (Fig. 14) illustrates the decrease in the extraction rate as a result of the clogging and wetting of the unsaturated soil zone in fields 1, 2 and 5.

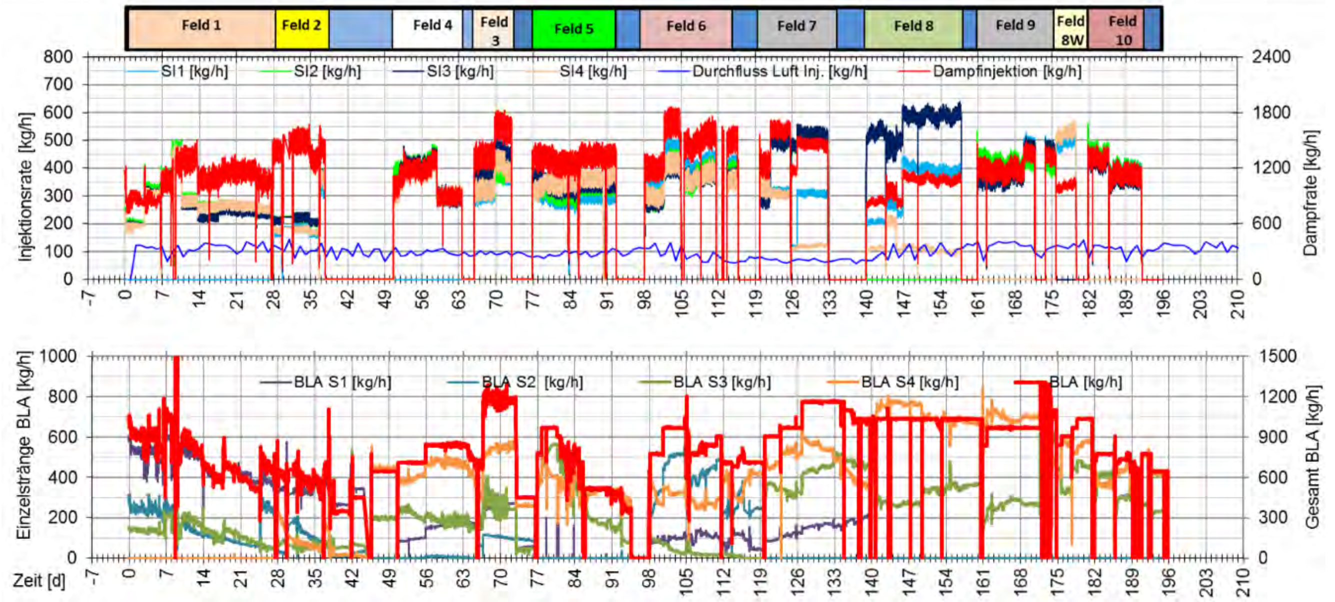


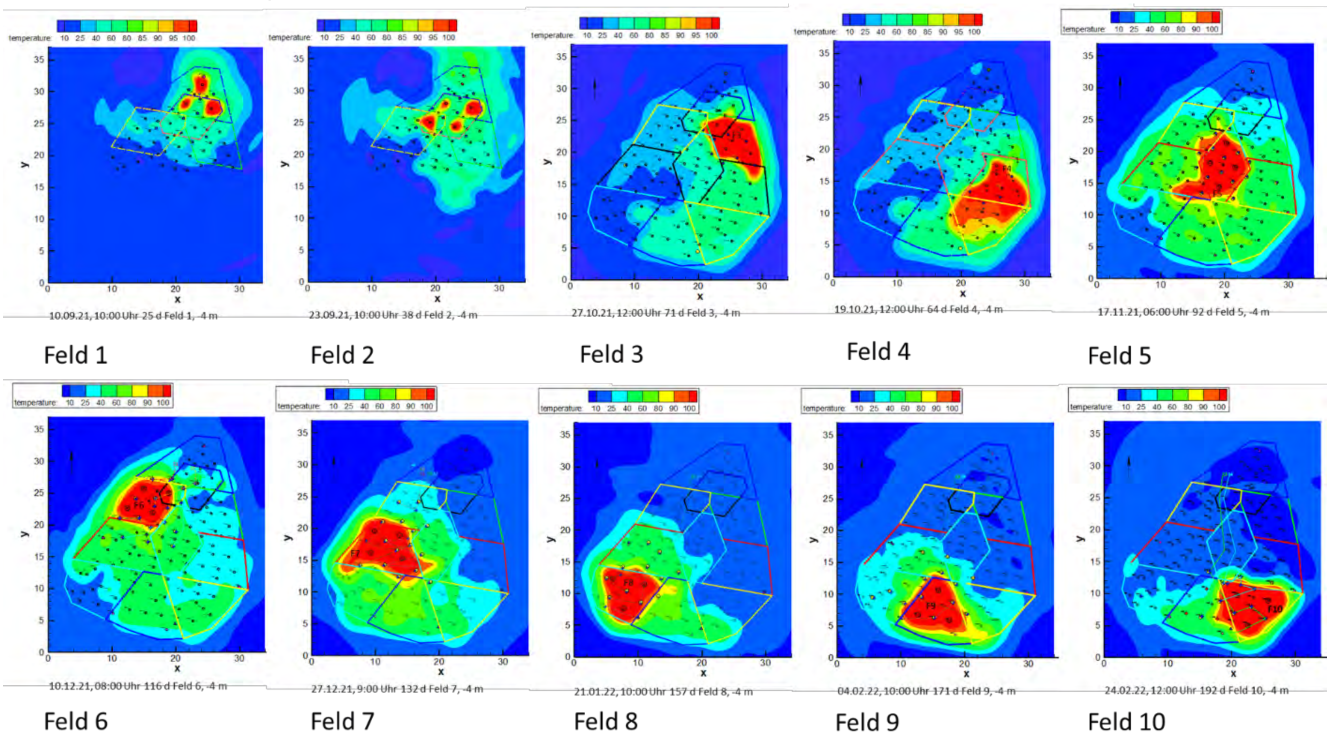
Fig. 14: Steam injection rates [kg/h] and soil vapour extraction rates [kg/h].

German	English
Feld	Field
Durchfluss Luft	Flow rate air
Injektionsrate	Injection rate
Dampfrate	Steam rate
Einzelstränge BLA	Single line SVE
Gesamt BLA	Total SVE

On average, the injected steam quantity was 1,200 kg/h and thus approx. 16% higher than projected. The soil vapour extraction rate was 860 kg/h on average; 1,270 kg/h were projected. An average of 250 kg/h condensate (190 kW heat) was extracted from the floor body via the soil vapour. The total amount of pumped condensate was 480 L/h, approx. 50% of the steam was already condensing in the extraction pipes. As a rule, approx. 40% of the vapour condenses in the groundwater or soil. The condensate flow rate should have been 720 instead of the 480 L/h pumped. 50% more vapour condensed in the soil body than expected, and moistened the unsaturated soil zone, which led to the decrease of the extraction rate or to the clogging of the wells.

5.1.3 Heat propagation

Using the data from the 108 temperature sensors in the remediation fields and interpolating the values in three-dimensional space, 2-D sections of the remediation-relevant depth layers were formed to prove the steam dispersion (Fig. 14). The initial low steam dispersion during the remediation of field 1 and field 2 is mainly due to the reduced soil vapour extraction rate and the associated reduced vapour quantity, which was approximately 300 kg/h per injection well. With a steam rate of 400 kg/h per injection well, it was possible to disperse the steam to the desired range of over 2.5 m radius from 5 m bgl (field 3-field 10).


Feld 1 Feld 2 Feld 3 Feld 4 Feld 5

Feld 6 Feld 7 Feld 8 Feld 9 Feld 10

Fig. 15: Temperature dispersion up to 4 m bgl during the respective evaporation phase.

In addition to the range, the average temperature in the different soil zones is relevant for pollutant discharge, as the mixture boiling temperature of 92 °C must be exceeded (Fig. 16). The area above 5 or 6 m bgl is of importance for remediation. The mixture boiling temperature could be exceeded in all fields for a sufficiently long time to discharge the hvCHCs.

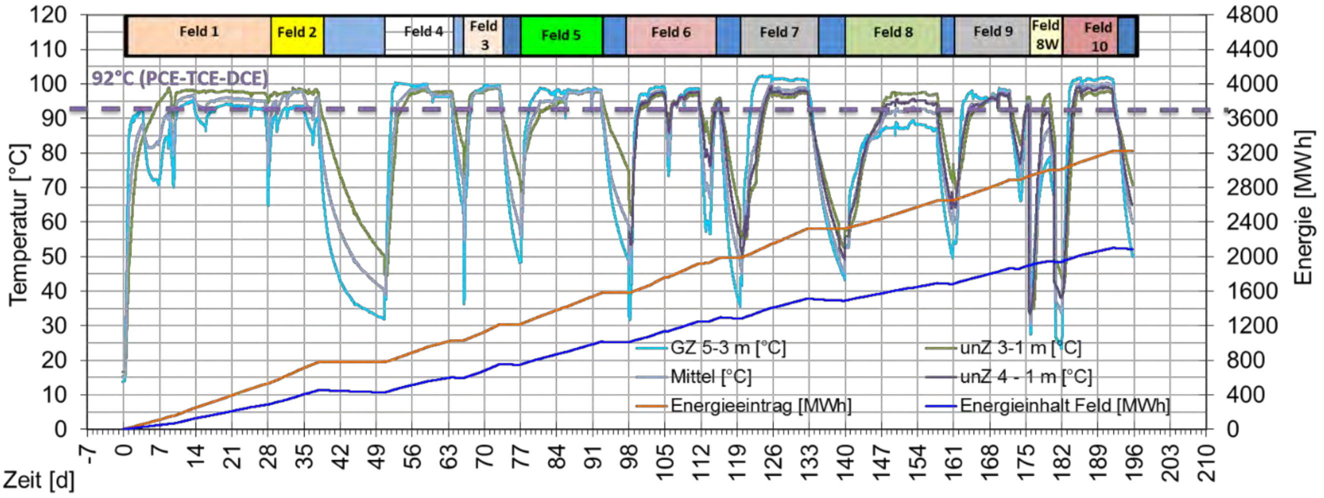


Fig. 16: Temperature development and energy balance in the respective renovation field

German	English
Temperatur	Temperature
Mittel	Average
Energieeintrag	Energy input
Energiegehalt	Energy content
Energie	Energy

5.1.4 Pollutant discharge

The pollutant discharge took place approx. 3 days after the start of the SAI in the respective remediation field via a high increase after the steam passage at the extraction wells (Fig. 17). In the subsequent evaporation phase, which lasts several days, the hvCHC contents slowly decrease according to the pollutant potential and reach the target value of 20 mg/m³ hvCHC at the end of the field treatment.

In total, 280 kg of hvCHCs, composed of approx. 82% PCE and 15% TCE, were removed by soil vapour extraction. About 175 kg of hvCHCs originate from the former contamination source, zones A and B. About 105 kg of hvCHCs were removed from the downstream area (zones B and C). Groundwater control was used to remove 20 kg of hvCHCs, primarily PCE, as well as TCE and cDCE as degradation and thermal decay products of the SAI.

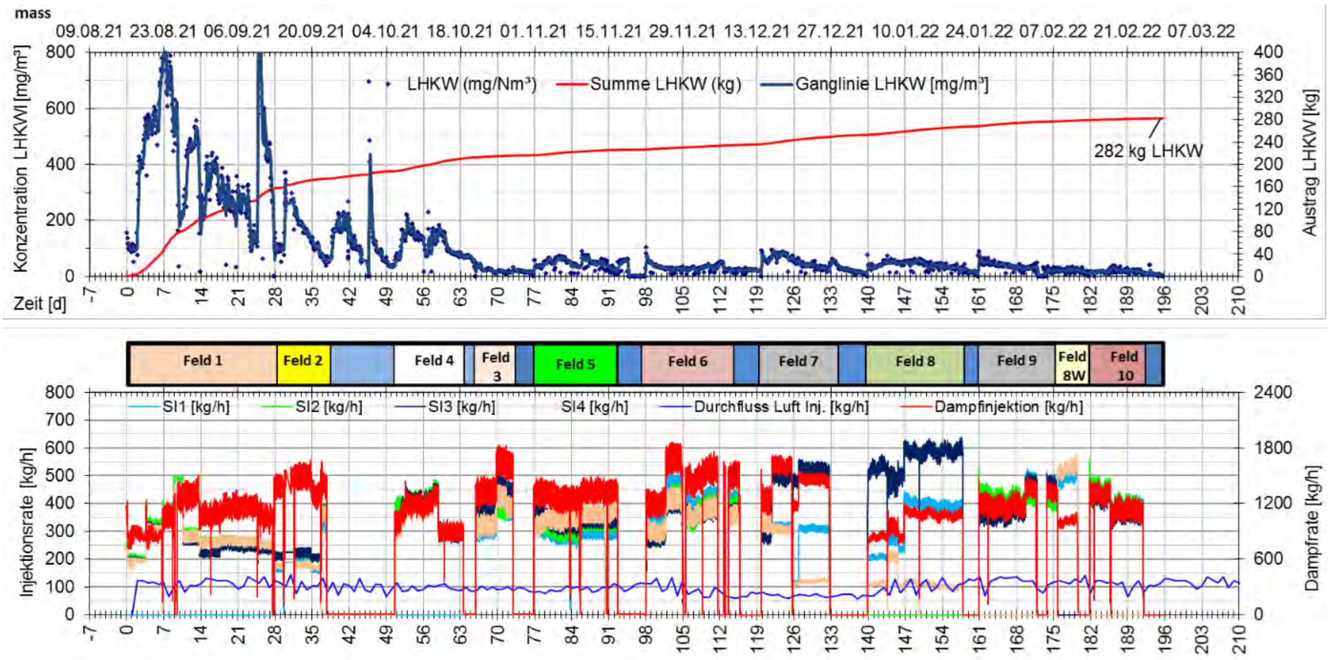


Fig. 171 - hvCHC discharge and SAI operation

German	English
Konzentration	Concentration

Injektionsrate	Injection rate
LHKW	hvCHC
Summe LHKW	Total hvCHC
Ganglinie LHKW	Hydrograph hvCHC
Austrag	Discharge
Feld	Field
Durchfluss Luft inj.	Air injection flow
Dampfinjektion	Steam injection
Dampfrate	Steam rate

For comparison, the total discharge of hvCHCs via the P&T measure operated since 2012 is 206 kg, with hvCHCs removed from the complete remediation wells over the entire aquifer thickness. Before the start of remediation, the annual discharge was around 22 kg of hvCHCs.

Of the 800 kg PCE pollutant inventory estimated in 2010, over 500 kg of hvCHC was removed from the site.

6. Post treatment and/or Long Term Monitoring

6.1 Post treatment and/or Long Term Monitoring

6.1.1 Soil samples

As remediation control, a total of 11 soil probings down to a depth of 7 m bgl were carried out in the three remediation zones A, B (contamination source) and C (downstream area), and a total of 62 depth-oriented soil samples were taken. The analysis of these soil samples, with hvCHC contents of less than 1 mg/kg, starting from a maximum of 8,100 mg/kg, proves the almost complete remediation of the site. Only at one borehole point, a hvCHC content of 1.1 mg/kg remained at the base, slightly above the remediation target value. All other samples comply with the remediation target.

6.1.2 Groundwater monitoring

The long-term monitoring of the remediation success is carried out as part of aftercare via groundwater monitoring over several years. Since the remediation measure is a hot-spot remediation of more contaminated areas, residual contamination remains in the subsoil, particularly in downstream direction and at depths > 6 m bgl. Therefore, an immediate decrease of pollutants with the setting of equilibrium concentrations at the control level at the property boundary is not to be assumed. The development of the hvCHC levels in the groundwater will continue to be monitored over a period of 5 years. It will be interesting to see whether the heat-induced microbial activity is reflected in a reduction of the hvCHC load.

6.1.3 Subsequent use

The city of Neumünster plans to convert the conveniently located site back into a new use. The resettlement of businesses, in particular, comes into question for this purpose. Due to the residual loads still remaining in deeper areas of the aquifer, there are still restrictions on usability in the western part of the property for the time being.

7. Additional information

7.1 Lesson learnt

The in-situ thermal remediation of the present site by steam-air injection (SAI) proved to be efficient, successful and more energy and resource efficient than conventional soil replacement.

The comparison of the CO_2 emission of the chosen in-situ method with an emission of approx. 585 tons of CO_2 and a soil replacement with an estimated CO_2 emission of 822 tons of CO_2 shows not only the financial, but also the ecological advantage of the steam-air injection at the site.

Despite the humidification caused by the formation of condensate in the unsaturated soil zone, the remediation was completed as planned, with a high level of system availability within the specified time frame. Over a period of 195 days, a total of approx. 280 kg of hvCHCs were removed from the site via soil vapour extraction and approx. 20 kg of hvCHCs via groundwater extraction.

The remediation targets were met with the mixture boiling temperature exceeded, typical pollutant discharge behaviour and the undercutting of the target value of 20 mg/m^3 of hvCHCs in the hot soil vapour by the end of remediation of the ten remediation fields.

The results of the soil samples taken for remediation control prove compliance with the remediation target values for hvCHCs of 1 mg/kg and do not indicate any further contamination of the groundwater, starting from the suspected entry point.

In view of the project costs of EUR 1.2 million net, the monetary input for the remediation of 650 m^2 area and approx. 5.7 m depth can be quantified at EUR 180 per ton of soil. The measures funded by the federal state of Schleswig-Holstein could thus also be successfully completed within the estimated budget.

7.2 Additional information

In-situ thermal remediation methods (ISTR) are particularly suitable for the remediation of contamination sources in the unsaturated soil zone and in the groundwater fluctuation zone, under certain conditions also in the water-saturated zone. Depending on the type of pollutant and the subsoil, the input of thermal energy into the subsoil is carried out by injecting water steam or by solid heat sources operated electrically or with fuels.

The two main advantages of the ISTR method compared to conventional remediation methods are, on the one hand, the greatly reduced remediation time and, on the other hand, the high cleaning capacity, especially in medium permeable subsoil by means of steam-air injection, and in poorly permeable soil by means of heating elements (conductive heating > 100°C). With the help of in-situ thermal remediation, very low residual concentrations can be achieved, which are not possible with other in-situ remediation methods.

Based on our extensive experience from numerous projects with in-situ thermal remediation (ISTR) [5], pilot studies are usually not required, unless the subsurface has a complex structure. For example, pilot applications were conducted in clayey soil and fractured bedrock, and subsequently the sites were completely remediated.

However, in order to predict the feasibility and success of the remediation measure, a careful detailed geological and hydrogeological investigation of the site is indispensable. The data generated therefrom can subsequently be used to dimension the in-situ thermal remediation using steam-air injection with the aid of the computer-aided SAI tool [3].

7.4 Additional remarks

7.4.1 References

[1] Trötschler, O., Koschitzky, H.-P. (2018): Machbarkeitsbewertung mit Kostenschätzung Thermische In-situ-Sanierung LCKW-Schaden Stoverweg 38 in Neumünster, Technischer Bericht Nr. 2018/1 (VEG 80), Universität Stuttgart

[2] Trötschler, O., Koschitzky, H.-P. (2012): DLI-Tool zur Dimensionierung einer thermischen In-situ-Sanierung mittels Dampf-Luft-Injektion (DLI), Vorstellung anlässlich der TASK Praxistage 2012, Workshop TisS, 18.09.2012, UFZ Leipzig

[3] DLI-Tool 2.0 (2020):
https://www.iws.uni-tuttgart.de/vegas/downloads/Downloads_ordner/DLI-ToolV2.0.zip

[4] Grathwohl, P., Reisinger, C. (1996): Formulierung einer Verfahrensempfehlung zur Bestimmung der Emission leichtflüchtiger organischer Schadstoffe (LCKW, BTEX etc.) aus kontaminierten Böden (Berechnungsverfahren und Methoden), Abschlussbericht LFU BW, Tübingen

[5] In-situ Technologies (2023) Brochure, Züblin Umwelttechnik GmbH.

Glossary of Terms

Term **(alphabetical order)**	**Definition**
bgl	Below ground level
DI	Detailed investigation
DP	Direct push
hvCHC	Highly volatile chlorinated hydrocarbons
ISTR	In-situ thermal remediation
P&T	Pump & Treat
RI	Remedial investigation
SAI	Steam-air injection
SVE	Soil vapour extraction
TOC	Total organic carbon

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.7

1.1 Name and Surname	1) Rigol, Niklas 2) Greco, Antonio 3) Mönter, Frederik
1.2 Country/Jurisdiction	1) 3) Germany 2) Switzerland
1.3 Organisation	1) Züblin Umwelttechnik GmbH 2) CSD Ingenieure AG 3) Züblin Umwelttechnik GmbH
1.4 Position	1) Project Manager 2) Project Manager - Overall Project 3) Department Manager
1.5 Duties	1) In-situ thermal Remediation (ISTR) 2) Consultant Remediation 3) In-situ thermal Remediation (ISTR)
1.6 Email address	1) niklas.rigol@zueblin.de 2) a.greco@csd.ch 3) frederik.moenter@zueblin.de
1.7 Phone number	1) +49 7145 9324-201 2) +41 41 319 39 10 3) +49 7145 9324-203

2. Site background

2.1 History of the site

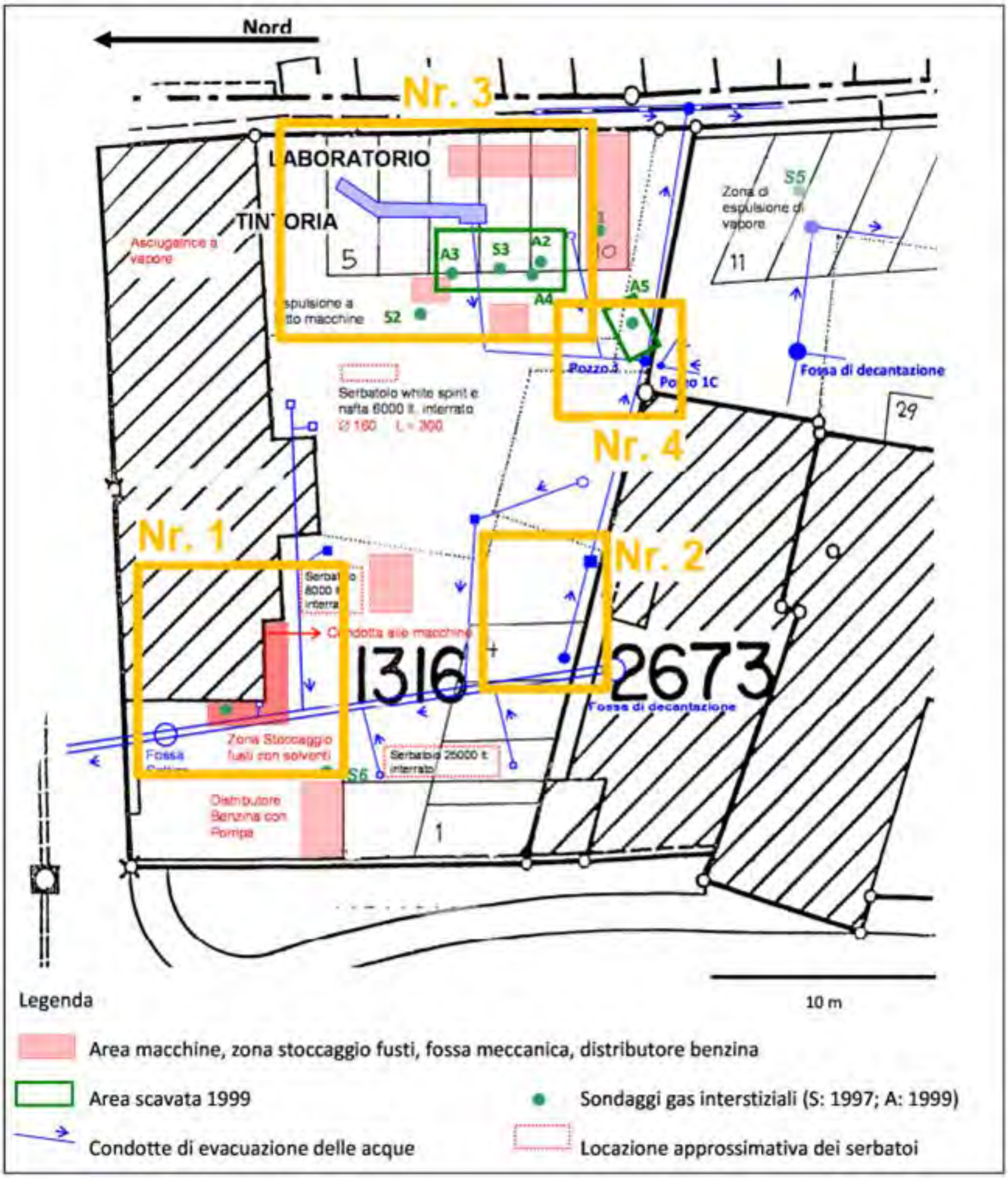


Figure 1 - Situation of the chemical dry cleaning with areas No. 1 - No. 4

The contaminated site is located on the premises of the former dry cleaner "Lavanderia Caviezel" on the outskirts of the old town in Bellinzona, Switzerland. The company's activities at the site began in 1927 and ended in 1988. In the course of the application of perchloroethylene (PER or PCE) as a chemical cleaning agent in the 1960s-80s, there was an uncontrolled discharge into the subsoil and groundwater. The discharge occurred due to losses on the surface, presumably from the barrel storage (No. 1), in the area of the washing machines (No. 3) and in the area of the discharge into the drainage system, which ends in various soakaways ahead of the sewer connection (No. 2 and 4), see Fig.1. The remediation area extends on the plot approx. over 35 m x 45 m, and thus on a total area of approx. 1,500 m².

Figure 2 - Remediation site (purple) with adjacent railway line to the east (yellow)

Detailed pedological, chemical and microbiological analyses showed that the organic pollutants (C>12 hydrocarbons) affected the unsaturated materials up to 3 m just above the water table level in a scattered, non-continuous way. Moreover, PGPR (Plant Growth-Promoting Rhizobacteria) microorganisms and fungi potentially able to degrade hydrocarbons and to establish a symbiotic relationship with the plant roots, were detected in the site. Based on a both environmental and technical-economic

sustainability and feasibility assessment, the best remediation option was an integration of two different bioremediation technologies: In Situ Thermal Desorption and biopiles. The choice of biological technologies was made with the aim of safeguarding as much as possible the ecosystem functions of contaminated soils by limiting the impact on the existing (agro) ecological equilibria to re-establish a safe area suitable for its traditional use in a relatively short time. The surroundings of the remediation site are characterised by the adjacent historic old town to the west, as well as the railway line of the SBB (Swiss Federal Railways - Gotthard line) bordering on the eastern side, see Fig. 2.
The plot was unused at the time of the remediation. In the future, the site will be used for the extension of the railway line (additional track and a suburban railway stop).

2.2 Geological setting

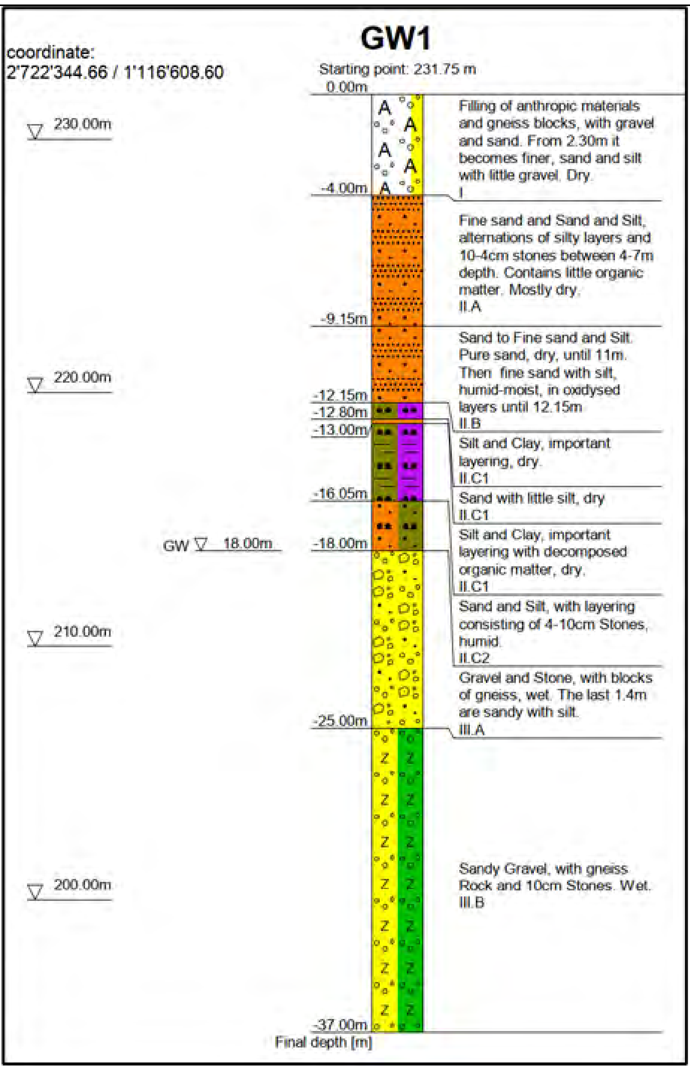
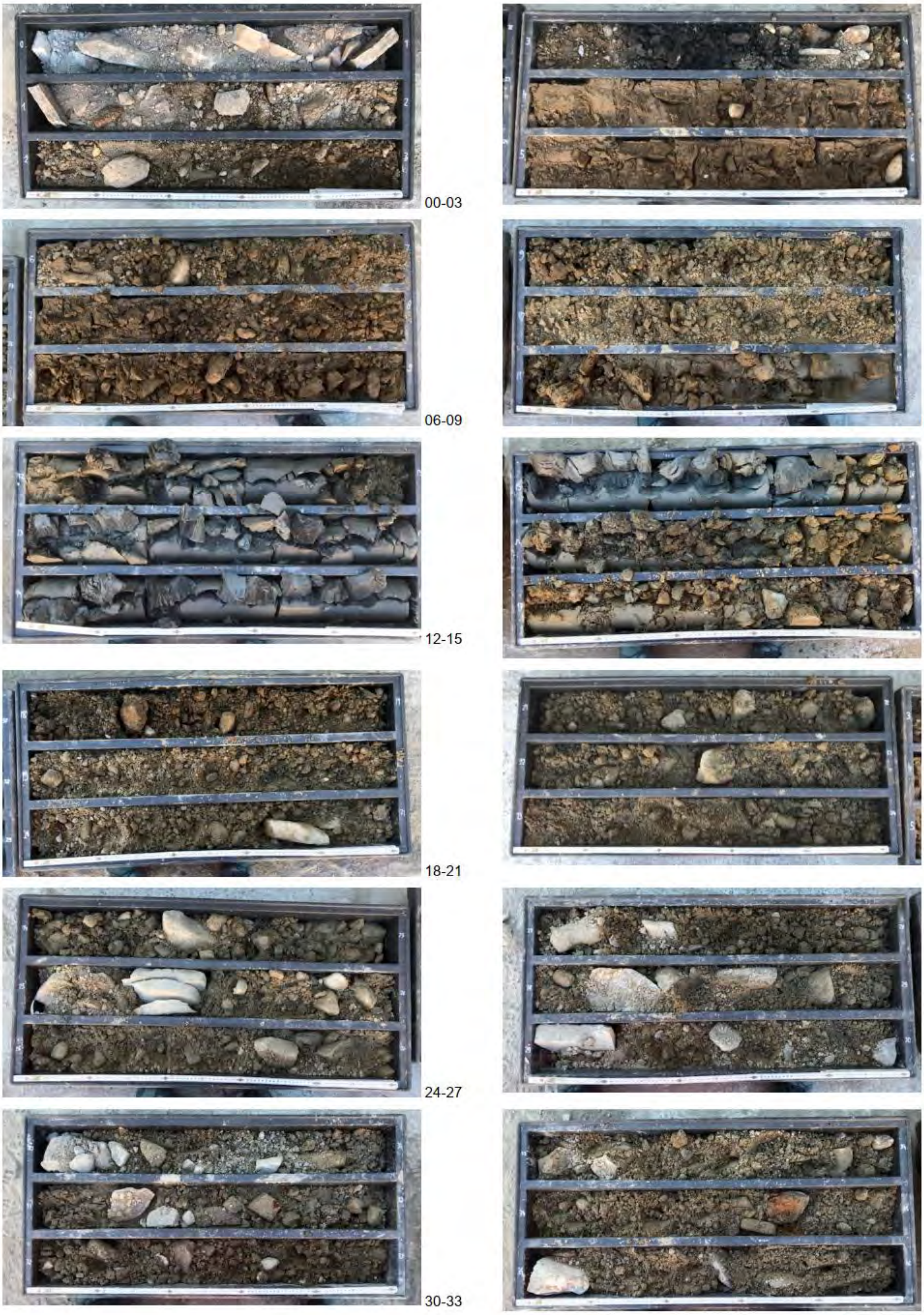


Figure 3 - Geological profile of the site



00-03

03-06

06-09

09-12

12-15

15-18

18-21

21-24

24-27

27-30

30-33

33-36

Figure 4 - Photo documentation of the site

The subsurface structure and hydrogeology are very heterogeneous, both vertically and laterally. The unsaturated area at the site consists of an alternating layer of sands and silts with varying organic content (II.A) and in places rich in gravel (II.B) under the fills (I.). From a depth of 10-12 m, these turn into silty-sandy flood sediments with organic admixtures and peat in places (II.C). At the site, saturated gravel occurs at a depth of 15-20 m below ground level. (III.A), which changes to sands at a depth of approx. 35 m. From about 38-40 m depth, the sands lie on rock (V.) or on loamy sands and clay.

Figure 5 - Image of a drill core of layer II.C

This lithostratigraphic structure has the hydrogeological consequence that, according to previous findings, two groundwater-conducting horizons occur: An upper aquifer up to the intermediate reservoir II.C (Fig. 4) and from 15-20 m bgl, a lower aquifer. In general, only the lower aquifer at the site carries groundwater with an average level at approx. 217.60 m above sea level (asl). The level variation is considerable at 3 m, with peaks up to 219 and dips to 216 m asl.

2.3 Contaminants of concern

No information is available on the amount of chemical cleaning agents used in the cleaning process, which are probably undiluted and should, however, amount to several hundreds of kg/year due to the size of the cleaning machines used. It can be assumed that over the years, the loss of several hundred kg at the site can be

expected.
The contaminant present was almost exclusively PCE; other hvCHCs (cDCE, TCE) are scarcely present, or only in small percentages. The contaminant was present in the subsoil, collected in its pores, presumably in dissolved, highly concentrated form, up to droplets and pools in the pure contaminant phase.
Over the years, seepage and groundwater flow have led to vertical and lateral transport of the contaminant in the soil layers.

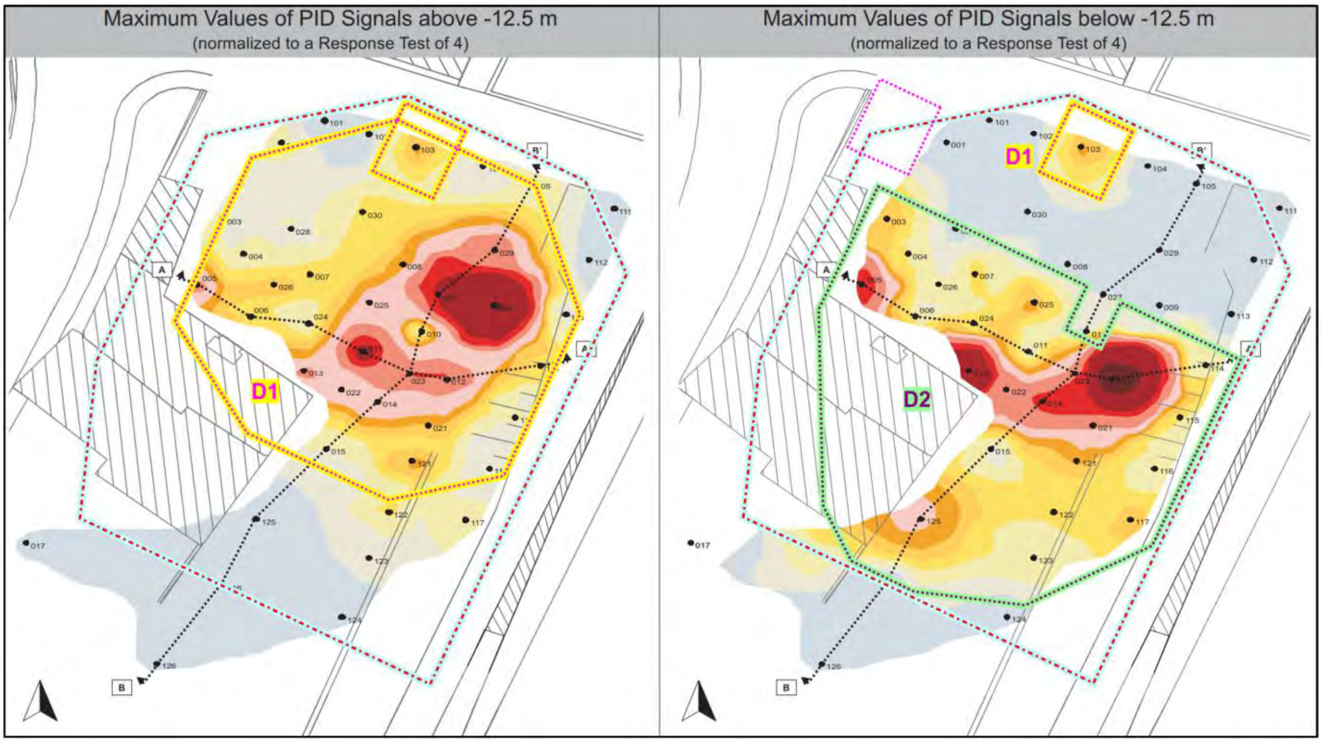


Fig. 6: Horizontal distribution of the maximum measured DELCD signals, in unsaturated (left - D1) and in (partially) saturated background (right - D2).

Contaminants in the subsoil above the aquifer
In order to determine the dispersion of the contaminant, in addition to the solid analysis of the soil samples, the results of the performed MIP soundings were primarily used, as there is a good correlation with the PCE concentrations due to the presence of a sole contaminant. From the resulting model, two soil zones at different depths with high concentrations can be identified, which retain the contaminant thanks to their loamy-sandy nature, see also Fig. 6:

- **D1:** Upper heavily polluted zone in the unsaturated area, mainly consisting of sands and silty sands (unit II.A). Zone D1 begins in patches already 1-2 m bgl and ends at a depth of approx. 10-11 m (221 m asl). The mean weighted PCE concentration was around 5 mg/kg dry matter.

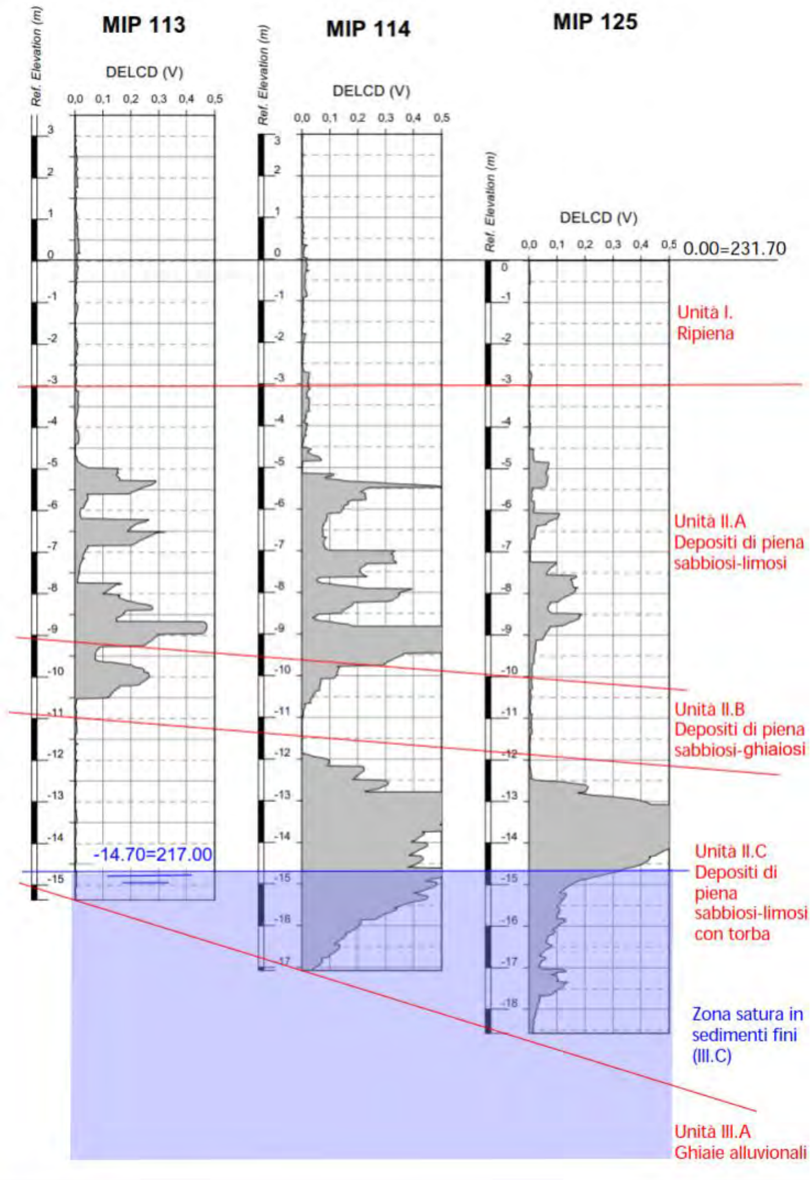


Fig. 7 - Typical depth distribution of the DELCD signals and correlation with the characteristic soil layers

- **D2:** Lower heavily polluted zone consisting of predominantly clayey to sandy loam, with organic admixtures in alternating bedding with sands (unit II.C). This zone is located within the fluctuation range of the groundwater table (216 to 219 m asl), at a depth of approx. 12 to 19 m bgl, and is consequently at least partially saturated, but has a very low permeability ($k_f < 10^{-6}$ m/s). The mean weighted PCE concentration was around 12 to 15 mg/kg dry matter.
- In the coarse-grained fills, and especially in the gravelly intermediate layer (II.B), the contaminant is completely absent. Finally, the decrease in MIP signals (Fig.) indicates that in the upper part of the aquifer, there is also hardly any contaminant in higher concentrations.

Depth-oriented sampling in aquifers indicates that a) the highest dissolved values are present in the upper part of the aquifer, and b) concentrations decrease sharply at depth. It is not known whether contaminant pools are present at the base of the aquifer, but the dissolved contents indicate that these are not/very little relevant for the pollution of the groundwater.

The number of contaminants present in the unsaturated and partially saturated zone at the site was estimated to be over 200 kg.

2.4 Regulatory framework

The need for remediation of the site arises from the contamination of the usable groundwater that is worthy of protection. According to Swiss law, a remediation requirement exists in this situation if the dissolved concentrations of PCE immediately downstream of the site exceed 20 µg/l. In the present case, 50 to 350 µg/l were measured, depending on the water level.

The need for remediation was already identified in the first phase of the investigations. In accordance with Swiss law, the findings at the site were at first progressively intensified in order to compare various remediation options in a concrete study. The variants were developed according to the site characteristics and compared in terms of feasibility, viability and costs. Basically, decontamination by excavation and disposal was assessed not only as disproportionately expensive but also as risky with regard to the stability of the railway facilities and private buildings in the vicinity. Securing the site, e.g. by means of P&T, was judged to be disproportionate due to the necessary long operating time and subsequent costs. This would also have significantly exceeded the time limit required under Swiss soil protection law to complete remediation. Securing the site would also have had the disadvantage that the development of the site or the extension of the railway line would have been impossible for decades. Therefore, in-situ remediation remained the only option.

As most promising method with the shortest operating times and lowest overall costs, the authorities have approved the removal of the contaminant through in-situ thermal remediation (ISTR) and an accompanying hydraulic barrier (P&T) [1].

The aim of the remediation measure is to reduce the contaminant content at the site to such an extent that the respective limit values for PCE (20 µg/l), TCE (35 µg/l), cDCE (25 µg/l) and VC (0.25 µg/l) in the groundwater downstream are permanently and reliably complied with. The permitted average concentration in solids should be less than 1 mg/kg Σ hvCHC.

3. Pilot-scale

3.1 Laboratory Study

During the variant study for the selection of the remediation method, laboratory tests were carried out in 2007-2008 to assess the microbiological conditions for an "enhanced natural attenuation". In the naturally prevailing soil conditions, degradation of PCE is not possible due to both the unfavourable redox conditions and the lack of microorganisms. The effort required to create favourable conditions, and the associated injections of the necessary microorganisms and nutrients was estimated to be too high in relation to the possible results. The chances of success were also considered to be very low.

3.2 Treatment unit (pilot scale)

To test the feasibility of the in-situ thermal remediation (ISTR), it is important that the contaminant is fully captured via a soil vapour extraction system. For this purpose, extraction tests were carried out in 2018 with the aim of obtaining knowledge about the possible extraction rates, the necessary under pressures and the resulting efficiency ranges of the wells.

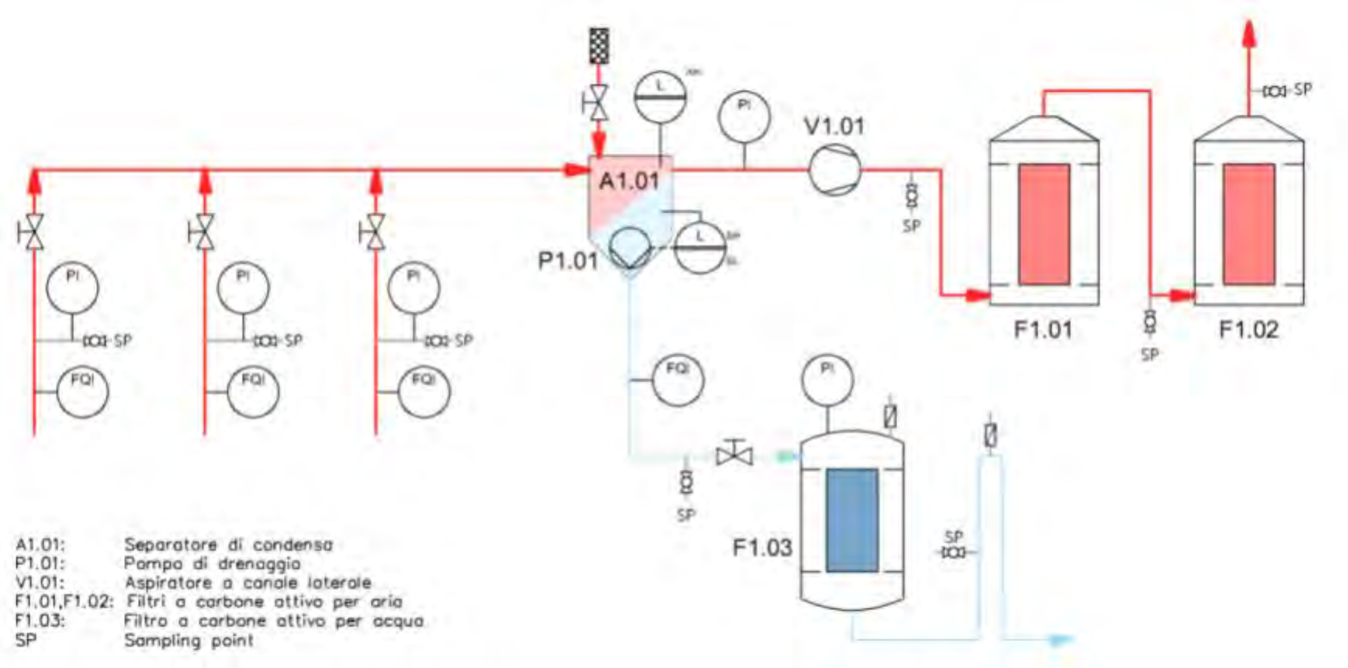


Figure 8 - Treatment units

Aim of these tests was to test the feasibility of the main extraction in the upper polluted zone D1, and to provide the corresponding dimensioning bases. In the plant design, it was assumed that the main part of the mobilised contaminants would have to be removed from the upper soil zone. Therefore, this part of the plant had to be carefully planned. The thermal desorption itself and the heating of the subsoil were judged to be feasible (silty-clay subsoil is a very good thermal conductor), and empirical values were used as a basis for dimensioning. Extraction tests were not carried out in the lower polluted zones D2, because due to the lithology, it was apparent that the extraction rate and the contaminant yield would be much lower here, despite higher pressures and short distances between the extraction wells.

3 extraction wells were drilled in the heavily polluted zone D1 (2" filter pipes). 8 piezometers (1" filter tubes) were used to measure the negative pressure in the subsoil. The extraction system is shown schematically in Fig. 8. Via the 3 extraction lines, negative pressure, flow rate and air pollution could be recorded separately for each well. Subsequently, any condensate water was separated from the air flow via a water separator. The extraction fan was installed downstream of the separator, which conveyed the extracted soil vapour into two activated carbon filters on the pressure side. The results of the extraction test are shown in Tab. 1.

Well	Soil unit	Filter depth bgl	Extraction rate	Negative pressure in the well	Efficiency range at -0.25 mbar
A01	II.A	4.2 to 10.2 m	50 m^3/h	-95 mbar	14m
A02	II.B (II.C)	9.2 to 14.2 m	70 m^3/h	-120 mbar	14,5m
A03	II.A	4.2 to 9.2 m	70 m^3/h	-100 mbar	14m

Table 1 - Results of the extraction tests

4. Full-scale application

4.1 Main treatment unit

Remediation technology

The operating principle of in-situ thermal remediation (ISTR) is based on input of thermal energy into the subsurface. This mobilises the existing contaminants by increasing their volatility and water solubility and reducing their viscosity and surface tension. The mobilised contaminants can then be captured and cleaned by suitable methods, e.g. in gaseous form. The energy input for mobilisation can take place via different technologies.

The method suitable for the site is based on the use of electric heating elements (HEL) as fixed heat sources, which are embedded in the soil body via soil drillings, see Fig. 9. The length of the heating elements and the necessary insertion depth are variable and designed according to the contaminant situation in the soil.

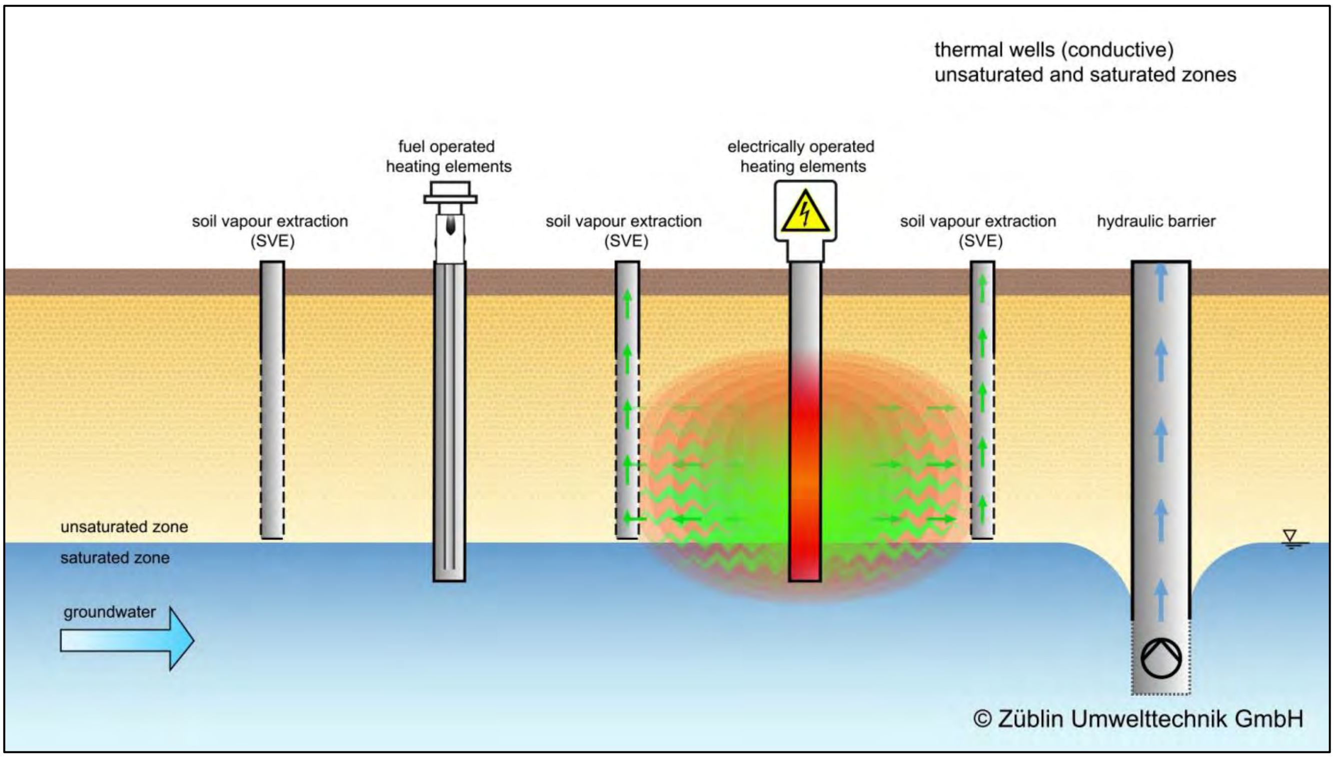


Figure 9 - In-situ thermal remediation (ISTR) using fixed electrical heat sources, principal diagram

The heat fronts forming due to the continuous heat input spread radially, symmetrically around the heating elements, vaporizing the contaminants. In this process, the contaminant-water mixture of the PCE contamination boils at a mixture boiling temperature of 88.5 °C. Due to the transition to the gaseous phase, the contaminants

can be extracted via the soil vapour of the unsaturated zone. Soil vapour extraction wells are distributed over the remediation area to cover the entire contaminated area; the necessary number as well as the filtering of the wells depends on the soil properties, the resulting ranges and the location of the contaminated areas. Subsequently, the extracted soil vapour has to be cleaned via air activated carbon filters of the soil vapour extraction system (SVE).
To regulate and control the heating elements, as well as to monitor the temperature of the entire surface, so-called temperature measuring lances TML (measuring bundles with Pt-100) are required at different radial distances from the HELs.

ISTR design

The parameters required for dimensioning the ISTR are essentially the hydraulic permeabilities in the remediation area, the groundwater levels, the number of contaminants and their location in the subsoil. With the help of a computer-based ISTR tool, it was possible to determine the required heating power, the number of soil vapour extraction wells, and their extraction rates.
Due to the two contamination horizons D1 and D2, which differ greatly in location and soil properties, it was necessary to divide the system into two sections that could be controlled separately, see Tab. 2.

	Remediation area D1	**Remediation area D2**
Number of HEL	25 pcs	35 pcs
Heated length	9m	4m
Insertion depths	221 m asl to 320 m asl	216.5 m asl to 220.5 m asl
Max. performance	18 kW / HEL	8 kW / HEL
Number of SVE wells	18 pcs	40 pcs
Total extraction rate	approx. 700 Nm³/h	approx. 350 Nm³/h
Temperature measuring lances	67 pcs (total of 445 measuring points)	

Tab. 2 -Technical equipment of contamination areas D1 and D2

The more compact soil layers prevailing in the lower, heavily polluted area D2 result in a higher negative pressure and thus a higher number of extraction wells being necessary, in order to be able to capture the contaminant in the entire area within the resulting range. According to the results (ranges, number of HELs), the development of the remediation area was planned, see Fig. 10. The SVE levels were positioned as centrally as possible and thus at the coldest point between two HELs. Per HEL, a temperature measuring lance was installed as a control variable at a distance of 1 m, and additionally for monitoring in settlement-critical areas (track area and residential buildings).

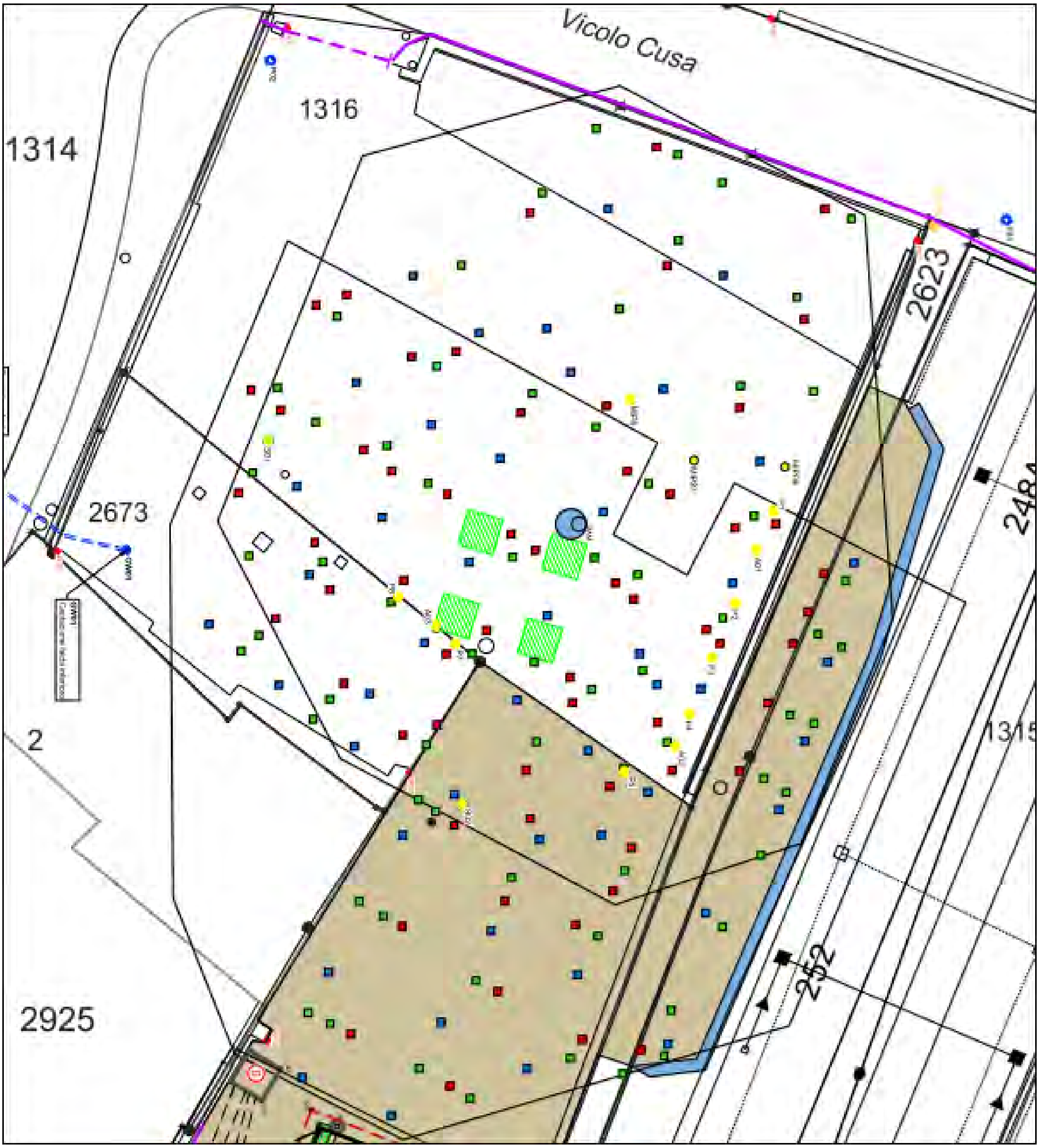


Figure 10 - Site plan of remediation area and installation area, red - HEL, blue - SVE, green - TML

Figure 11 - Erecting a protective tube with the help of a tower crane near the railway tracks

Figure 12 - Electric heating element (HEL) of 8 m length (left) and a protective tube (right)

Figure 13 - Control cabinet in the field

Holes with a diameter of 200 mm were required to mount the heating elements, into which stainless steel protective tubes (DN125) were inserted first. These protective tubes are tightly welded and are designed to prevent water ingress as well as direct contact of the heating element with the soil body.

Due to the required insertion depth in the contaminated area D2 and TGL heights of up to 233.5 m asl, boreholes and protective tube lengths of up to 17 m were necessary. In addition to the limited space available, the proximity to the SBB railway track and the associated increased demands on occupational safety posed a particular challenge. The crane work for the installation of the protective pipes and HELs took place with a position limitation system (limitation to safety distances of the railway installations) and under the temporary supervision of safety personnel.

After the protective tubes had been inserted into the subsoil, the heating elements were suspended in the protective tube at the appropriate height using wire ropes. For the control of the HELs and for signal and data processing, control cabinets were distributed on the remediation area (Fig. 13).

For the power supply of the plant technology, 2 transformers with a capacity of 1,000 kVA each were temporarily installed in the remediation area, especially for the remediation project. The connected load of the HEL for D1 was 324 kW and for D2 320 kW. The electricity consumption of the thermal system was approx. 1,316 MWh during the entire heating operation.

SVE system design

The connection between the soil vapour extraction wells and the system was made via a total of 8 extraction manifolds (extraction lines), 4 of which were assigned to each of the remediation areas D1 and D2. The lines were installed with a continuous slope in the direction of the soil vapour extraction system, so that the removal of the generated condensate was always guaranteed. In the first step, the hot, saturated soil vapour is passed through water separators to separate condensed water droplets entrained in the air flow. For the cooling of the hot soil vapour and the condensation of the humidity contained in the air, air/water heat exchangers, equipped with a cooling water system were installed. For the remediation areas D1 and D2, 2 side channel blowers each were installed as extraction fans (Fig. 14), which were operated frequency-controlled with constant flow rates. After compression in the extraction fans, the air was cooled down again to approx. 25 °C in an additional heat exchanger for optimum contaminant adsorption on the activated carbon. The purification of the cooled soil vapour was carried out via two air activated carbon filters connected in series, each with a volume of 2 m^3. The captured condensate from the condensate separators and the heat exchangers was cleaned via a water activated carbon filter before being discharged into the duct system.

Figure 13 - Extraction fan (foreground) and air/water heat exchanger in the background

The components of the extraction system were installed in 3 containers, the installation of the cooling water systems and air activated carbon filters took place outside, see Fig. 14. The contaminant load was determined by means of online PID measurement with measuring point switch, and the cleaning performance of the activated carbon air filters has been monitored.

Miscellaneous

To prevent precipitation water from penetrating into the soil, the remediation surface was covered with a PVC sheet in those areas that were not covered by e.g. asphalt. In addition, this prevented the intake of atmospheric fresh air and outgassing. A storm drain with pumping station was installed at the lowest point of the remediation area to collect and drain off the rainwater.

Due to the adjacent SBB infrastructure and residential development, special attention was paid to the settlement processes associated with the heating and drying of the soil. For this purpose, an online measuring system was installed, which was able to detect displacements occurring at over 100 measuring points in the track area, on the noise barrier and on the adjacent residential building. When limit values were exceeded, alarms were automatically sent by the system. The settlement processes that occurred at the beginning of the thermal remediation could thus be reliably detected. Appropriate countermeasures were subsequently implemented quickly.

Fig. 14: Drone shot of the remediation area with SVE plant and transformers (right)

4.4 Post-treatment of water / groundwater treatment

Since the operation of the thermal system causes the mobilisation of the contaminant into the aquifer, a groundwater treatment plant was installed as a hydraulic barrier in western direction, outside the remediation area, see Fig. 15. The extraction well was located at the western edge of the remediation area in the downstream of the lower aquifer. After purification, the extracted groundwater was discharged into two infiltration wells located within the installation area of the groundwater treatment plant (GWTP).

Fig. 15 - Aerial view of the remediation area (blue) and installation area of the GWTP (yellow)

The groundwater treatment plant was designed for a maximum flow of 25 m^3/h. The extracted groundwater is first pumped through a sand filter to separate particulate impurities. Then, the water passes through two activated carbon filters connected in series, each with a bed volume of 5 m^3, to adsorb the hvCHC contamination, and thus comply with the limit values for discharge concentrations of $c < 1$ µg/l (per individual hvCHC substance).

4.5 Control parameters

During the in-situ thermal remediation, the following parameters were measured in order to monitor the proper operation of the plant and to ensure the efficiency of the contaminant removal:

- Temperatures in the soil
- hvCHC concentrations: Online PID and laboratory analytics
- Flow rates of the soil vapour well groups
- Extraction pressures
- Other measurement, control and regulation technology for process control of the SVE plant

5. Results

5.1 Removal rate

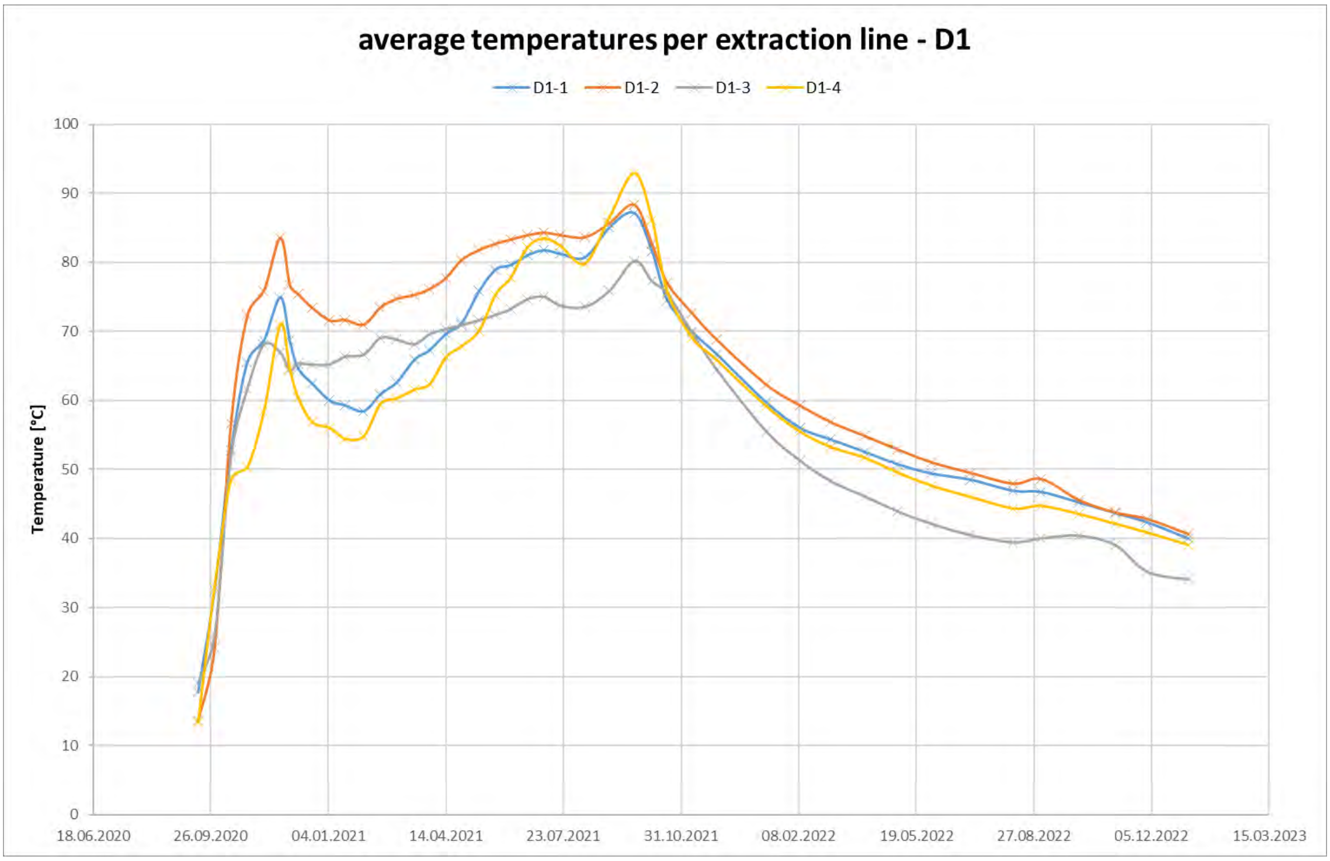


Fig. 16 - Temperature curve per extraction line in the contaminated area D1

The operating data of the plant was evaluated to assess the remediation progress and the process control. The decisive factors for the plant operation were the temperature developments in the soil and the contaminant trends in the extracted soil vapour. The achievement of the target temperatures in the remediation areas in connection with the contaminant discharge behaviour was essential for the determination of the remediation completion. The course of the operational phase is as follows:

1. Cold soil vapour extraction:

Initially higher contaminant concentrations in the soil body due to accumulation in the soil vapour. After a rapid decrease in concentrations, the thermal system was started after 14 days.

2. Heat-up phase:

Continuous increase of soil temperatures by the electrical power of the heating elements to reach the target temperature and mobilise the contaminant. The heat-up phase lasted approx. 9 months. Due to deformations on the surface as a result of settling processes, there was a temporary interruption (strong reduction of heating power). After the deformations had receded, heating was resumed. To reduce the risk of further settlement, this 2nd heat-up phase was slower than at the beginning, with a gradual increase of the heating power.

3. Discharge phase:

Maintaining the target temperature for an almost complete contaminant removal. The entire heating phase (heat-up and discharge phase) took a total of 13 months.

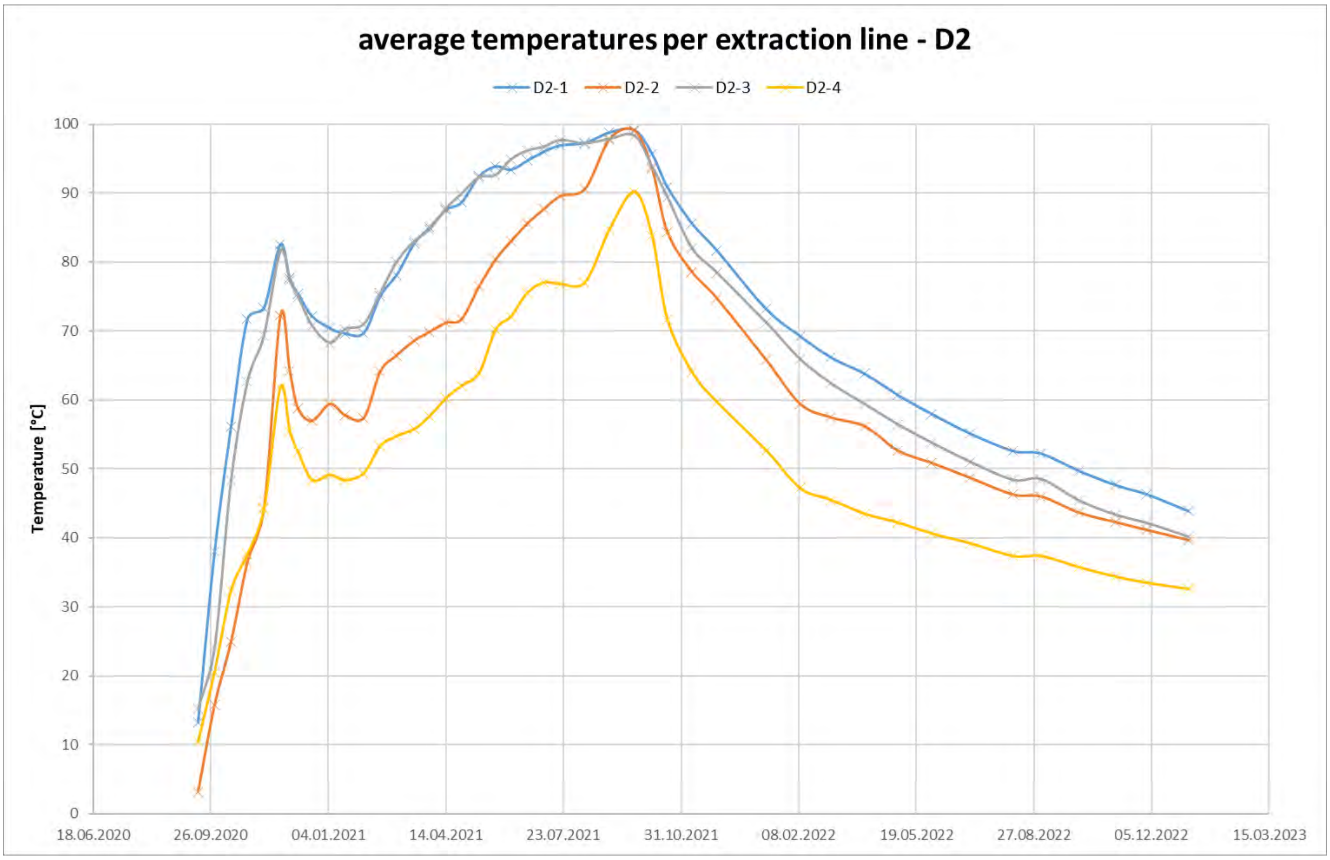


Fig. 17 - Temperature curve per extraction line in the contaminated area D1

4. Cooling phase:

In order to capture the residual concentrations, present in the soil vapour, the SVE system remained in operation even after the heating elements were switched off. In addition, thermal energy was actively extracted from the soil body via the extracted soil vapour. Due to the cooling in the soil body, the concentrations continued to decrease continuously in accordance with the polluting potential, so that after falling below a target value of 10 mg/m³ PCE, the SVE plant was shut down on 18.01.2022 after a 3-month cooling phase.

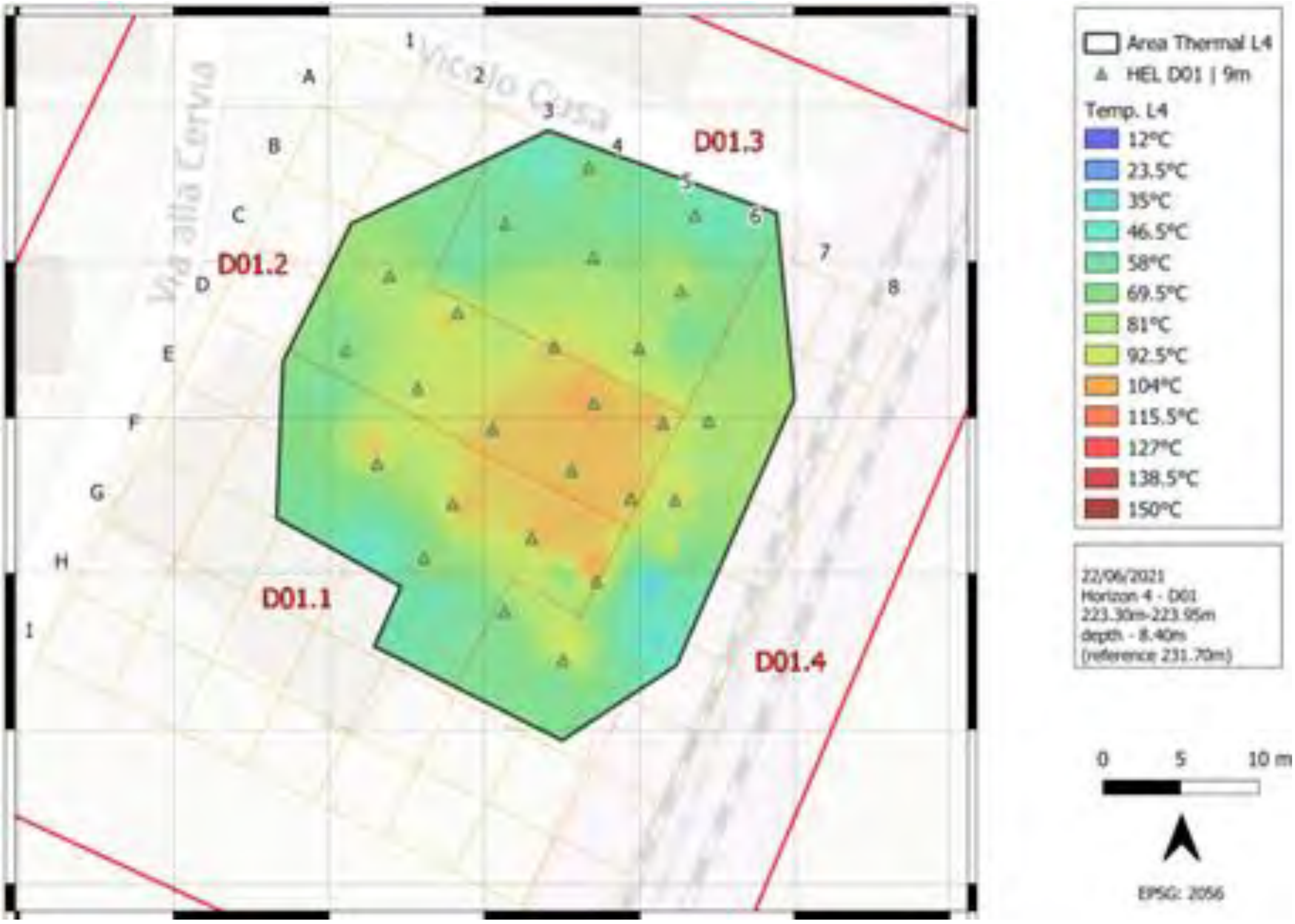


Fig.18 - 2-D sections of the temperature distribution, Level 4 in D1

Using the data from 67 temperature measuring lances, which in turn were equipped with 445 temperature sensors in 8 depth levels, it was possible to map the temperatures in the entire remediation area. The characteristic temperature curves of the extraction lines (gauge groups) are shown in Fig. 16 and Fig. 17. After a strong temperature increase in the first heat-up phase, a decrease of the temperatures is noticeable due to the described reduction of the heating power due to surface deformations. In the subsequent second heat-up phase, the temperatures increased more slowly and continuously until the cooling phase was initiated after the discharge phase was completed and the heating elements were switched off.

Using the data from the temperature sensors and interpolating the values in three-dimensional space, 2-D sections of the remediation-relevant depth layers were created for better illustration and assessment of the heat propagation (Fig. 18 and Fig. 19).

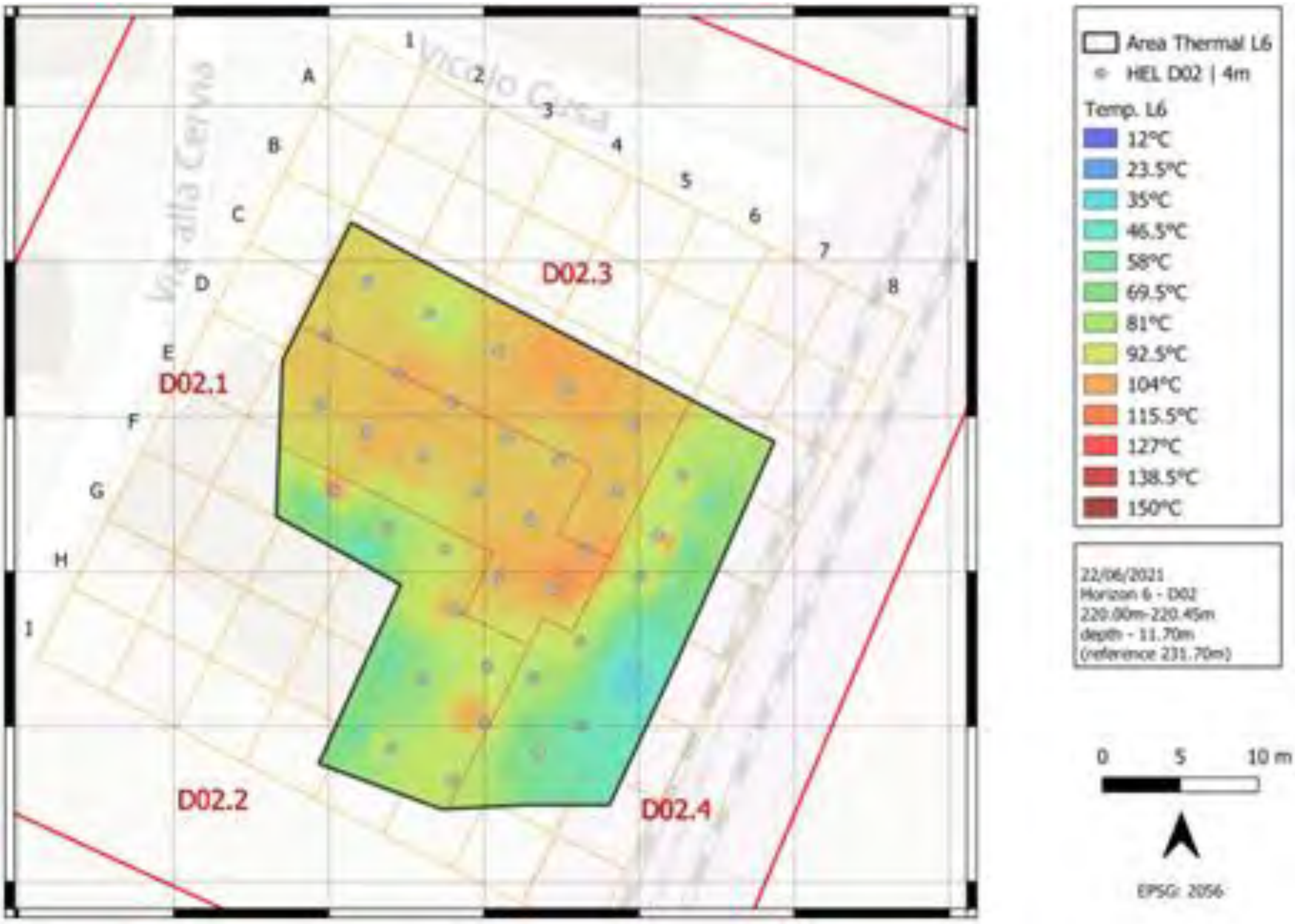


Fig.19 - 2-D sections of the temperature distribution, Level 6 in D2

The concentration curve of PCE (mg/m³) in the soil vapour and the curve of the average soil temperatures at the relevant depths are shown in Fig. 20. The highest contaminant discharge, with soil vapour concentrations exceeding 20 mg/m³, began when the average soil temperature exceeded 70 °C (with locally warmer zones exceeding 90 °C). Despite further increases in temperatures above 80 °C, soil vapour concentrations decreased rapidly in July 2021. Hence, despite increasing the areas with temperatures > 80 °C, no further contaminant sources could be reached. At the end of September 2021, it could therefore be assumed that the contaminant discharge had been completed. The heating elements were then shut down.

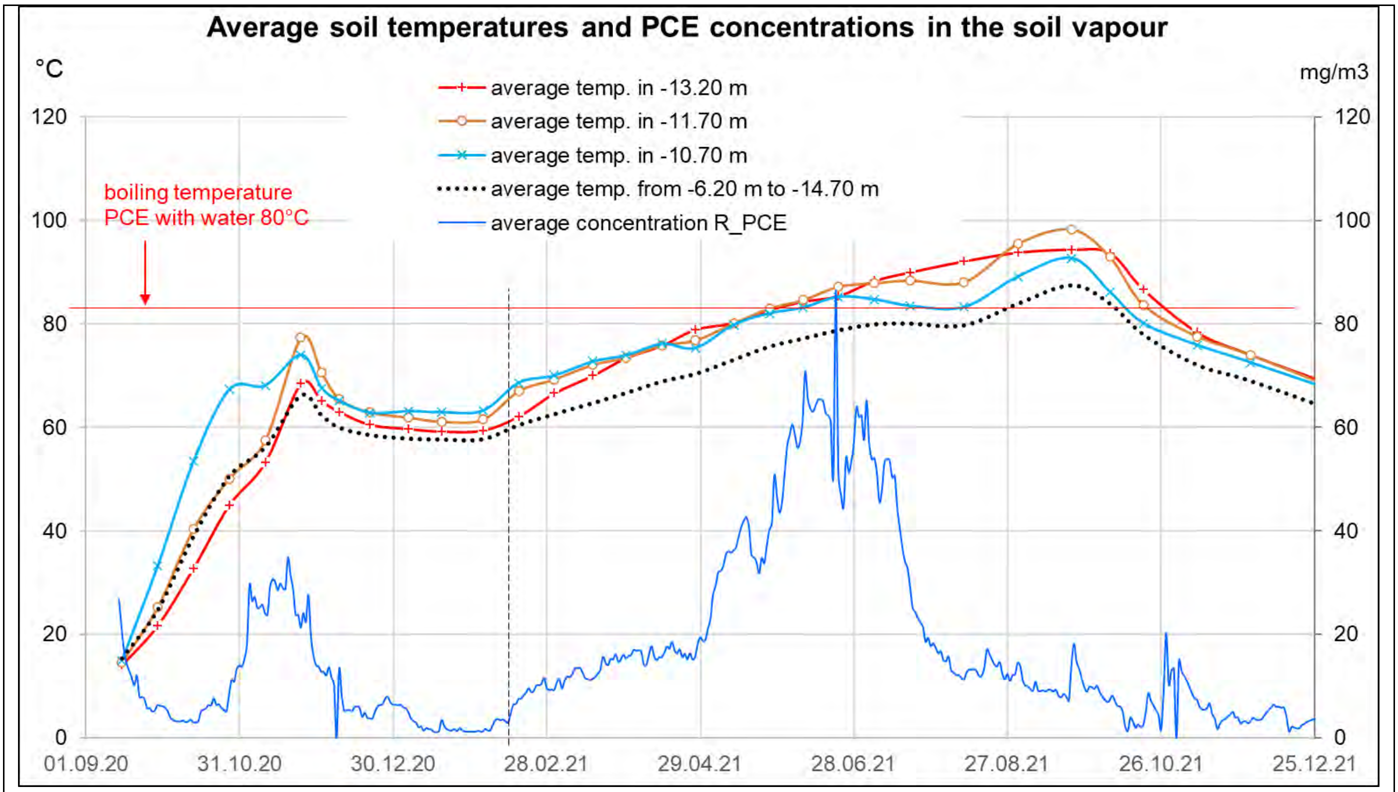


Fig. 20 - Concentration curve PCE (mg/m³) in the soil vapour with average soil temperatures

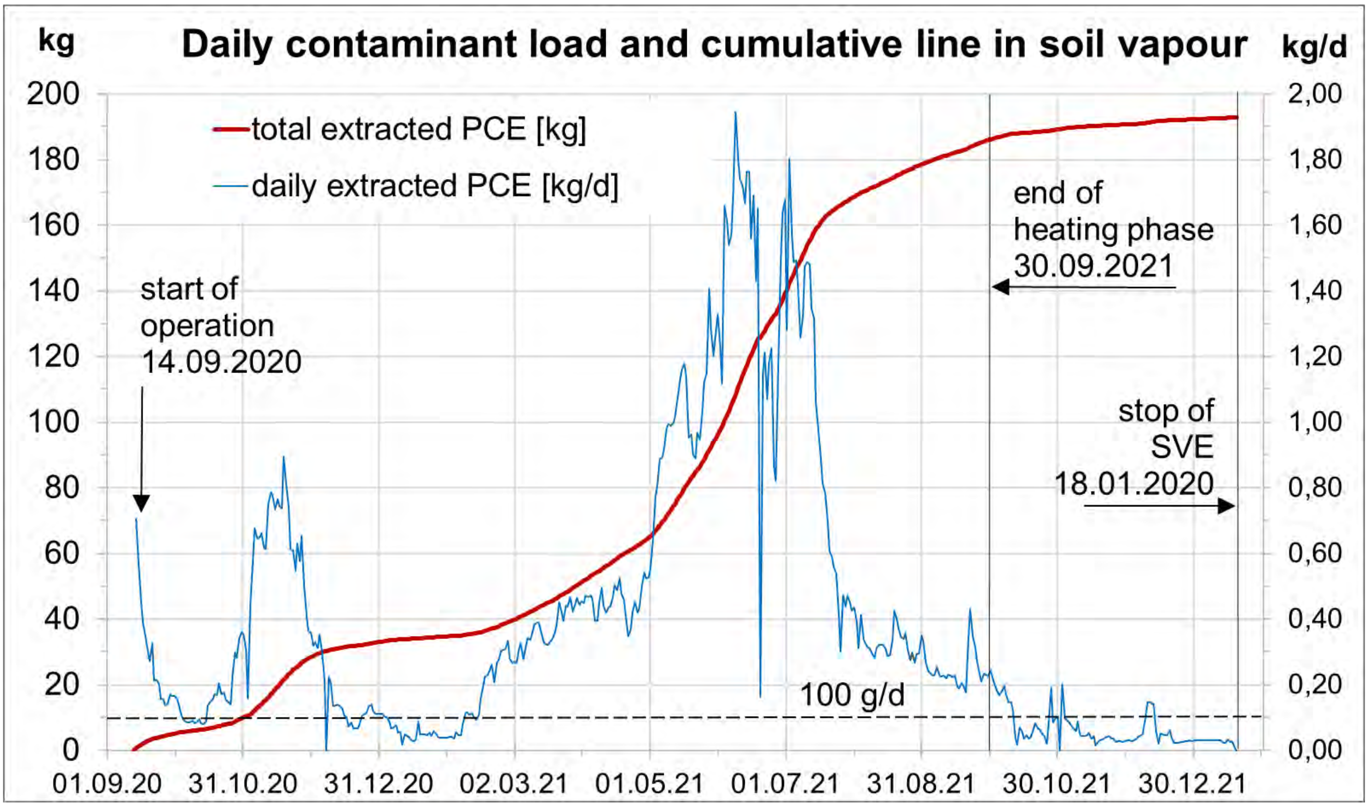


Fig. 21 - Daily contaminant load and cumulative line in soil vapour

The extraction via the soil vapour was continued during the cooling phase. It decreased steadily despite various operating conditions (continuous and interval operation). Because no relevant quantities of contaminants could be extracted via the soil vapour or had reached the lower measurement limit in the soil vapour, the extraction was shut down in January 2022. At this time, the average soil temperature fell again below 70 °C.

The daily number of contaminants extracted, and the cumulative line of contaminant discharge are shown in Fig. 21. In total, more than 190 kg of hvCHCs (represented as R_PCE) were removed.

6. Post treatment and/or Long Term Monitoring

6.1 Post treatment and/or Long Term Monitoring

During the cooling phase, even after the soil vapour extraction system was switched off, the downstream control continued to operate due to the contaminant concentrations measured in the groundwater.

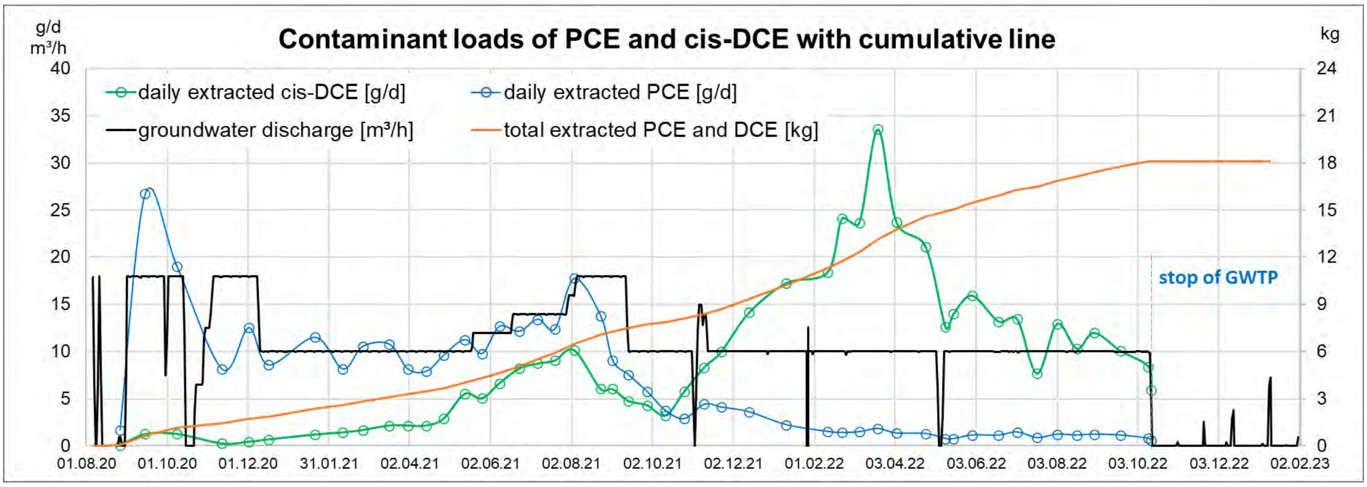


Fig. 22 - Contaminant loads and cumulative line in groundwater

The contaminant extraction via the downstream control is shown in Fig. 21. Due to the degradation of PCE in the soil, cDCE was measured in higher concentrations (up to 140 µg/l) from October 2021. As a result, the downstream control operation was extended until October 2022. In total, more than 18 kg of hvCHCs were removed from the groundwater.

In December 2022, more than a year after the heating elements were switched off and the ground temperatures were below 40 ºC, monitoring wells were drilled with sampling and analysis of the subsurface. The aim was to control the residual contamination still present in the soil. In general, most of the soil samples were below the analytical detection limit of 0.005 mg/kg dry matter. The upper subsoil zone down to a depth of around 11 m proved to be completely uncontaminated. In the deeper zones, layers with relevant loads were still measured; however, the concentrations decreased significantly by a factor of more than 10. These are the clay-rich horizons, which could not be fully reached by extracting the pore air.

In total, almost 210 kg of hvCHCs were removed via soil vapour and groundwater, primarily as PCE and TCE and cDCE as degradation and thermal decay products of ISTR.

Approximately 13 kg of hvCHCs remain in the subsurface today, mostly as TCE and cDCE, and little PCE. These are in the clay-rich strata and therefore in areas with hardly any flow. The thermal remediation was thus able to remove approx. 95% of the contaminants.

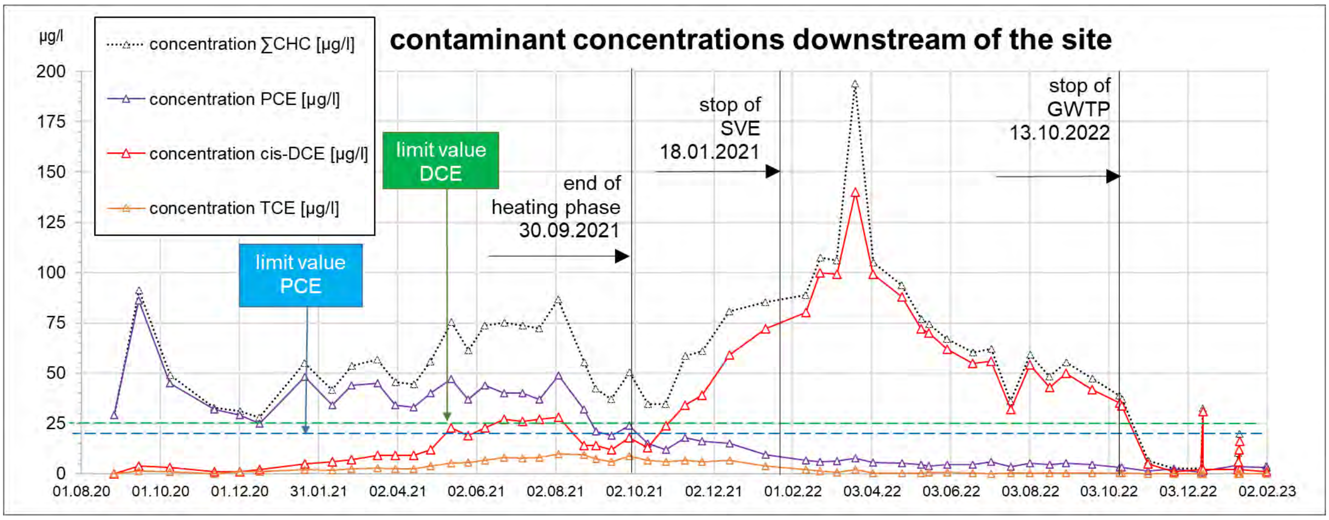


Fig. 23 - Results of longer-term groundwater monitoring downstream of the site

The longer-term results of groundwater monitoring are shown in Fig. 23. The PCE concentrations in the immediate downstream of the site were above the limit value of 20 µg/l for the entire duration of the heating phase. From October 2021, this limit value was initially undercut and then exceeded again locally for a short period (March-October 2022). Since November 2021, concentrations have continued to decrease steadily and are largely below the remediation limit.

From the end of the heating phase, cDCE concentrations in groundwater were high in some cases. These could be completely contained by the downstream control and did not spread further downstream. Since the potential of cDCE in the soil is limited, the concentrations decreased significantly and are now at safe levels. However, it can be assumed that some cDCE residues are still present, but these are only mobilised for a short time in exceptional situations.

Relevant TCE concentrations in groundwater were not detected at any time during the

thermal remediation. Vinyl chloride was not measured at any time.
It is planned to monitor the groundwater for another 2 years. In principle, the site is considered remediated under Swiss law. For the areas with proven residual contamination, restrictions on use are imposed from a depth of 11 m bgl to avoid perforation of the layers that are still contaminated.

7. Additional information

7.1 Lesson learnt

In general, to understand and adequately manage the various processes of a thermal remediation, extensive monitoring is necessary. Not only the operationally relevant parameters but also the environmental parameters such as soil displacements, subsoil temperatures and groundwater concentrations must be intensively measured and continuously evaluated.
Despite good exploration of the site in advance, there are always surprises. In this case, the high water saturation of the fine-grained subsoil above the groundwater table was higher than assumed (leachate but also rising capillary water from the underlying aquifer). In addition to the greater heating capacity required to extract the hvCHCs, the drainage of the water and drying of the soil was responsible for soil settlements in the remediation and the adjacent areas. The ground settlements could be limited to an acceptable range with a series of measures. Above all, intensive monitoring (online measuring system) made it possible to reliably always assess the resulting risk. The extent of the settlement processes is very difficult to estimate in advance. Depending on location and subsoil, it is therefore necessary to gradually increase the control temperatures and closely monitor the deformations when starting up the thermal system and heating up the soil.
The accumulation of water from the soil vapour also posed a great challenge for the plant technology. As the soil vapour temperatures increase, the amount of condensate in the pre-separation, and especially in the air coolers increases. Insufficient drainage of the water can lead to the extraction system being switched off. Since plant availability is of great importance for capturing the contaminants, sufficient reserve for the collection and discharge of the condensate must be considered when planning the plant technology.
In an advanced phase of thermal remediation, a transformation of the initial contaminant PCE to the direct degradation products TCE and cDCE occurred [2]. The degradation is incomplete and was probably favoured due to the high temperatures and the presence of higher levels of organic material in the subsoil. A strongly reducing

environment with sulphide and methane production developed. The degradation therefore took place by chemical and not bacterial means. Due to the higher solubility (cDCE is about 40 times more soluble than PCE), there was an increased risk to the groundwater, which could, however, be attenuated by the sufficiently dimensioned downstream control.

Finally, it was demonstrated that even in fine-grained, dense subsoil (sand, silt), thermal remediation can lead to a complete removal of the contaminants. Soil vapour extraction and collection of the substance from clay-rich subsoil is difficult, especially if the subsoil cannot be completely drained (capillary water). On the other hand, the mobility of the contaminants in these horizons is also significantly lower and the hazard is therefore low, despite the residual pollution.

7.2 Additional information

In-situ thermal remediation methods (ISTR) are particularly suitable for the remediation of contamination sources in the unsaturated soil zone and in the groundwater fluctuation zone, under certain conditions also in the water-saturated zone. Depending on the type of contaminant and the subsoil, the input of thermal energy into the subsoil is carried out by injecting water steam or by fixed heat sources operated electrically or with fuels.

The two main advantages of the ISTR method compared to conventional remediation methods are, on the one hand, the greatly reduced remediation time and, on the other hand, the high cleaning performance, especially in low-permeability subsoil. With the help of in-situ thermal remediation, very low residual concentrations can be achieved, which are not possible with other in-situ remediation methods.

Based on our extensive experience from numerous projects with in-situ thermal remediation (ISTR) [3], pilot studies are usually not required, unless the subsurface has a complex structure. However, to predict the feasibility and success of the remediation measure, a careful detailed geological and hydrogeological investigation of the site is indispensable.

7.3 Training need

The application of the ISTR tool, as well as the assessment of the results, requires experience and should be trained, for example, in workshops. To continuously improve the application, it is also important to compare the underlying results with the actual situation after the project has been completed.

7.4 Additional remarks

[1] Fachtagung ChloroNet praktisch (Amt für Abfall, Wasser, Energie und Luft des Kantons Zürich AWEL), Zürich 24.05.2022, „Ex-lavanderia Caviezel Bellinzona: eine komplexe thermische In-situ-Sanierung“, Matthias Damo (SBB), Antonio Greco (CSD)

[2] UFZ Helmholtz Centre for Environmental Research (2013) Guidelines In situ thermal treatment (ISTT) for source zone remediation of soil and groundwater

[3] In-situ Technologies (2023), Brochure, Züblin Umwelttechnik GmbH

Glossary of Terms

Term (alphabetical order)	**Definition**
asl	above sea level
bgl	below ground level
cDCE	cis-1,2-Dichloroethylene
DELCD	Dry Electrolytic Conductivity Detector
GWTP	Groundwater treatment plant
HEL	Electric heating element
hvCHCs	highly volatile chlorinated hydrocarbons
ISTR	In-situ thermal remediation
MIP	Membrane interphase probe
PCE	Tetrachloroethylene, Perchloroethylene
PER	see PCE
PID	*Photoionization detector*
P&T	Pump and treat
TCE	Tetrachloroethylene
SBB	Swiss Federal Railways
SVE	Soil vapour extraction
TML	Temperature measuring lance
VC	Vinyl chloride

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.8

1.1. Name and Surname*	1) Thomas Meyer 2) Hans-Georg Edel
1.2. Country/Jurisdiction	Germany
1.3. Organisation	ZÜBLIN Umwelttechnik GmbH Maulbronner Weg 32 D-71706 Markgröningen
1.4. Position	1) Senior Engineer, Manager International 2) Head of R&D
1.5. Duties	1) Development and supervision of international remediation projects, specialist for ISTR remediation with gas-fired burners and electrical heating elements 2) Head of R&D, Consultant remediation, Lecturer, Author of several publications
1.6. Email address	1) thomas.meyer@zueblin.de 2) hans-georg.edel@zueblin.de
1.7. Phone number	1) +49 160 94143260 2) +49 7145 9324-249

2. Site background

2.1 History of the site

The Shougang steel factory, the centre of that precarious "black shift," was in the far west of Beijing on the Fifth Ring Road. Founded in 1919 under the name Capital Steel Group and then called Shougang Group, the Beijing site employed 100,000 people during the best of times, producing up to 10 million tons of steel per year. When business was booming, around a quarter of Beijing's tax revenue came from the Shougang Group. However, everything has its price: contemporary witnesses report how catastrophic the environmental conditions in and around the production site, which covers around 22 square kilometres, once were. People could often barely see their hands in front of their own eyes. Shougang, that was the epitome of Beijing's environmental problems.

Figure 1 - Status of Shougang coking plant before remediation

The coking plant has 1896 sets of equipment with a total installed capacity of 30,000 kW, 5 modern coke ovens and supporting coal preparation system, gas purification system and quality inspection system. The annual output of coke was more than 1.9 million t, the daily output of coke oven gas is 2.1 million m3, the annual processing capacity of light benzene and tar was 25,000 t and 75,000 t respectively, and more than 20 kinds of chemical products such as benzene, naphthalene, phenol, asphalt, and ammonium sulphide could be produced.

In February 2005, the Chinese National Development and Reform Commission issued document 273, "Approval of Shougang's Relocation, Structural Adjustment and Environmental Remediation Plan," which required Shougang to reduce its steel production capacity in phases, cease all smelting and hot rolling production by the end of 2010, and retain only Shougang's headquarters and research and development system, as well as businesses that do not cause environmental pollution.

Only Shougang's headquarters and R&D system, as well as its sales, logistics, and third industry businesses that do not cause environmental pollution, will be retained. At the same time, according to the urban layout determined by the Beijing Urban Master Plan (2004-2020), the development principle of the area where the Shougang plant is located is "to guide the concentration of eco-friendly industries such as high-tech R&D and services, tourism and leisure, commercial logistics, education, etc., to optimize, integrate and im-prove the existing development space, and to prevent high-density construction”.

This former site of the Chinese state-owned steel company Shougang in Beijing was prepared to host several events of the Winter Olympics in 2022. Before work could begin on the sports facilities, remediation was necessary of the subsoils around the former steelworks’ old coking plant. The main pollutants on the site were BTEX aromatics, polycyclic aromatic hydrocarbons (PAHs) and coking-specific compounds in very high concentrations.

Figure 2 - Geographical position of coking area inside the former steel factory

The coking area is in the Shijingshan District in the western suburbs of Beijing. Shougang coking plant remediation area mainly includes the coke operating area in the coke oven unit and the chemical area of the recycling unit. Irregular rectangle, about length of 827 m, width of 150 m, with a total area of about 104,000 m^2.

In Fig. 3 and 4 the landscape air view of the planned ecological restoration park project design can be seen.

Figure 3 - Project design of ecological restoration park

Figure 4 - Third stage of ecological restoration park

The remediation program for Shougang coking plant area is prepared based on the results of the environmental investigation and risk assessment, with reference to advanced remediation technologies in developed countries, to prevent land pollution on the environment and the adverse impact of society.

2.2 Geological setting

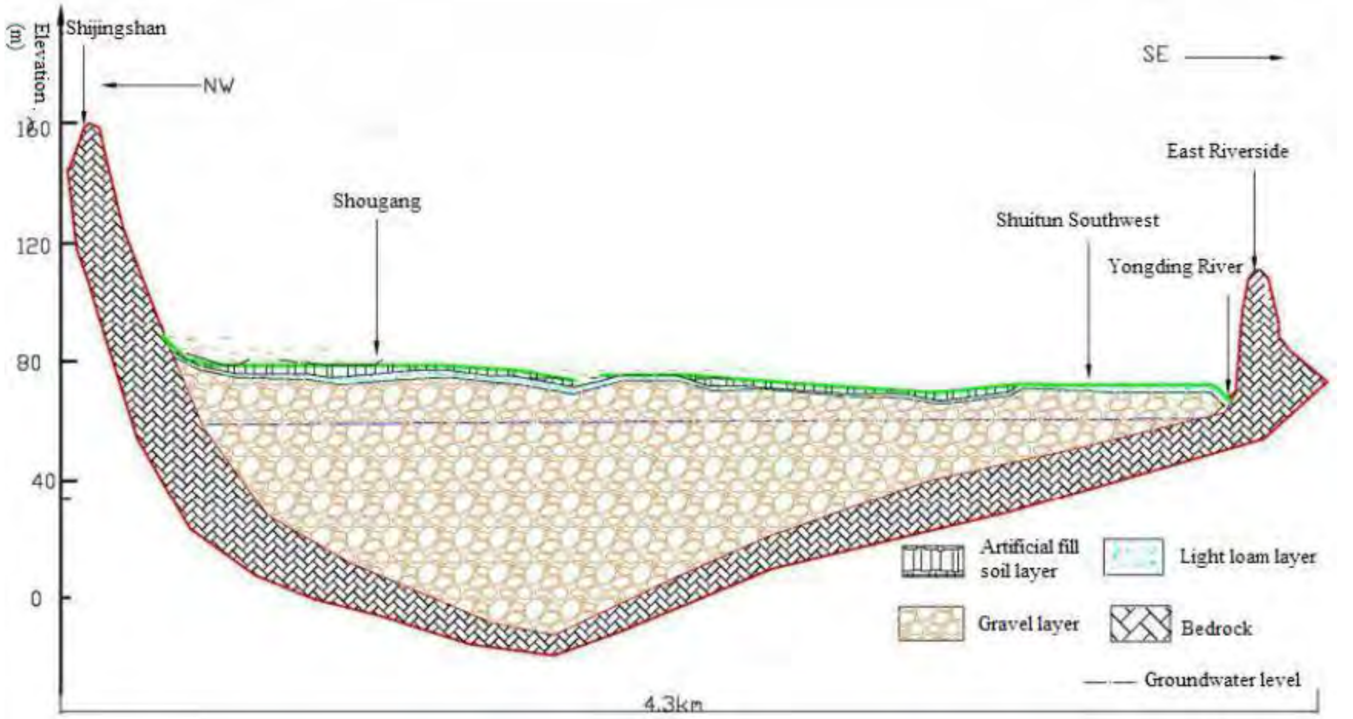


Figure 5 - Vertical distribution of layer lithology in Shougang area

Shougang area is west of the Beijing urban region, stratigraphy is relatively simple, mainly composed of single sand and gravel. Due to long-term construction in Shougang areas, its surface formation lithology has changed, currently roughly divided into four soil layers: (1) artificial fill soil layer, (2) light loam layer, (3) gravel layer, (4) sand formations layers. An overview of the Shougang entire area, the vertical distribution of formation lithology is shown in Fig. 5.

(1) Artificial fill soil layer: more complex components, composed by the ashes, brick blocks, slag, slag, gravel, and clay. Gray mottled, slightly wet to wet, loose. This layer is not level ruled, the thickness of each position in the factory is not the same, ranging from 0.5 to ~2.0 m.

(2) Light mild clay layer: Alluvial formation containing a small amount of small gravel, yellow ~ brown, yellow. Slightly wet to wet, plastic to hard plastic. Thickness is about 1.0 m.

(3) Gravel layer: The distribution of the layer is stable. Components of pebbles is quartzite, diabase, and other hard rock. Size of pebbles is 20 to 80 mm, the maximum is more than 100 mm, the contents is more than 60%, roundness is preferably, mostly sub round. This layer is mottled, slightly wet, dense, by sand filling. The stratigraphy is groundwater aquifers, in diving area at the top of the alluvial fan, sand and gravel exposed on the surface, directly receives surface water supplement, the average thickness of the stratigraphy is 40 m, the groundwater depth is about 20 m.

(4) Sand formation layers: Local top surface has a thin layer of highly weathered material, earthy, usually moderate weathering, massive, yellow green.

Groundwater conditions

There are two levels of the Quaternary aquifer in the project location and surrounding area, which are shallow and deep groundwater. The shallow groundwater is submerged, and the water table depth is high in the west and low in the east. The main source of groundwater recharge is underground runoff and surface rainfall, and the direction of regional groundwater runoff is from west and northwest to east and southeast. According to the information in 1996, the water level in Zone II is about 7.5 m and that in Zone III is about 30 m below ground level.

According to the geological data of Shougang Company and the data of nearby wells, the highest underground water level in Area III of the project site in the past 50 years was about 10 m below the surface. The investigation data in recent years shows that the current depth of groundwater in this layer is already about 55-60 m.

The single layer thickness of water-bearing layer is large, the lithology is mainly gravel and pebbles, the accumulated thickness is about 30 m, the permeability coefficient is $5*10^{-4}$ m/s, which is the main mining layer of the former industrial and agricultural wells.

The precipitation in the region is extremely uneven between the months of the year, with June to September accounting for more than 80% of the annual precipitation, and precipitation is mostly concentrated in late July to early August each year, with January to May accounting for only about 10% of the annual precipitation, and from October to February generally accounting for only about 6% of the annual precipitation, with a multi-year average precipitation of about 600 mm.

2.3 Contaminants of concern

The main pollutants on the site are BTEX aromatics, polycyclic aromatic hydrocarbons (PAHs) and coking-specific compounds in very high concentrations.

Extensive investigation works in the coking plant area were realized. As an example, see the vertical distribution of Benzene in soil gas during detailed sampling in Fig. 6.

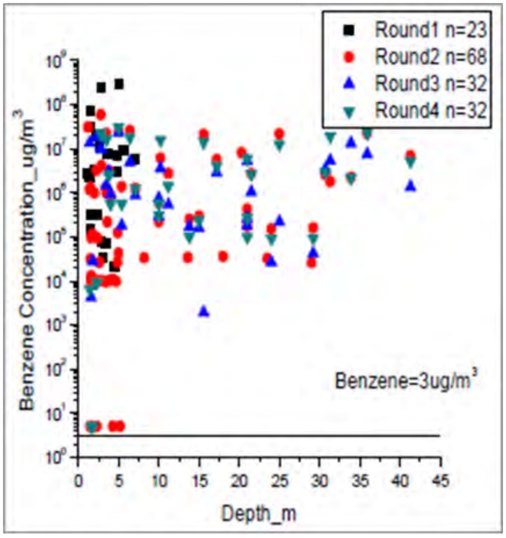


Figure 6 - Vertical distribution of Benzene in coking area in soil gas

Figure 7 - Soil sample with high concentration of PAH

2.4 Regulatory framework

Final remediation target values, based on risk assessment

According to the land use function, for the remediation of coking plant area are used target value of soil and soil gas by "park green" scenario.

In accordance with the finalized remediation target values for the pollutants of concern, the exceedance areas for PAHs, benzene, and naphthalene below 1-5 m of the site and the corresponding exceedance soil volumes were determined. For the contaminated area below 5 m, the determined soil gas remediation target will be used as the standard, combined with the soil gas test results, to determine the area of the site below 5 m where the health risk of VOCs respiratory exposure pathway, and its area should be controlled. The target values are shown in Tab. 1.

Contaminants	**Depth**	**Park green land**
benzene	0-1m	51.6
	1-5m	51.6
	>5m	3.61E+04
Toluene	>5m	3.29E+07
Ethylbenzene	>5m	5.44E+04
Xylene	>5m	7.74E+05
1,2,4-trimethylbenzene	>5m	1.84E+04
1,3,5-trimethylbenzene	>5m	5.33E+04
Naphthalene	0-1m	168
	1-5m	168
Benzo (a) anthracene	0-1m	15
Benzo (b) fluoranthene	0-1m	15
Benzo (k) fluoranthene	0-1m	150
Benzo (a) pyrene	0-1m	1.5
Indene (1,2,3, -cd) pyrene	0-1m	15
Dibenzo (a, h) anthracene	0-1m	1.5
Pb	0-1m	400

Table 1 - Final remediation target values [mg/kg]

3. Pilot-scale

3.1 Laboratory Study

To verify the efficiency of the selected remediation process ISTR (In Situ Thermal Remediation), a pilot project was designed and realised [1]. The ISTR pilot project began in September 2017 and lasted 6 months until its completion and presentation of the results in February 2018, with continuous supervision of our experts on-site.

Figure 7 - Area for ISTR pilot scale project

During this period, a total area of 100 m² in the highly contaminated regions of the site at depths of up to 9 m below the surface was cleaned. For the full and complete desorption of the contaminants, the soil in this area is heated to temperatures above 270°C.

As the ground is being heated, the contaminants transfer into the soil vapour, which can then be extracted and remixed with the feed air in the gas burners. The burner exhaust gases are collected, monitored, and removed through a chimney. To avoid any emissions, hot soil vapour was extracted from the subsoil and treated by a combined system of quencher/washer and GAC-filters. Several temperature sensors installed in different depths continually monitored the temperature development and heat dispersion in the subsoil. In Fig. 7, the gas-fired burners and the gas treatment plant can be seen.

The ISTR treatment system consists of:

- 33 heating elements, heated with gas-fired burners, using natural gas
- Multiple temperature monitoring sensors, installed in different depths
- Soil vapour extraction wells
- SVE system to extract hot vapours
- Treatment system for the extracted gases

The target temperature to destroy PAH – with Benzo(a)pyrene as focus – was determined with >270°C. The development of the temperature in the field is shown in Figure 8. In the most parts, this temperature was achieved and even exceed, to a maximum of 455°C, after approximately 7 weeks.

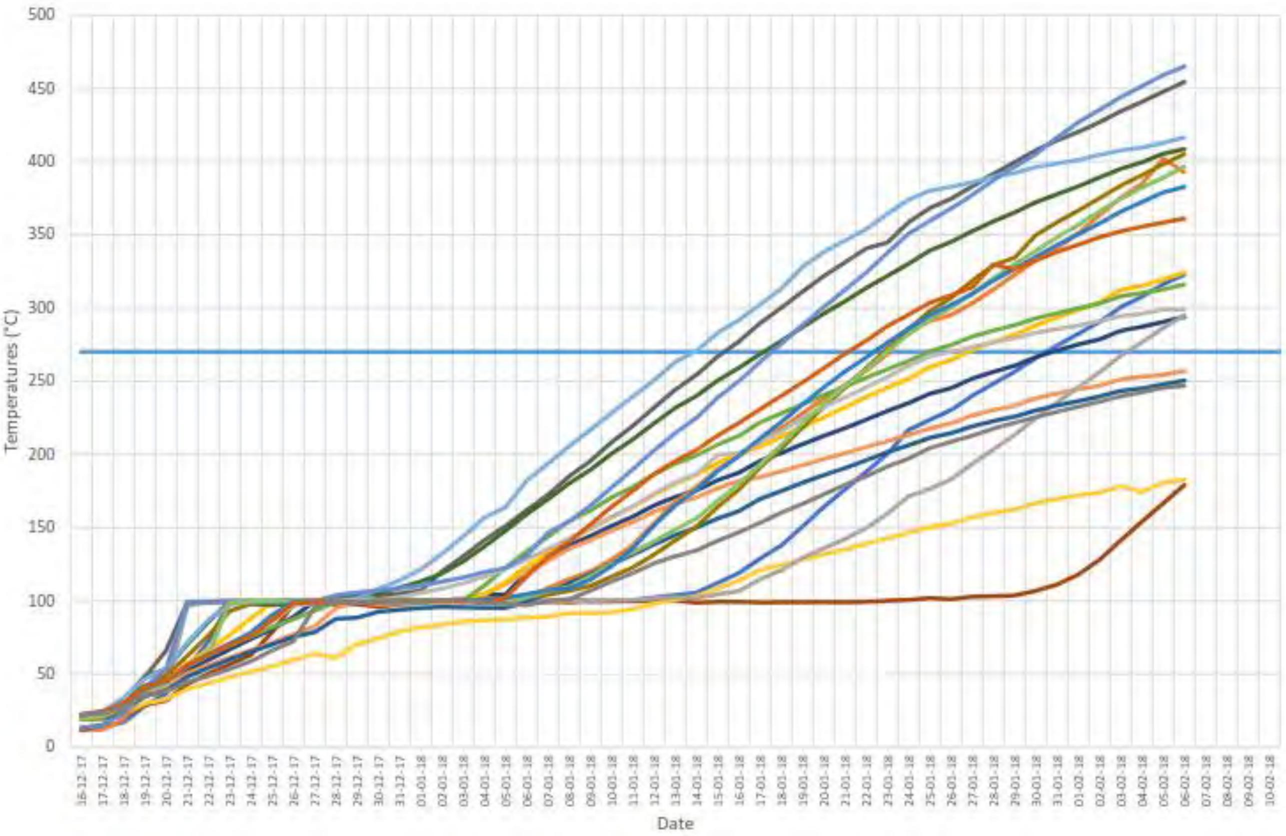


Figure 8 - Temperature development during ISTR pilot scale project

4. Full-scale application

4.1 Main treatment unit

Remediation technology for the full-scale application in Beijing

The operating principle of in-situ thermal remediation (ISTR) is based on introducing thermal energy into the subsoil. This mobilizes the contaminants present there by increasing their volatility and water solubility and reducing their viscosity and surface tension. The mobilized pollutants can then be captured by suitable methods, e.g., in gaseous form, and cleaned off. The energy input for the mobilization can be done by different technologies.

The method suitable for the site is based on the use of gas-fired heating elements (HE) as fixed heat sources, that in this case are operated with the exhaust gas of burners using natural gas, whereby convection and conduction are the decisive processes of the heat input/transport. These heating elements are installed in the soil via soil borings, see Fig. 9. The length of the heating elements, as well as the necessary suspension depth are variable and are designed according to the pollutant location in the soil.

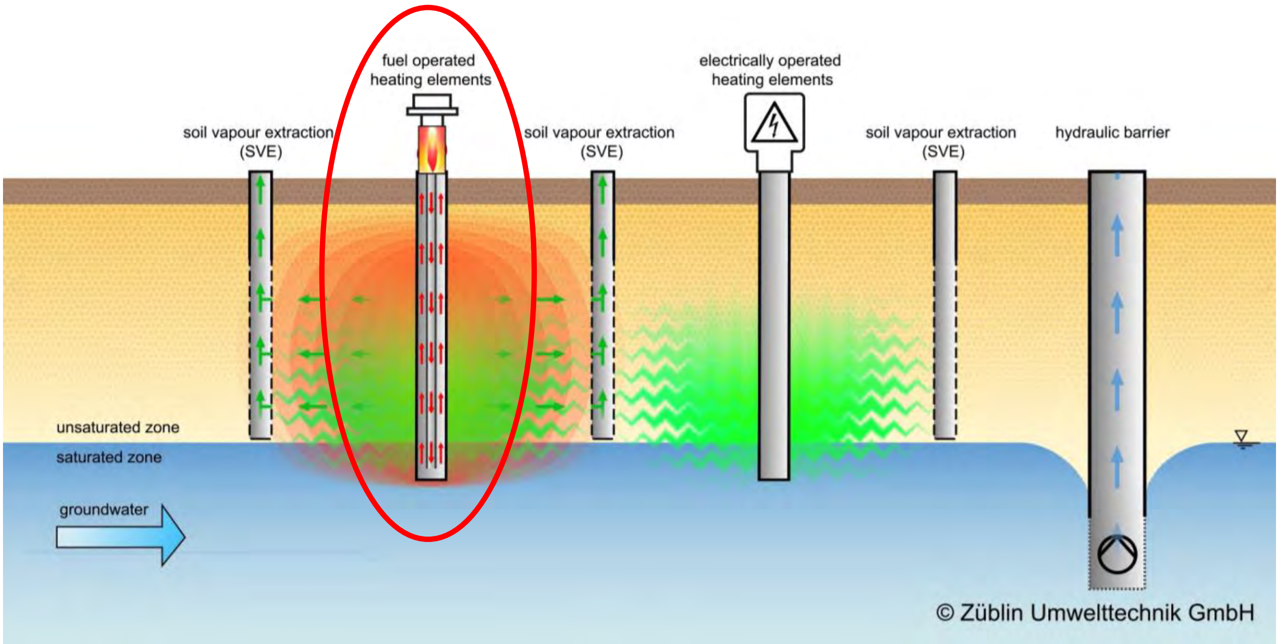


Figure 9 - In-situ thermal remediation (ISTR) using fuel operated heating elements, principal diagram

The heat fronts that form due to the continuous heat input spread radially symmetrically around the heating elements, vaporising the pollutants. In this process, the pollutant PAH (in particular Benzo(a)pyrene) requires for its destruction a temperature of >270 °C. Due to the transition of other contaminants to the gaseous phase, the pollutants can subsequently be extracted via the soil air of the unsaturated zone.

Soil air extraction wells are distributed over the remediation field to cover the entire polluted areas. The required number as well as the filtering of the gauges depends on the soil properties, the resulting ranges, and the location of the damage areas. The soil air extracted with a specific system, adapted to the high gas temperature, must then be cleaned by different methods.

For regulation and control of the heating elements, as well as for temperature monitoring of the total area, so-called temperature measuring lances TML are required at different radial distances to the HE.

Large scale ISTR remediation

The large-scale ISTR intervention began in April 2018 and lasted 10 months until its completion by 31st of January 2019, with continuous supervision of our experts on-site.

During this period, a total area of about 15,000 m² in the highly contaminated regions of the site at depths of up to 5.5 m below the surface was cleaned with seven batches, operated consecutive and partially parallelly. For the full and complete desorption of the contaminants, the soil in this area is heated to temperatures above 270°C.

The ISTR treatment system consists of:

- 750 burners, fired with natural gas
- 1,500 fixed heating elements
- Multiple temperature monitoring sensors, installed in different depths
- Soil vapour extraction wells
- Several SVE system to extract hot vapours
- Several treatment systems for the extracted gases, mainly by incineration using flares with support of backing gas

During the operation time, about 4.5 million m³ natural gas were used to remediate the seven sectors, fired in the burners of the heating elements and the flares.

Based on the remediation plan, the coking area was divided in several sectors, to be remediated with two different methods:

1) In situ thermal treatment
2) In-situ barrier landfill (covering with clean soil)

In Fig. 10 is shown the coking area with the different sectors. As well, the seven sectors which were treated by Züblin Umwelttechnik GmbH applying the ISTR technology, are indicated.

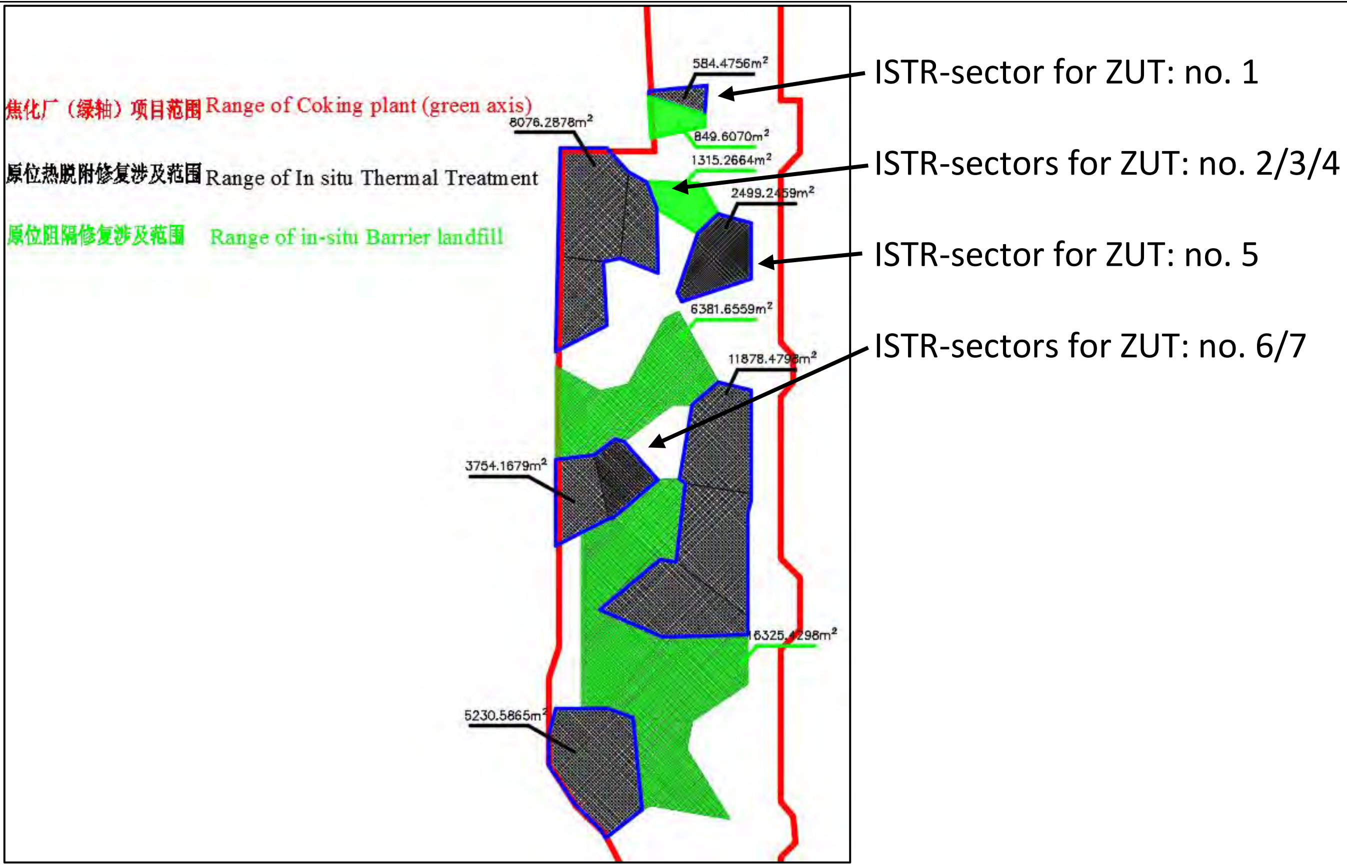


Fig. 10 - Coking area with sectors to be remediated with ISTR

Description of the plants for the extraction & treatment of hot soil vapours

For the design of plants used for the extraction and treatment of vapours, generated during the in-situ thermal remediation with high temperatures ~270°C, the following basic conditions had to be considered:

- The capacity to extract vapours must be designed based on the permeability of the soil
- The water (humidity) in the hot steam will condensate (at least partially) after having left the SVE-wells on the way to the treatment plant
- The capacity to separate and to treat contaminants transported with the vapours had to be designed for the specific case, considering chemical-physical parameters:
  - concentration of contaminants in water and in vapour
  - solubility in water in function of temperature
  - melting point
- As suitable process to treat the extracted vapours were determined:
  - Separation with low temperature (air cooling, quencher),
  or, with higher temperature:
  - Treatment with activated carbon in case of low concentrations, or

- Treatment with catalytic oxidation, or
- Combustion in case of high concentrations with a flare stack (torch)

With this design of the ISTR remediation process can be handled efficiently, even with very high concentrations of the organic contaminants – TPH, beside the coking plant typical PAH.

In the following Fig. 11-13 are shown the treatment plants.

Figure 11 – 12 – 13 - Treatment plants (flare stack, SVE-plants)

Fig. 14 and 15 show ISTR areas with gas-fired burners and treatment plants.

Fig.

Figure 14 - Heating elements and treatment plants in ISTR-area 4

Fig. 15 - Heating elements and treatment plants in ISTR-area 5

5. Results

5.1 Removal rate

For the verification of the efficiency of the in-situ thermal treatment, this process was first applied in pilot scale (see chapter 3.2), on a very high contaminated area of 100 m². In Fig. 16 can be seen this pilot test area and the sampling points (SP).

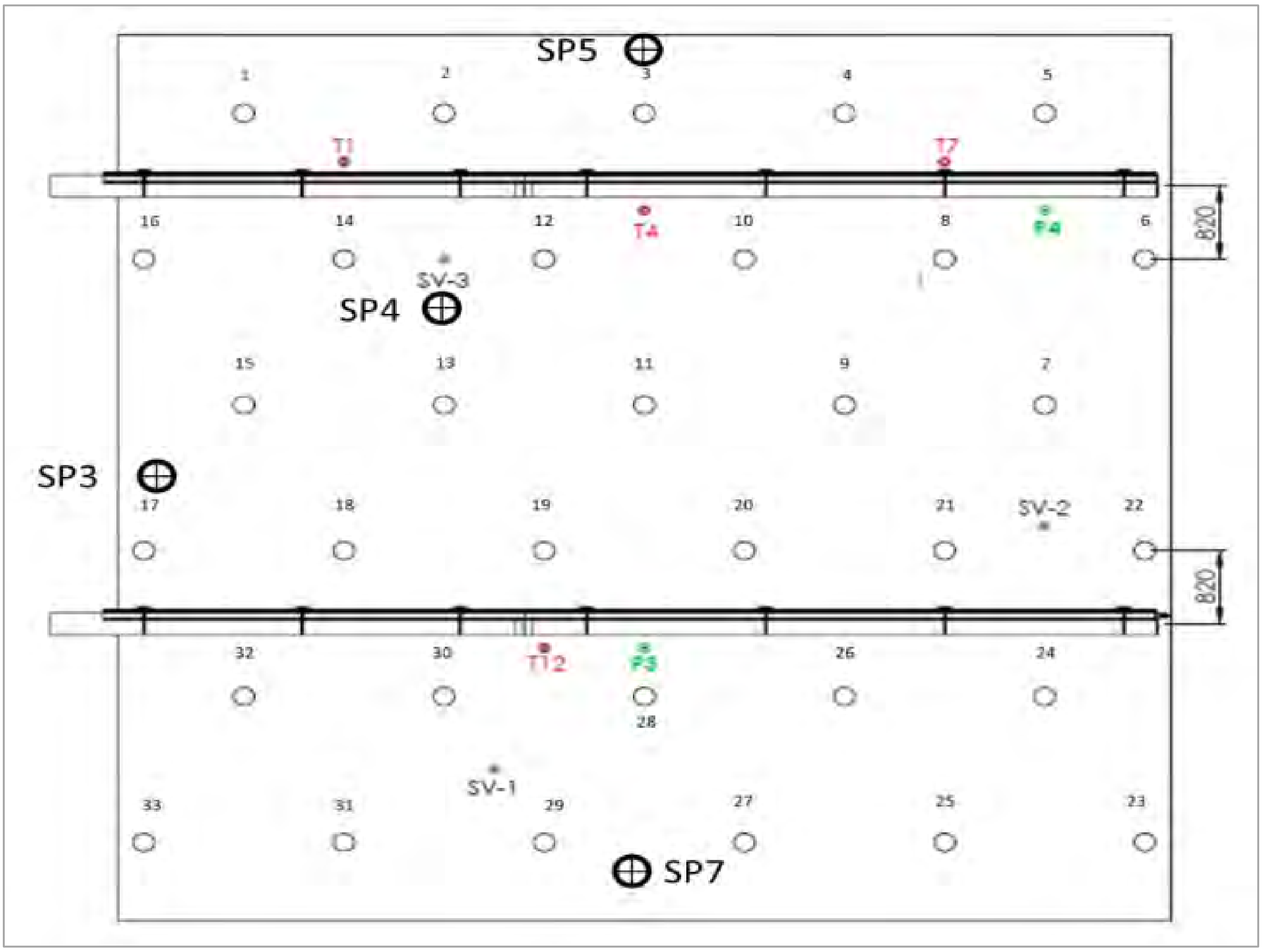


Figure 16 - Area for ISTR-application in pilot scale

Before the thermal treatment, the different contaminants in this area have been detected in this concentration range (Figures 17 a/b):

- PAH: from 7,000 – 10,000 mg/kg DS
- TPH: from 4,000 – 23,000 mg/kg DS
- BTEX: from 20 – 200 mg/kg DS

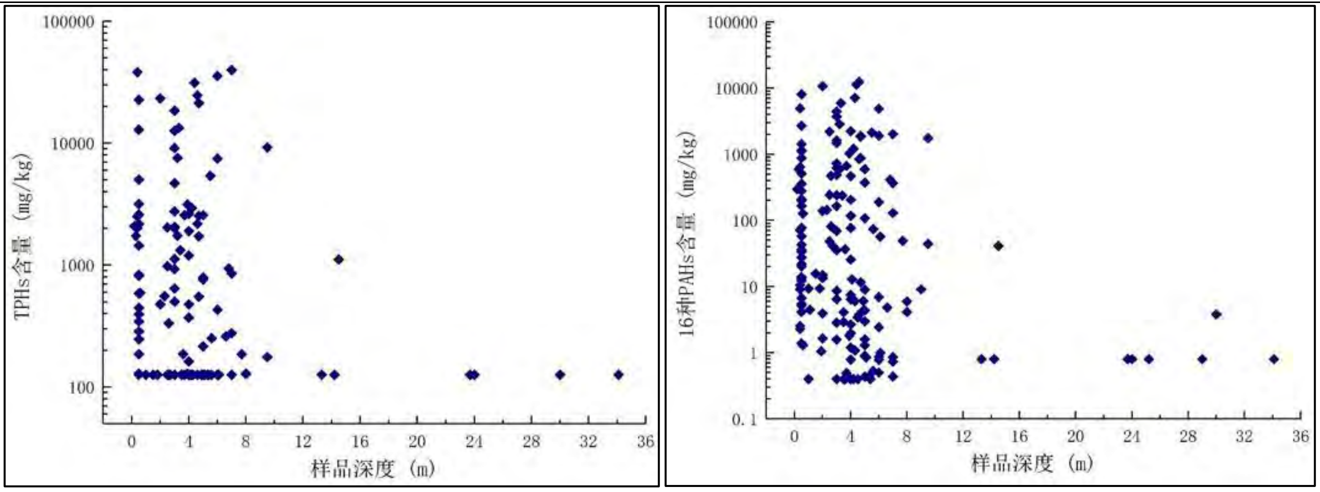


Fig. 17 a/b - left: TPH concentration, right: PAH concentration

The ISTR pilot scale operation has started 15th of December 2017. The development of the temperature in the subsoil was documented continuously, here are two milestones:

- Status 10.01.2018, at 26 days operation of the ISTR system:
  - maximum temperature: 228°C
  - average temperature: 144°C
  - minimum temperature: 92°C
- Status at 06.02.2018, at 52 days operation of the ISTR system)
  - maximum temperature: 465°C
  - average temperature: 333°C

To verify the reduction of the contaminant concentration, sampling was done once more in the still hot soil. In Tab. 2 are shown the results:

	苯	多环芳烃	苯并（a）芘	
样品名称Sample Name	Benzene		Benzo(a)pyrene	**Σ TPH**
	mg/kg	**Σ PAH**	mg/kg	mg/kg
	0,01		0,02	
SP4 0.5m	<0.01	**1,9**	0,174	**8**
SP4 1.0m	<0.01	**0,2**	<0.02	**0**
SP4 2.0m	0,02	**0,5**	<0.02	**6**
SP4 3.0m	<0.01	**1,0**	<0.02	**0**
SP4 4.0m	0,06	**0,1**	<0.02	**6**
SP4 4.5m	0,01	**0,0**	<0.02	**0**

Table 2 - Analytical results of ISTR application in pilot scale

The achieved efficiency for the contaminants:

- ∑ PAH: < 2.0 mg/kg DS → removal efficiency > 99.97 %
- Benzo(a)pyrene: < 1.5 mg/kg DS → removal efficiency > 99.90 %
- TPH: < 8.0 mg/kg DS → removal efficiency > 99.99 %
- Benzene: after remediation, not detectable

Based on these very good results, it was decided to apply this ISTR technology for the full-scale remediation.

7. Additional information

7.1 Lesson learnt

In general, to understand and adequately control the various processes of thermal remediation, extensive monitoring is necessary. Not only the operationally relevant parameters but also the environmental parameters such as soil displacements, subsoil temperatures and possible water intrusions must be intensively measured and continuously evaluated.

Fig. 18 - Drilling works during night shift

Despite good investigation of the site in advance, there are always surprises. In this case, the high saturation of viscose tar in the fine-grained subsoil was higher than expected.

During extraction of hot soil vapour, highly loaded with different hydrocarbons, even the incineration with a torch came to a limit, so that only dilution was helpful to manage these peaks.

What we learned from this remediation project in China:
Time schedules, which in Europe or in Germany seems to be realistic, are considered as much too long in China. To meet short and very ambitious time frames, in China the works will be done with a large personnel and machine effort and, if necessary, during day and night (Fig. 18).

7.2 Additional information

In-situ thermal methods (ISTR) are particularly suitable for the remediation of contaminated sites in the unsaturated soil zone and in the groundwater fluctuation zone, under certain conditions also in the water-saturated zone. Depending on the type of contaminant and the subsurface, thermal energy is introduced into the subsurface by injecting water vapour or by solid heat sources that are electrically, or fuel operated [2].

The two main advantages of the ISTR process over conventional remediation methods are, firstly, the greatly reduced remediation time and, secondly, the high cleaning performance, especially in low-permeability subsoil. With the help of in-situ thermal remediation, very low residual concentrations can be achieved, which are not possible with other in-situ remediation methods.

Based on our extensive experience from numerous projects using in-situ thermal remediation (ISTR), pilot studies are usually not required unless the subsurface has a complex structure. However, to predict the feasibility and success of the remediation measure, a careful detailed geological and hydrogeological investigation of the site is essential.

7.3 Training need

ZÜBLIN Umwelttechnik GmbH has a digital ISTR tool, to predict the duration and the estimated energy consumption of this type of in-situ thermal remediations.
The application of the ISTR tool, as well as the assessment of the results, requires experience and should be trained, for example, in workshops. For continuous improvement of the application, it is also important to compare the underlying results with the actual situation after project completion.

7.4 Additional remarks

[1] MEYER T, KLEFFEL G und EDEL, H-G (2019) In-Situ thermische Sanierung (ISTH) des ehemaligen Stahlwerk-Standorts von Shougang in Peking, 21. Symposium Strategien zur Boden- und Grundwassersanierung, DECHEMA, 25.-26. November 2019 in Frankfurt a.M.
[2] In-situ Technologies (2023) Brochure, Züblin Umwelttechnik GmbH

Glossary of Terms

Term **(alphabetical order)**	**Definition**
HE	Heating elements
ISTR	In-situ thermal remediation
PAH	Polyaromatic hydrocarbons
SVE	Soil vapour extraction
TML	Temperature measuring lances
TPH	Total petroleum hydrocarbon

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.9

1.1 Name and Surname	Aline Jordens
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	aline.jordens@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

During the US-Vietnam War, millions of litres of herbicides were dropped over Vietnam: The Rainbow agents.

Those Rainbow Agents were sprayed throughout the Operation Ranch Hand to clear thick jungle, by defoliating crops and forest. Bien Hoa Airbase was a joint operating base for the South Vietnam Air Force and the United States Air Force. Agent Orange was proven to cause severe health issues, including birth defects, neurological problems, and cancers. Agent Orange is a mixture of 2,4-dichlorophenoxyacetic acid and 2,4,5- trichlorophenoxyacetic. Traces of dioxins were also found in some Agents. Indeed, dioxin 2,3,7,8-Tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) can be formed by condensation of 2,4,5-trichlorophenol during 2,4,5-trichlorophenoxyacetic synthesis.

Dioxins are highly toxic environmental persistent organic pollutants. More than four decades after the Vietnam War ended (in 1975), the stability and bioaccumulation of dioxins still affect the inhabitants. Measures had to be taken to improve living conditions for residents, starting with the remediation of dioxin contaminated soil.

2.3 Contaminants of concern

Dioxins are a family of highly toxic and persistent chemicals that are produced by human activities. They can have harmful effects on human health, including cancer, reproductive and developmental disorders, and immune system damage. The most toxic dioxin is 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), which is used as a reference standard for comparing the toxicity of other dioxins.

The TEQ (Toxic Equivalency) is a measure of the toxicity of a mixture of dioxin-like compounds, which includes not only the most toxic dioxin (2,3,7,8-tetrachlorodibenzo-p-dioxin or TCDD) but also other dioxins, furans, and polychlorinated biphenyls (PCBs) that have similar toxic effects. The toxicity of each individual dioxin-like compound is expressed as a TEQ value, which is based on the compound's toxicity relative to TCDD. When a mixture of dioxin-like compounds is present, the TEQ value for the mixture is calculated by adding up the TEQ values for each individual compound, weighted by the concentration of each compound in the mixture. This provides a single value that represents the overall toxicity of the mixture. TEQ values are used in environmental and human health risk assessments to estimate the potential harm of exposure to a mixture of dioxin-like compounds. The TEQ concept is also used in regulations and guidelines to establish maximum allowable levels of dioxin-like compounds in food, air, and soil.

2.4 Regulatory framework

The thermal pile is made of materials from three origins: contaminated soils, contaminated sludges and washing cake. Soil washing is a remediation technique using physical separation technique to remove contaminants from soils. Small particles are separated from larger ones (sand and gravel) by breaking adhesive bonds and by mean of filtration. The smaller particles are then filtered and generate a highly contaminated filter-cake.

The level of contamination of the different materials and their respective treatment objective are listed in the table below.

Material	Unit	Initial concentration	Treatment goal	Target DRE[1]
Soil	ppt TEQ	> 11.400[2]	300 (Urban residential) 1200 (Industrial)	97,3 % 89,5 %
Sludges	ppt TEQ	> 5.410[3]	150	97,2 %
Washing cake	ppt TEQ	> 17.200[4]	300	98,2%

Table 1 – Contamination levels and treatment goals

3. Pilot-scale

3.2 Treatment unit (pilot scale)

The heating phase is carried out in a thermally insulated metal container. The soil is heated inside the latter by an electric resistance located in the center of the container. The electrical resistance is controlled by a temperature controller in the ON / OFF mode, which allows the temperature of the resistor to be set to reach the target temperature. A perforated vapor tube, designed to collect the polluted vapours created by heating, is located at about 7cm from the resistance. The vapor tube is connected to a refrigerant in serpentine condensing the vapours which are recovered in a round-bottom flask. A fan creates the negative pressure in the vapor network and blows the remaining vapours into the activated carbon filters before the exhaust in the atmosphere.

These results report that for the dioxins and furans, thermal desorption treatment can ensue efficient outcomes. Treating the soil at +/-350°C and maintaining this temperature during at least 5 days reduces the TCDD concentrations by 77,5%.

3.4 Post Treatment for effluent (pilot scale)

For this laboratory scale project, dioxins are recovered using activated carbon.

3.6 Control parameters (pilot scale)

The evolution of the temperature in the soil is monitored using several K-type thermocouples placed in the soil sample at various positions.

4. Full-scale application

4.1 Main treatment unit

The Ex-Situ Thermal Desorption (ESTD) is conducted in a landfill area of Bien Hoa Airbase, where contaminated soils have been stored and restrained over the years.

The ESTD is composed of 15 horizontal heating tubes and 13 exchanger tubes.

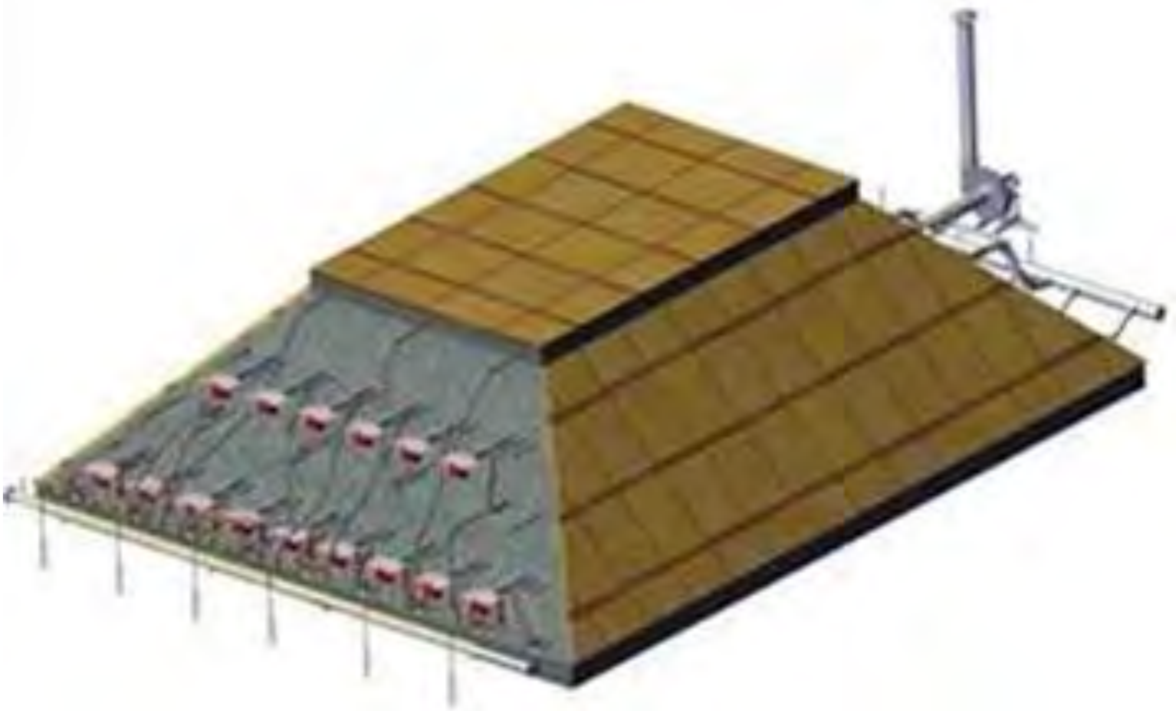


Figure 1 – Front overview of the pile

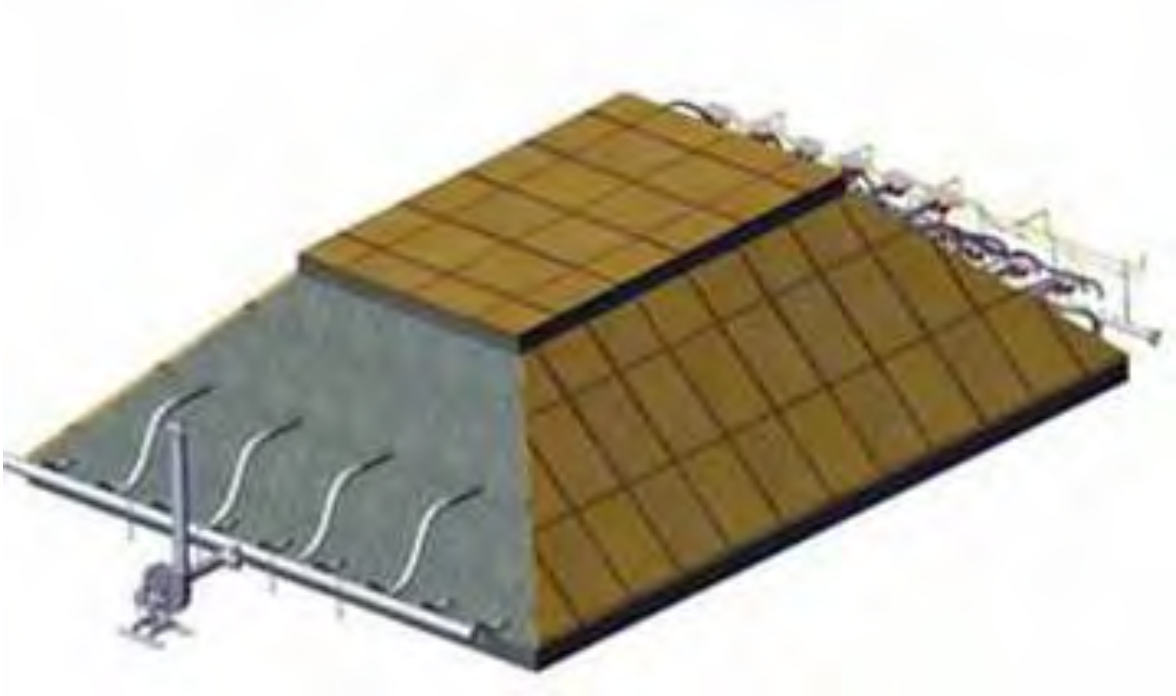


Figure 2 – Back overview of the pile

The exchanger tubes recover the combustion gases after their passage through the heating tubes, allowing a second passage through the pile. The fan, located at the back of the pile, drives the combustion gases from the burners through the tube network to the chimney. The combustion gases never encounter the contaminated soil and circulate through the tube network until they are released into the atmosphere. Conversely, the polluted vapours generated by the temperature rise in the pile are collected by the vapor tubes placed inside the pile and connected to a collector, placed in front of the plie, leading the polluted vapours to the vapor treatment unit.

The main goal of treatment is to lower the TCDD-TEQ concentration in contaminated soils to target objectives by heating the soil to the target temperature of 335°C.

The top of the pile is covered with a layer of gravel, in which more vapor tubes, called secondary vapor tubes, are placed. These secondary vapour tubes are an additional security to avoid any fugitive emission or contamination of the concrete. The whole pile is then covered with concrete and thermal insulation.

Figure 3 – Front picture of the pile on site

4.3 Post treatment for effluent

The purpose of the VTU (Vapor Treatment Unit) is to handle the contaminated vapours produced in the soil and reduce their concentrations below legal emission standards. Two main options are available: Condensation and Absorption on Activated Carbon or Thermal Oxidation.

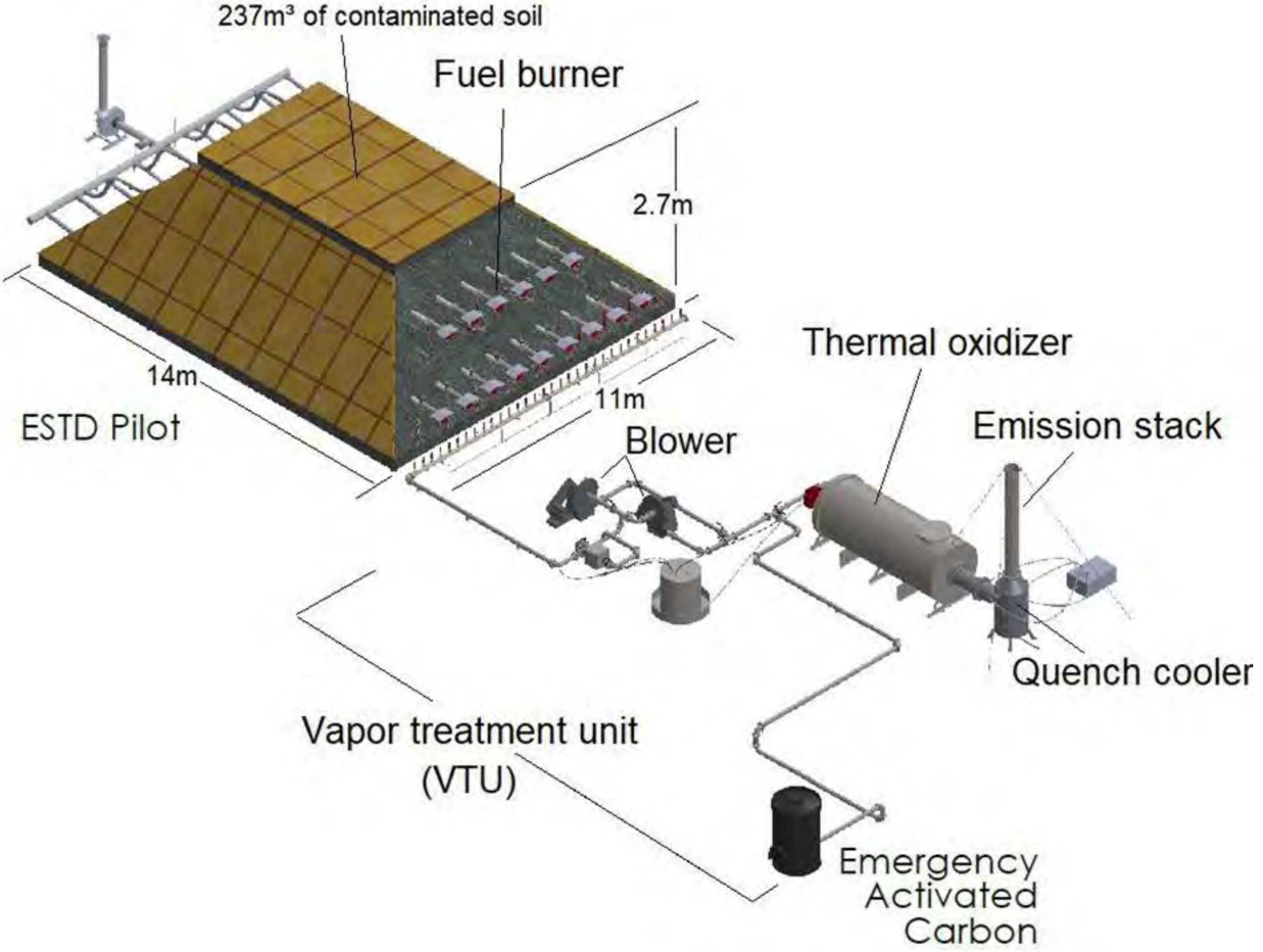


Figure 4 – Pile overview with its Vapor Treatment Unit (VTU)

The main advantage of the first option is the low energy consumption. Nevertheless, liquid and solid waste are produced: the liquid obtained after condensation must be post-treated and the activated carbon is a solid hazardous waste which must be disposed of.

On the other hand, using a Thermal Oxidizer allows to avoid any liquid/solid waste. The vapours are directly incinerated to destroy all dioxins. Proper oxidation guarantees compliant air emissions. An insulated piping network collect the vapour and route them to the VTU; some condensation occurs, and the condensates are recovered and treated in the Thermal Oxidizer as well, leaving zero-waste.

Energy efficiency for thermal oxidation can be improved by installing a recuperative heat exchanger.

The chosen design for vapor treatment consists of a Direct Fired and Thermal Oxidizer. To reach a destruction rate efficiency over 99,99%, the following criteria must be fulfilled in the oxidation chamber:

- Temperature of minimum 1100°C (preferably 1200°C)

- Oxygen content of min 6% (preferably 10%)
- Residence time of minimum 1 second (preferably 2 seconds
- Good mixing conditions - High Turbulence (Re>>2500).

Dioxin compounds reformation can happen in the cooling phase, in a temperature range between 200°C and 500°C, with maximum formation occurring at 350°C. Dioxins can be reformed in the presence of oxygen, chlorine (Cl2) and hydrocarbons. Other parameters such as presence of dust and/or presence of metals, can also promote the dioxins/furans formation. To avoid the reformation process, the hot gases pass through a Quench tower to be cooled below 200°C before being released into the atmosphere.

To comply with Vietnamese regulations, a maximum temperature of 180°C at the stack has been set.

4.4 Post Treatment for water (pilot scale)

The contaminated water from the condensation of the vapours is sent to the thermal oxidiser for zero waste treatment.

4.5 Control parameters

The parameters that are continuously monitored during the treatment are the following:

- The temperature at the coldest points in the thermopiles
- The emissions at all chimneys to guarantee regulatory compliance
- The depression in the pile to ensure proper extraction
- The temperature in the Thermal Oxidizer
- The oxygen content in the Thermal Oxidizer
- The temperature of gases at the quench tower output to avoid dioxin reformation

5. Results

5.1 Removal rate

Soil sample after treatment were collected in the cooled thermal pile. The results of the final sampling are available in the table below.

Material	Unit	Initial concentration	Treatment goal	Treated soil Results	DRE[1]
Soil	ppt WHO-TEQ$_{2005}$	11.400[2]	300 (Urban residential) 1200 (Industrial)	4,84[3] 96,29[4]	99,96% 99,16%
Sludges	ppt WHO-TEQ$_{2005}$	5.410[5]	150	ND[6.4]	> 99,99%
Washing cake	ppt WHO-TEQ$_{2005}$	17.200[7]	300	6,7[4]	99,96 %

Table 2 – Soil samples after treatment

[1] Destruction Rate Efficiency

[2] Environmental Assessment of Dioxin Contamination at Biên Hòa Airbase, USAID (2016), page 115

[3] Analysis performed by Agrolab (Accredited European laboratory)

[4] Analysis performed by Eurofins

[5] Environmental Assessment of Dioxin Contamination at Biên Hòa Airbase, USAID (2016), page 115

[6] Non-Detected

[7] Analysis performed by an accredited European laboratory on sample before treatment (Eigen method NEN-EN-1948)

The treatment objective of each material (soil, sludges and washing cake) were met. The Destruction Rate Efficiency is over 99% for all samples.

7. Additional information

7.1 Lesson learnt

Haemers Technologies' pilot thermal desorption treatment of very heavily dioxin-contaminated soils has demonstrated that:

- Ex-situ thermal desorption can effectively recycle highly dioxin-contaminated soils to residential levels for subsequent beneficial use.
- Haemers Technologies' design has proven to be effective in destroying dioxin and producing zero waste.
- Haemers Technologies’ operations have proven to be fully compliant with air
- emission and did not affect ambient air quality.

The pilot project demonstrated that Ex-Situ Thermal Desorption with diesel burners is a very effective technology for treating dioxin-contaminated soils in the most sustainable way.

7.2 Additional information

Temperature in the thermal pile

This section presents the thermographies generated at different stages of heat treatment (10, 22, 30 and 40 days of treatment). Thermographies are heat maps representing the temperature distribution inside the thermal pile.

Each thermography illustrates a vertical slice of the thermal pile: the front, the middle and the back of the pile.

The evolution of the thermographies enables to visualize the evolution of the heat front in the pile.

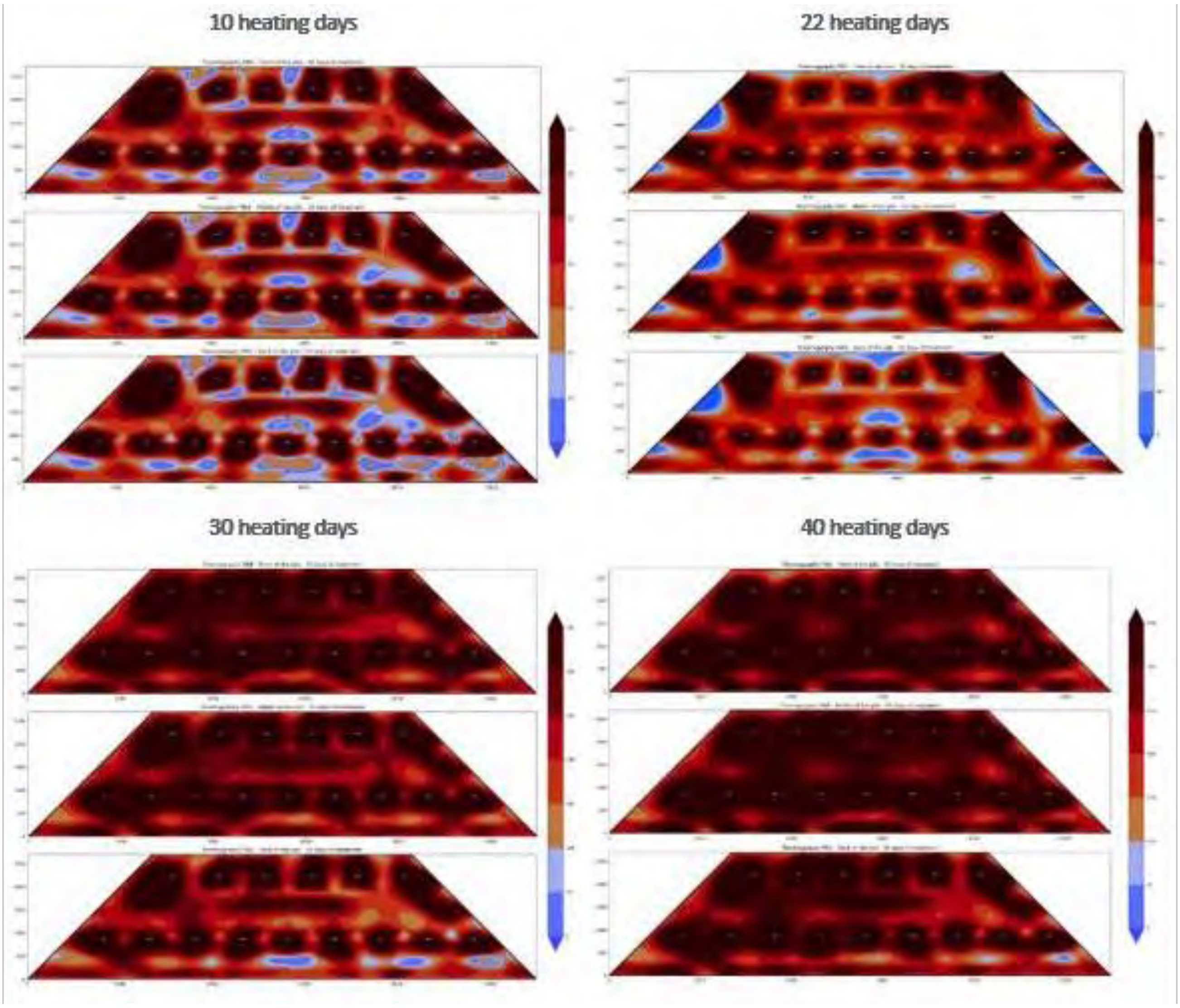


Figure 5 – Thermographies of the pile

The thermographies show that the whole mass of the thermal pile has heated up to the target temperature. After 10 and 22 days, the hot spots are localized next to the heating elements. As the treatment progresses, when 30 and 40 days of treatment are reached, the heat front gradually moves away from the heating tubes towards the so-called cold points (the most distant points from the heating elements.

The mean temperature in the thermal pile has reached the target temperature of 335°C after 35 days of treatment. The target temperature has been maintained for 5 days before stopping thermal treatment.

Pressure monitoring

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P<P_{atm}$), which will consequently prevent fugitive emissions during the treatment. The constant vacuum created in the soil also improves the decontamination. For this project, 2 pressure wells (P1-P2) were installed and measurements were performed manually every day. Vacuum was maintained in the thermal pile throughout the treatment (pressure < 0 mbar). These results demonstrate that no fugitive emissions occurred. Results of ambient air monitoring also confirm these findings

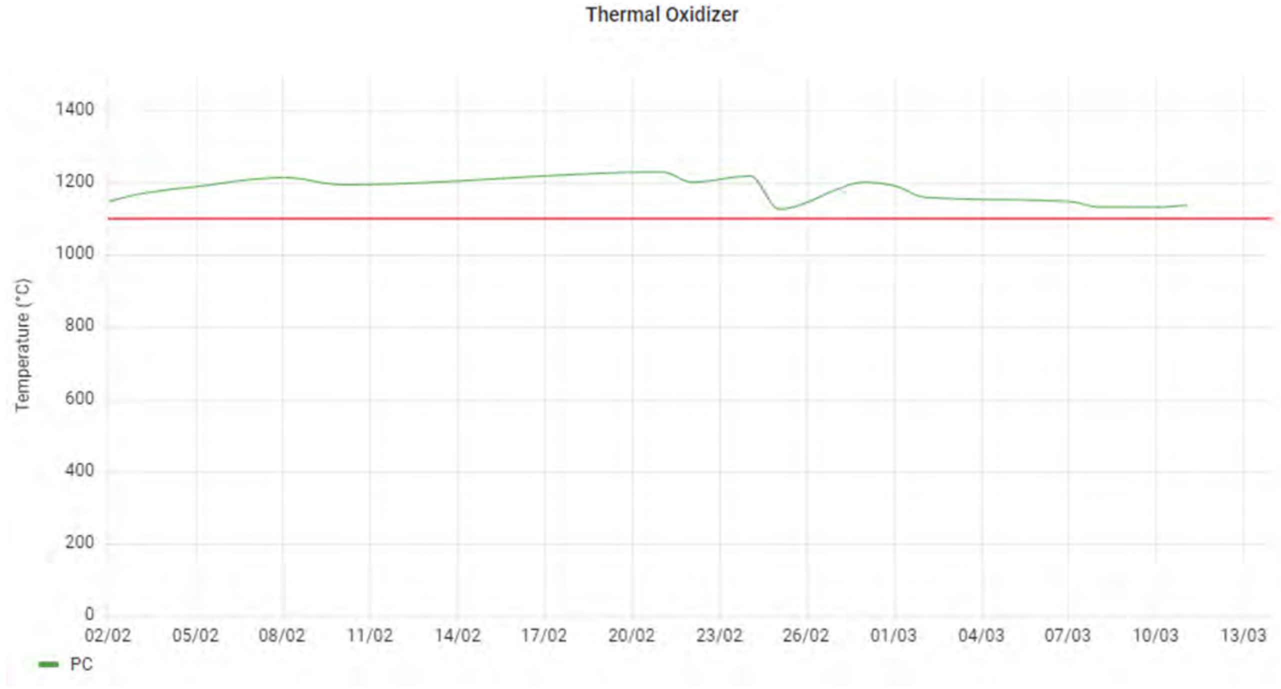


Figure 6 – Temperature evolution in the thermal oxidizer

Temperature in the Thermal Oxidizer

Temperature in the Thermal Oxidizer is continuously monitored to ensure a temperature that guarantees the destruction of dioxins. The graph presented on below shows the evolution of the temperature in the Thermal Oxidizer during the treatment. The vertical axis represents the temperature in the Thermal Oxidizer, the horizontal axis the treatment time.

The green line is the temperature in the Thermal Oxidizer while the orange line is the threshold value, i.e. the minimum required temperature to achieve complete oxidation of the contaminants (1100°C).

The temperature of destruction of the dioxins (>1100°C) was maintained during all the treatment.

Emission control

Sampling at the outlet of the chimney (after the Thermal Oxidizer and the quench tower) was performed during the whole treatment by a certified center. The sampling method follows EPA-23 method.

The sampling was performed with a A-2000 Auto Isokinetic Flow Integrator (Environmental Supply Company, Inc – USA). The analysis equipment is a high-resolution gas chromatograph Agilent 7890A and an Autospec Premier M834 spectrometer. The emission standard is 0,1 ng TEQ/Nm^3 (or 100 pg TEQ/Nm^3). During the whole project the norm is respected, and all emissions are compliant.

Glossary of Terms

Term **(alphabetical order)**	**Definition**
Target DRE	Target of Destruction Rate Efficiency

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.10

1.1 Name and Surname	Maël Makoudi
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	mael.makoudi@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

This site is in Belgium, in the basement of an administrative building of Uccle (Brussels) in a sensitive neighbourhood with school and kinder garden directly next to it (see below – google aerial view). The pollution was due to leaking of oil tanks in the basement. The pollution covered 160 m² and was 4,5m deep over 4 different cellars.

Figure 1 – Localization of the area

2.2 Contaminants of concern

The lithology is mainly composed of loamy and sandy soils.

2.3 Contaminants of concern

The Contaminant of Concerns (COCs) are hydrocarbons (C10-C40) with concentrations up to 30 000 mg/kg dry soil.

2.4 Regulatory framework

The treatment target was set at 720 mg/kg dry soil.

3. Pilot-scale

3.1 Laboratory Study

No laboratory test was carried out for this project, it is a well-known contamination.

4. Full-scale application

4.1 Main treatment unit

The in-situ Smart Burner^{TM} Technology developed by Haemers Technologies, shown in Figure below, heat polluted soil using thermal desorption process with no excavation involved. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then either treated in a vapour treatment unit (VTU) or re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} (in the case of hydrocarbons pollution).

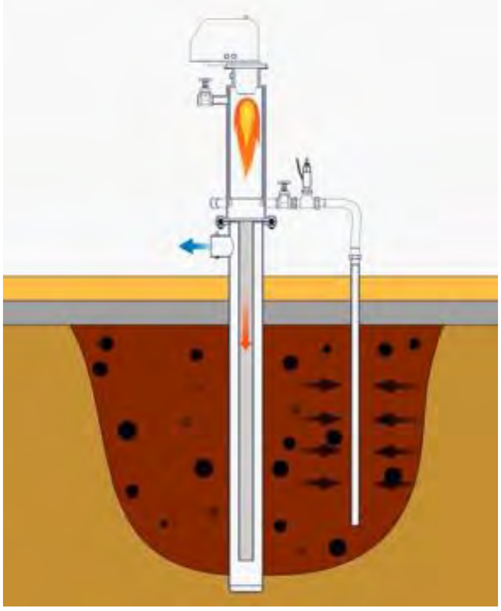


Figure 2 - In-situ Smart Burner^{TM} Technology with reburn

The batch of 720m³ (1300 tons) was treated with 42 natural gas Smart Burners^{TM}. For this project, the reburn technology was used to burn the hydrocarbons and decreased fuel consumption.

Figure 3 - Reburn set-up

The target treatment temperature was set to 220°C and it took around 50 days to reach this temperature and remediate the soil.

Figure 4 - Site installation overview

Figure 5 - One of the cellars of the site

4.3 Post treatment for effluent

The post treatment for effluent was based on the reburn technology. The vapours from the soil are extracted through the steam tubes. The negative pressure in the tubes is created by the fans, and the vapours (water and hydrocarbons) exit through the steam tubes. The vapours and gases are directly reinjected into the burners to undergo different degradation mechanisms: hydrolysis, partial oxidation and total oxidation.

The main mechanism expected from the treatment after recovery is a complete oxidation in the burners. The products of combustion are then drawn off and sent to the chimney.

4.5 Control parameters

Connected monitoring boxes were installed to monitor during the treatment and the cooling phase the soil temperature at different points in the pile. It allowed HT team to keep a close eye on the heating profile evolution of the soil. These devices were also used to monitor the 42 Smart Burner temperatures.

Atmosphere emissions of CO_2, CO and C_xH_y were also monitored manually periodically to ensure a good quality of the treatment. Soil pressure points were also placed in every cellar to ensure that the pressure always remained negative.

5. Results

5.1 Removal rate

A removal rate over 98% was achieved at all points (final concentrations < 260 mg/ kg dry soil).

7. Additional information

7.2 Additional information

1) Soil temperatures

This section presents the temperature during the heat treatment at two different depths, 2m and 4m. The temperature is monitored at so-called "cold points" at the center of the triangle formed by three heating tubes.

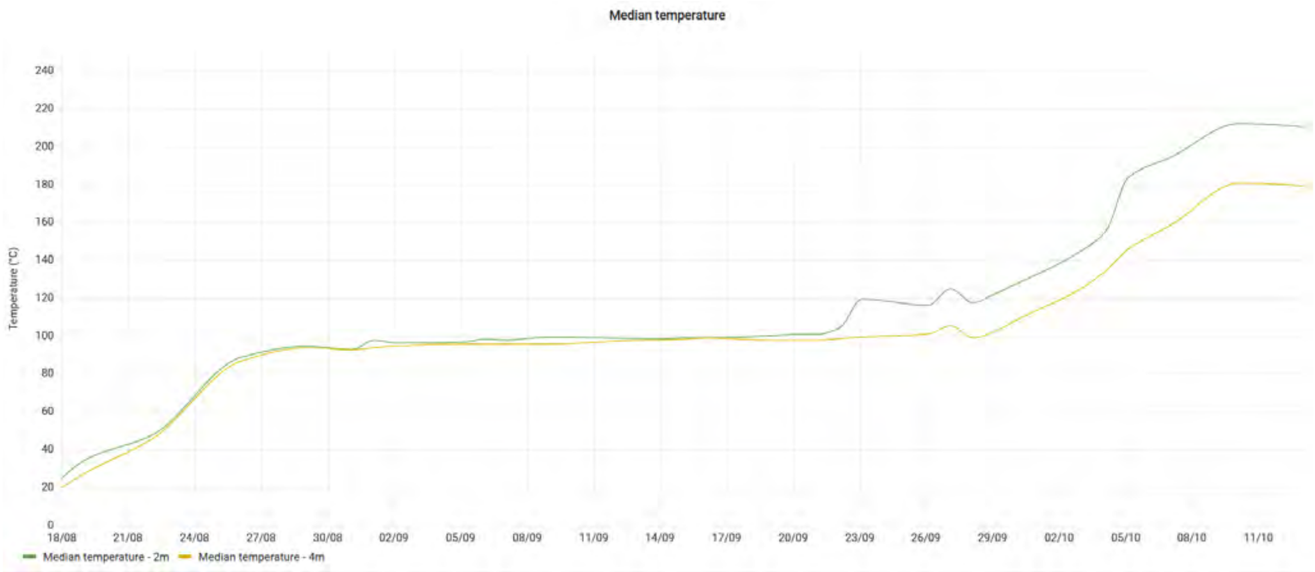


Figure 6 – Soil median temperature at 2 and 4m depth

Emission control

Various parameters (O_2, CO_2, CO, SO_2) were manually monitored with relevant gas analysers at the chimney, making sure that these emissions respected the local norms. The graph below shows the emissions obtained during treatment at the chimney.

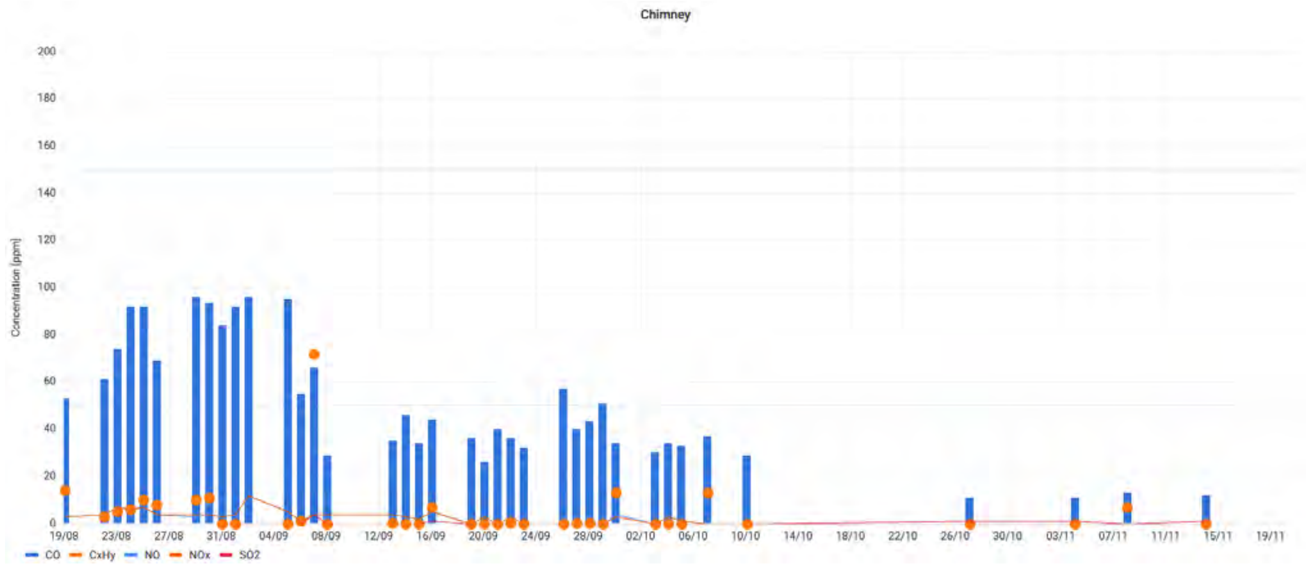


Figure 7 – Emission at the chimney during treatment

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.11

1.1 Name and Surname	Willian Felipe Do Prado
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	willian.doprado@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The site is in Woluwe-Saint-Pierre (Brussels), at 7/9 Place Dumon. The pollution was caused by the onsite activities of a former dry-cleaning shop. Several studies have been conducted on the parcel over the years. The latest study was a soil survey study performed on March 2020. The site was composed of two zones, one located in the patio outside (25m²) and another one located in the basement (17m²). Two types of treatment were used as the soil and the water table were contaminated: thermal desorption (by Haemers Technologies) for the unsaturated zone and high oxidative compounds injection for the saturated zone (by Injectis S.A).

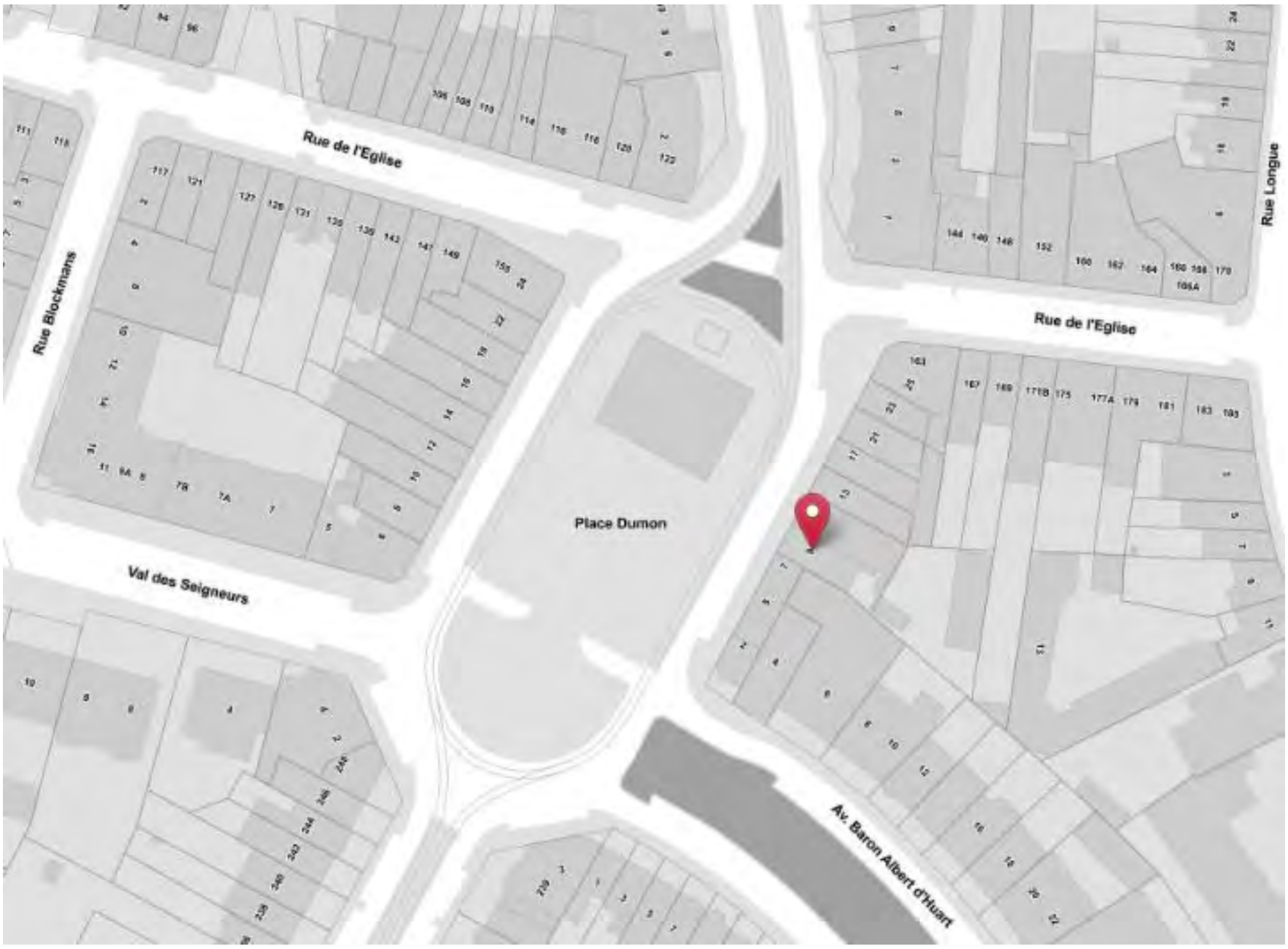


Figure 1 – Site localization

2.3 Contaminants of concern

The latest study was a soil reconnaissance study performed on March 2020. Those studies revealed the presence of chlorinated solvents in the soil and the underground water table: DEC, PCE and TCE. With a maximum concentration respectively of:

- 2 mg/kg DM
- 490 mg/kg DM
- 19 mg/kg DM

2.4 Regulatory framework

The soil concentration limits after treatment have been defined at 1mg/kg of dry soil for all the chlorinated pollutants.

4. Full-scale application

4.1 Main treatment unit

The in-situ Smart Burner^{TM} Technology developed by Haemers Technologies, heat polluted soil using thermal desorption process with no excavation involved. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then either treated in a vapour treatment unit (VTU) or re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} (in the case of hydrocarbons pollution).

For this project, the exhaust gas and polluted vapor were directly sent to a granulated activated carbon (GAC) filter before their release to the atmosphere. The GAC filtered the gases to capture chlorinated compounds.

To treat the polluted area, one batch of 22 burners, separated into two treatment zones was implemented. Zone 1 located in the outside yard (about 25 m^2) was made of 12 burners. Zone 2 located in the basement (about 17 m^2) was made of 10 burners.

Figure 2 - Activated carbon tank

Figure 3 – Treatment Zone 1 in the outside yard

Figure 4 - Treatment Zone 2 in the basement

The batch of 230m³ (414 tons) was treated with 22 natural gas Smart Burners and a small VTU made of one activated carbon tank to treat the vapours. The contaminant was located between 0 and 6,5m depth and the target temperature of treatment was 95°C.

4.4 Post treatment for water

Groundwater was observed at a depth of 6,5m from ground level (4m from the basement level). As pollution was also observed in the saturated zone, Injectis SA was charged to treat the saturated zone through injections of sodium permanganate solutions. Haemers Technologies treated the unsaturated zone of the treatment areas (down to 6,5m from the ground level).

No groundwater management was needed during the Thermal Desorption treatment phase.

4.5 Control parameters

Monitoring boxes were installed to monitor the 22 burners' temperatures. Three soil temperature points with measurements at 1, 3.5 and 6.5m below ground level were placed in Zone 1. Two soil temperature points with measurements at 1 and 3.5 m below ground level were placed in the Zone 2.

Temperature measurement points were also placed at the inlet of the fan and at the inlet of the activated carbon filter as well as the stack. Two soil pressure point measurements (one per treatment zone) were also placed.

The temperature at the inlet of the GAC (Granulated Activated Carbon) is another critical parameter which must be monitored throughout the entire treatment. A too high temperature can lead to spontaneous combustion of the activated carbon. It was therefore important to keep the temperature around 65° at the inlet of the GAC.

Also, various parameters (O_2, CO_2, CO, COV) were manually monitored with relevant gas analysers at the chimney, after the activated carbon filter to control emissions to the ambient air, making sure that these emissions respected the local norms.

5. Results

5.1 Removal rate

To validate the treatment objectives, 7 sampling locations have been chosen by the client's advisor. Three locations were in the basement where samples were collected at the surface just under the concrete slab, at 2-2.5m and at 3.9-4.2m (FC1, FC2 and FC3). Four locations were in the outside yard where samples were collected at the surface just below gravel, at 1.8-2m and at 6.3-6.5m (FC4, FC5, FC6 and FC7).

DCE and TCE results show that the target concentration is achieved after the first hot sampling campaign. After the second sampling campaign, a remediation rate of more than 98% was observed for the PCE.

The remediation showed a global (i.e. all contaminants combined) mass decontamination rate of more than 98.5%.

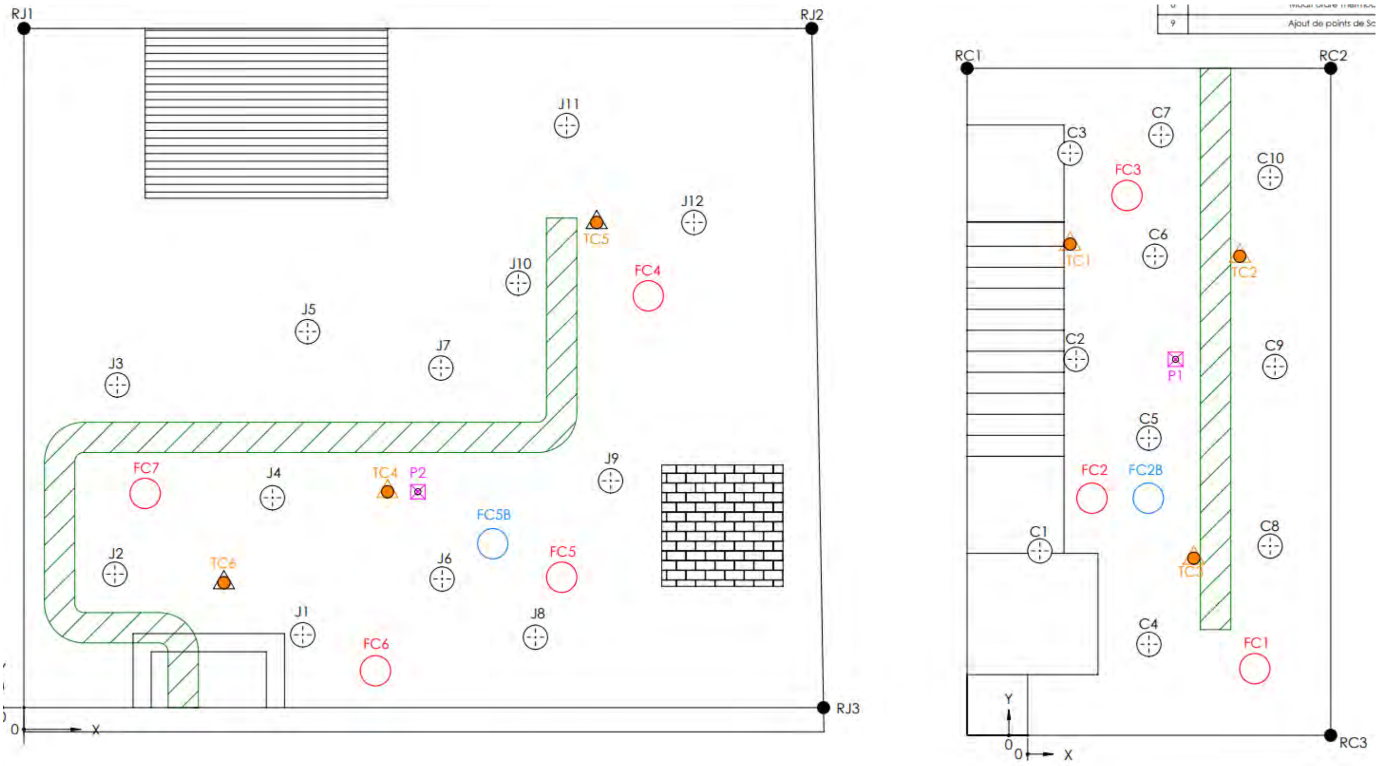


Figure 5 - ISTD installation with monitoring points - overview

7. Additional information

7.2 Additional information

The treatment of the soil was complete after a cumulated heating time of 20 days.

1) Soil temperatures:

At 1m depth in the basement, the three measurement points followed the same temperature path and reached the target after 12-13 days while the three measurement points in the outside yard remained a bit below the target temperature, especially T5 with a maximum temperature of 72°C. The cooling was uniform across all wells.

At 3.5m depth, all measurement points reached a temperature close to the target except for T5 which reached a maximum temperature of 85°C. The cooling was uniform across all the wells (see Figure 4).

At 6.5m depth, T5 quickly reached the target temperature while T4 and T6 remained respectively at 93°C and 92°C.

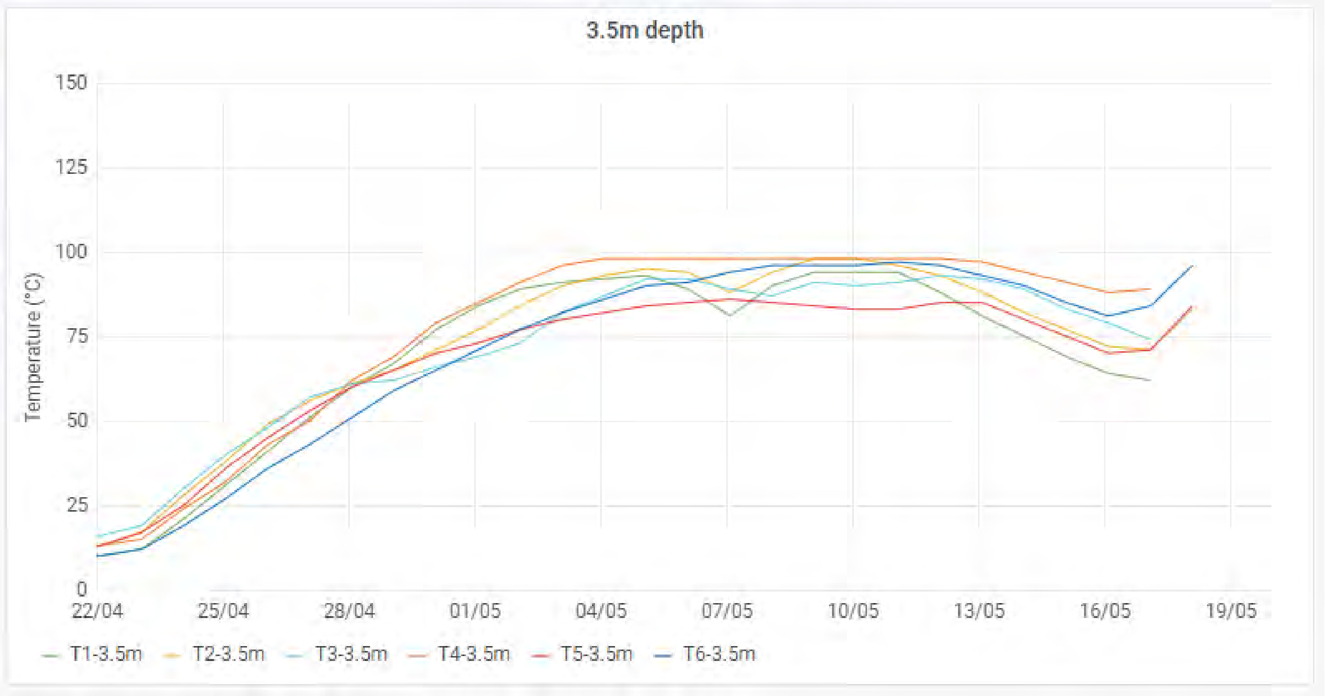


Figure 6 - Temperature evolution at 3.5m at the different monitored localisation

For all 6 monitoring wells, an increase of the temperature at the end of the monitoring during the cooling phase was observed. This is mainly due to the continuous heat front from the heating wells to the cold points, as the aspiration was stopped and any remaining preferential paths for fresh air insulating the temperature tubes were no more influencing the temperature readings

2) Pressure monitoring:

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P<P_{atm}$), which will consequently avoid fugitive emissions during the treatment. For this project, 2 pressure wells (P1 and P2) were installed, and measures were done manually every day. It can be observed on the figure below that the relative pressure always remained negative at the location of the pressure measurement wells throughout the entire treatment. A small increase in relative pressure was observed at the end of the treatment, related to the increase of the water vapour production as the overall soil temperature in the treatment areas approached 100°C.

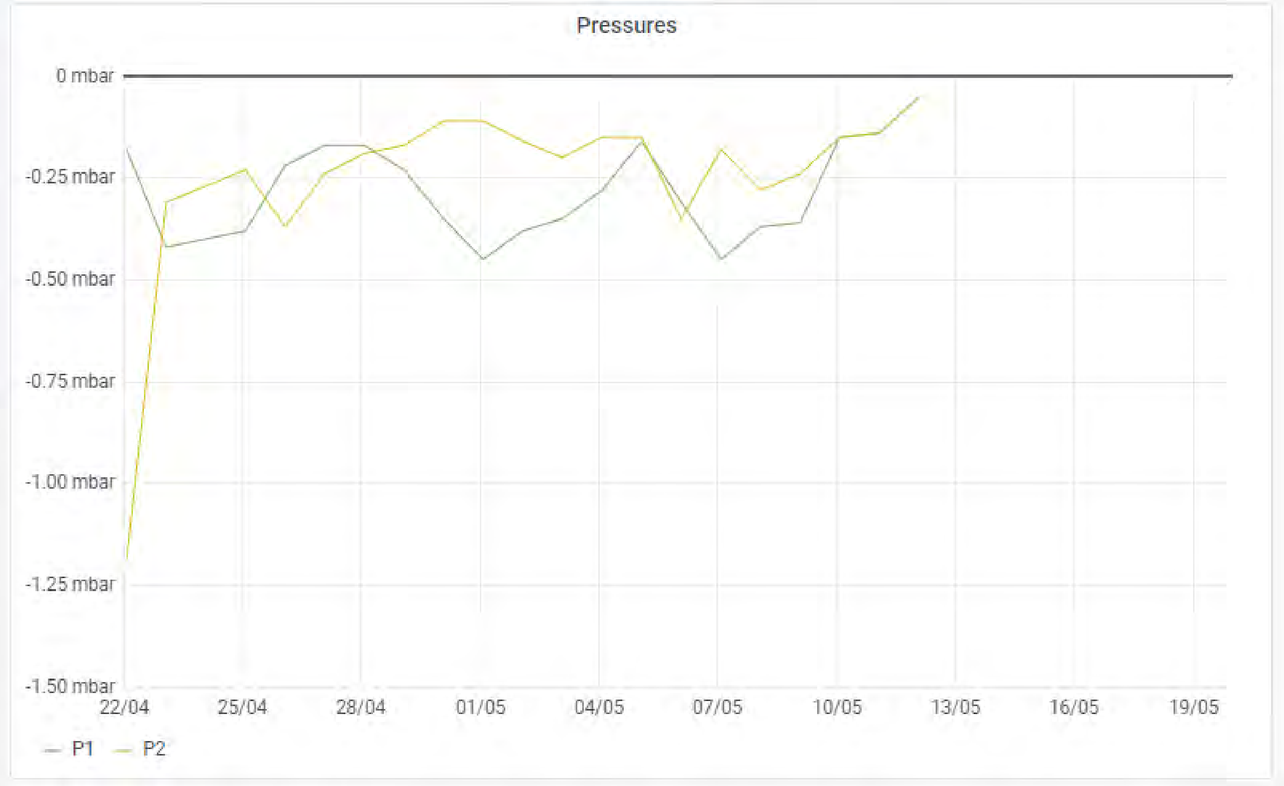


Figure 7 - Soil pressure evolution

3) Emission control

Various parameters (O_2, CO_2, CO, T°) were manually monitored at different points with a gas analyser (MRU Optima 7) and the COVs were monitored using a PID with a 10.6eV lamp.

Regarding the emissions before the fan, the CO concentration always remained in the acceptable range of 0-50ppm, except for one day where it reached 100ppm (median value of 21ppm). A cooling valve was also placed at the inlet of the fan to limit the

temperature of the fan motor.
The temperature at the inlet of the GAC (Granulated Activated Carbon) is another critical parameter which must be monitored throughout the entire treatment. A too high temperature can lead to spontaneous combustion of the activated carbon. It was therefore important to keep the temperature around 65° at the inlet of the GAC. It can be observed on the figure below that the temperature remained around 60°C – 65°C throughout the process, with a maximum of 67°C on May 10th. The cooling valve, as well as the heat exchange throughout the collector connecting the fan to the activated carbon filter, allowed to maintain the temperature at the inlet of the GAC into the operating range.

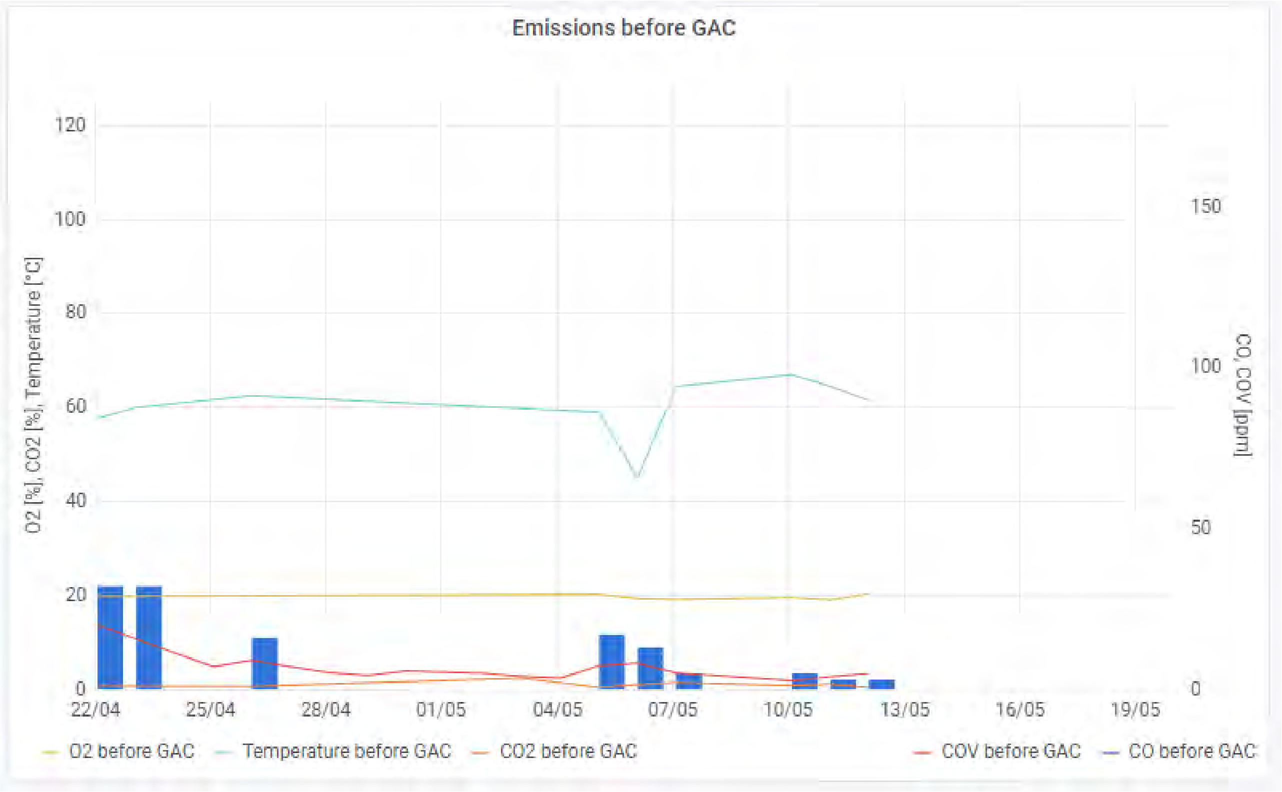


Figure 8 - Emissions and temperature before GAC

Various parameters (O_2, CO_2, CO, COV) were manually monitored with relevant gas analysers at the chimney, after the activated carbon filter to control emissions to the ambient air, making sure that these emissions respected the local norms. The emissions and the temperature at the chimney are shown on the figure below.

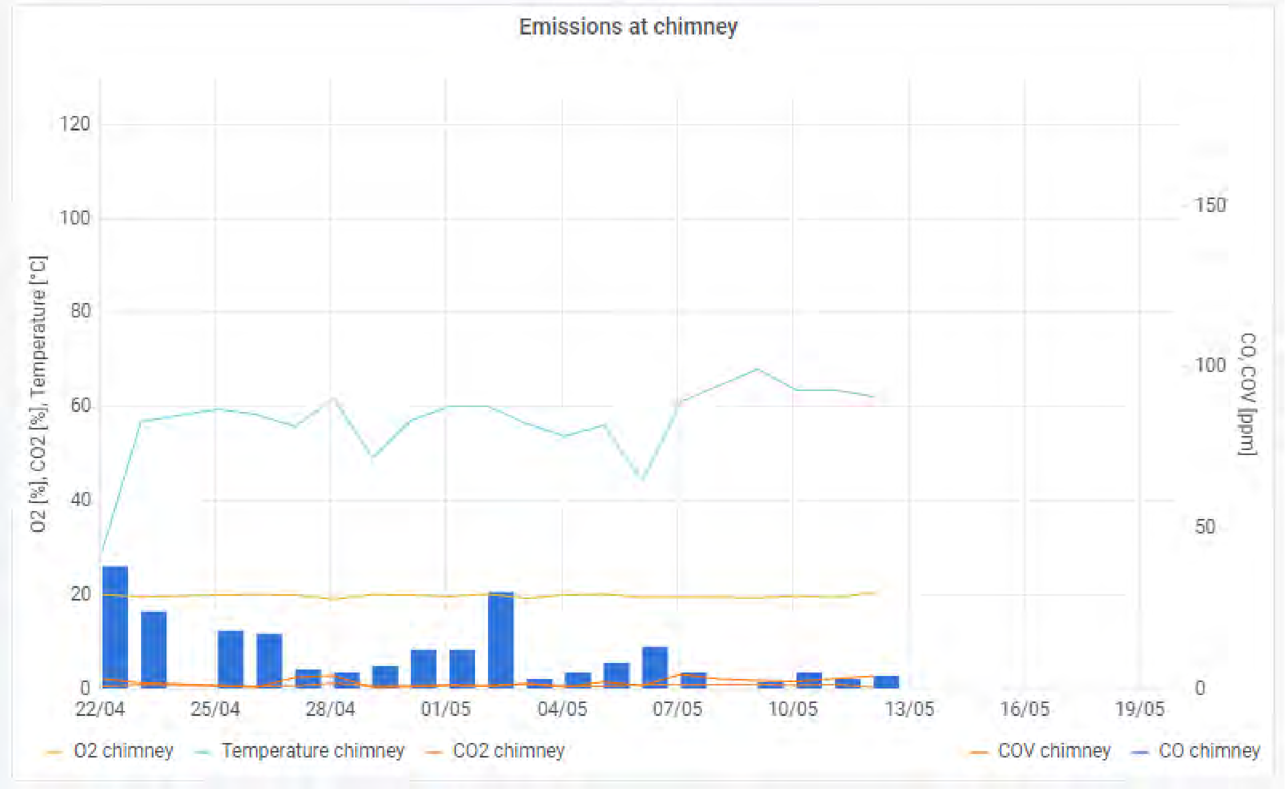


Figure 9 - Chimney emissions

7.4 Additional remarks

The in-situ project demonstrated to be a fast and reliable approach for the remediation of contaminated soil with chlorinated solvents in a frequented urban area.

Glossary of Terms

Term **(alphabetical order)**	**Definition**
DM	Dry Matter

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.12

1.1 Name and Surname	Willian Felipe Do Prado
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	willian.doprado@haemers-tech.com
1.7 Phone number	+32 2 219 13 53

2. Site background

2.1 History of the site

The Danish Defense Ministry appointed Arkil to undertake the pilot remediation works at the former Grønnedal military base in Greenland for soils contaminated with hydrocarbons. Arkil has then sub-contracted Haemers Technologies to provide its expertise in thermal desorption.

Figure 1 – Site localization

2.3 Contaminants of concern

Three types of hydrocarbon contaminant are considered for the remediation, each present in separate soil samples: one is contaminated with C6-C15 hydrocarbons (helicopter fuel), the second one is contaminated with C10-C20 hydrocarbons (diesel fuel), and the third one is contaminated with C20-C35 hydrocarbons (heavy fuel/oil).

With an TPH average concentration of:

- Helicopter fuel: 1.665 ppm
- Diesel: 8.620 ppm
- Heavy fuel: 11.956 ppm

2.4 Regulatory framework

The key objective of the trial treatment was to demonstrate the effectiveness of the thermal desorption technology. Therefore, no specific target has been set for the remediation.

4. Full-scale application

4.1 Main treatment unit

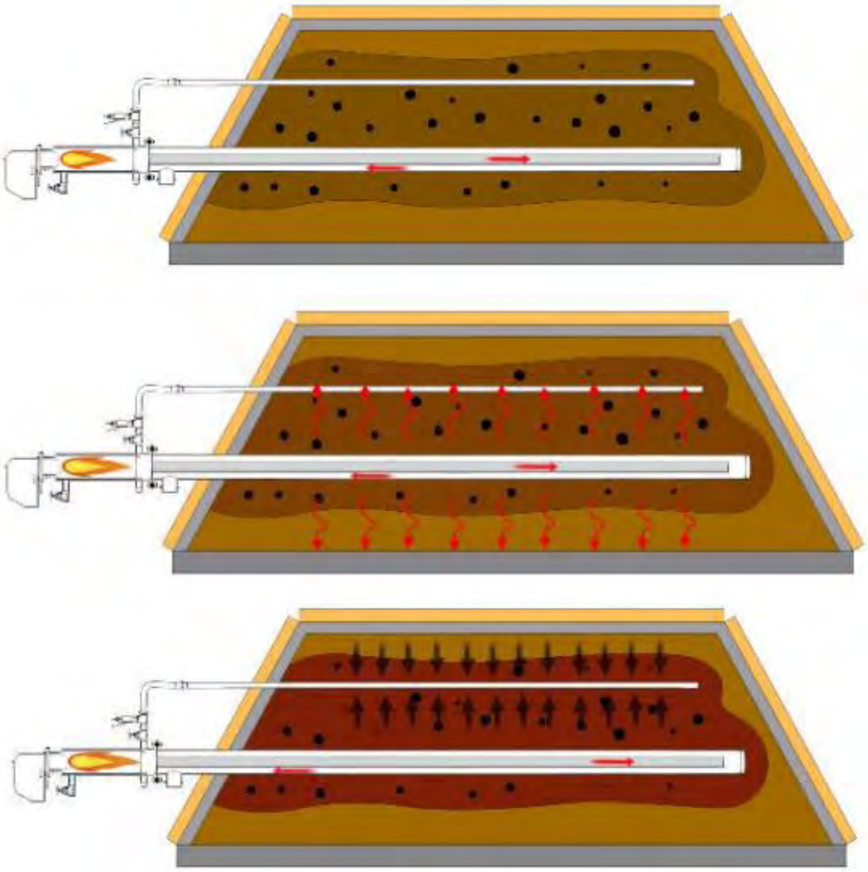


Figure 2 - Ex-situ Smart Burner^{TM} technology with reburn

To treat the three samples, it has been decided to build a container made with sheet piles based on the ex-situ Smart Burner^{TM} Technology developed by Haemers Technologies. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burners, circulate in the tubes to transfer heat to the soil.

This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then either treated in a vapour treatment unit (VTU) or re-injected (reburn mode) into the flame generated by the Smart Burners (in the case of hydrocarbons pollution). Considering the type and concentration of the contaminants, the Reburn technology was selected to destroy the vaporized hydrocarbons.

The volume was divided in 3 parts and the heating wells were installed all along the container to treat the three contaminated soils concurrently.

The design of the container is represented on the various schematics below. The dimensions of it were as follow:

Length (m)	Distance between heating pipes (m)	Width (m)	Height (m)	Volume (m³)	Payload (tons)
14,75	0,8-1	2,7	2	79	142

Table 1 – Dimension of the container

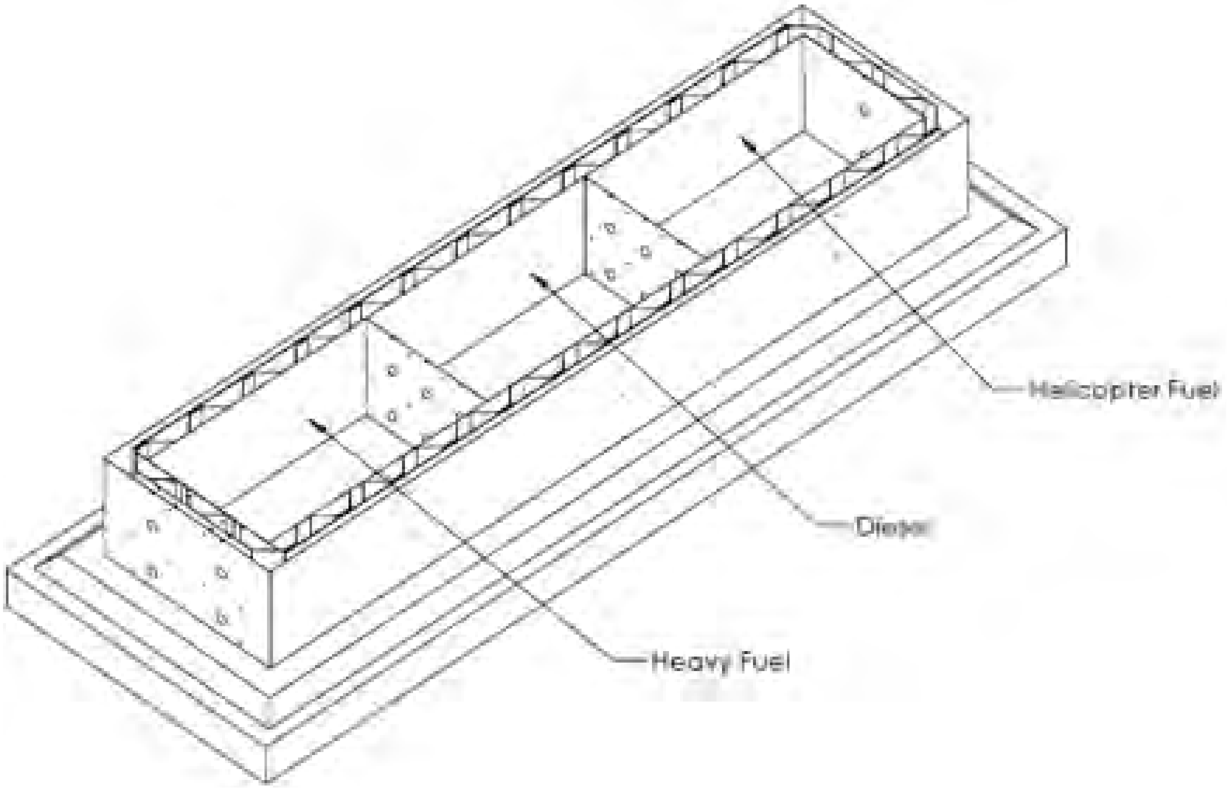


Figure 3 – Contaminated soil repartition in container

It allowed HT team to treat 79m³ (142 tons) while using only 6 Smart Burners^{TM}. It has been decided to put the soils contaminated with the heaviest hydrocarbons on the side with 4 burners for remediation optimization. Then the last two burners were installed on the other side for heat homogeneity optimization. The treatment of the soil was in effect for a total cumulated heating time of less than 20 days and reached the target temperature of 350°C.

Figure 4 – Container on site (back)

Figure 5 – Container on site (front)

4.3 Post treatment for effluent

The post treatment for effluent was based on the reburn technology. The vapours from the soil are extracted through the steam tubes. The negative pressure in the tubes is created by the fans, and the vapours (water and hydrocarbons) exit through the steam tubes. The vapours and gases are directly reinjected into the burners to undergo different degradation mechanisms: hydrolysis, partial oxidation and total oxidation.
The main mechanism expected from the treatment after recovery is a complete oxidation in the burners. The products of combustion are then drawn off and sent to the chimney.

4.5 Control parameters

To follow-up the trial, the treatment area was divided into 5 parts:

- Daily temperature monitoring for the soil at different depth (every 50cm) at 5 cold point locations
- Daily temperature monitoring behind the plywood walls at 12 different locations
- Daily soil temperature monitoring under each compartment of the container
- Daily pressure monitoring at 6 locations
- Daily emission control at the venting and VOCs measurement at pressure monitoring locations

5. Results

5.1 Removal rate

After treatment, 3 samples from each compartment, all taken at 1,5m inside the container, were collected and brought back for preliminary analysis by HT. As expected, all 3 samples show very dry and below detection limits results for TPH and all analysed fractions.

Sample location	Dry matter (%)	TPH (ppm)	C10-C12 Fraction (ppm)	C12-C16 Fraction (ppm)	C16- C21 Fraction (ppm)	C21- C35 Fraction (ppm)	C35- C40 Fraction (ppm)
C2 1,5m	100	<50	<8,0	<8,0	<10	<14	<10
B2 1,5m	99,7	<50	<8,0	<8,0	<10	<14	<10
A2 1,5m	99,6	<50	<8,0	<8,0	<10	<14	<10

Table 2 - ISTD installation with monitoring points - overview

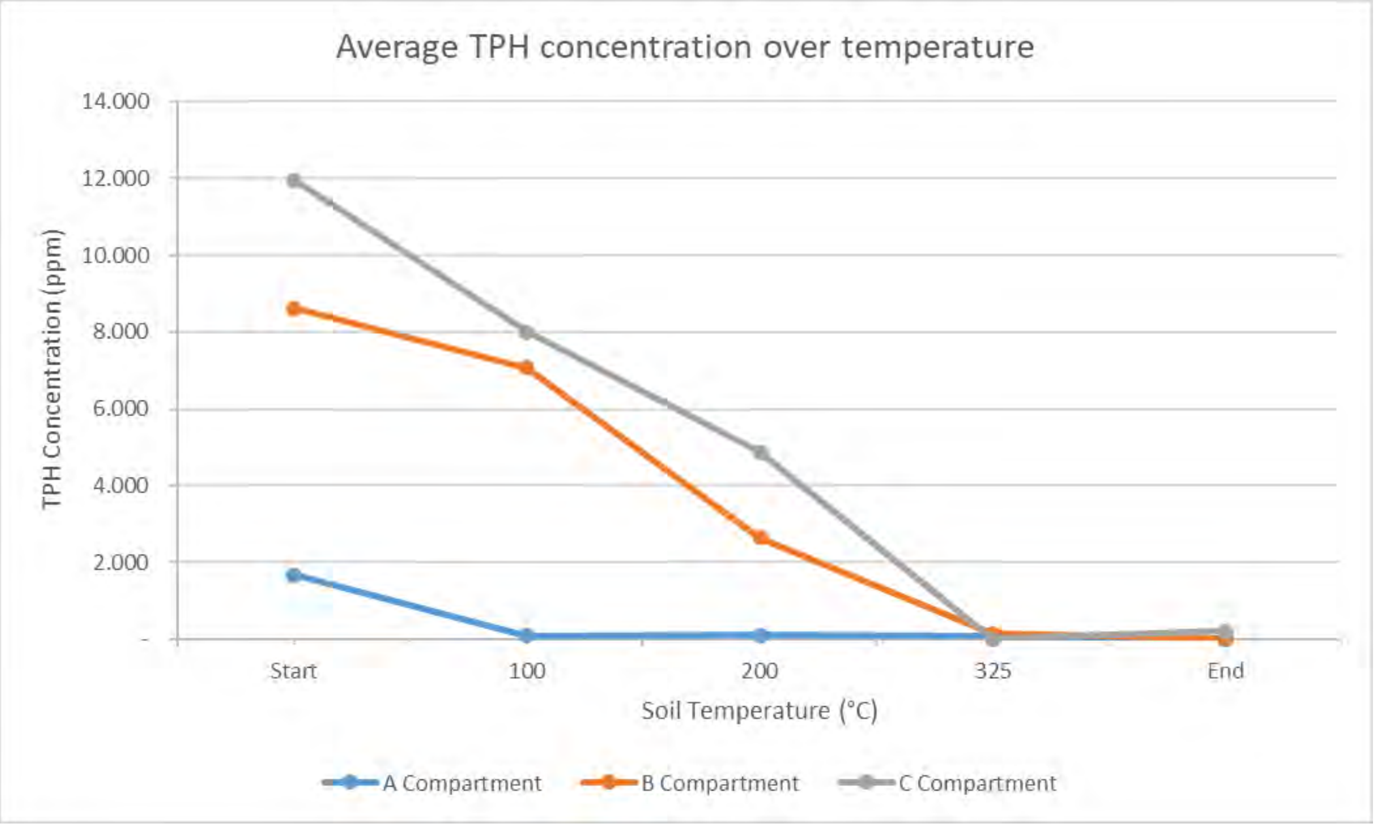


Figure 6 – Average TPH concentration over temperature in the container

The evolution of the average TPH concentration per temperature target level for each compartment is shown on the graph above.

As per results, the contaminant concentration for the A compartment was reduced by 95% already at the 100°C target, therefore kept stable over the next target temperature levels. The contaminant concentration for the B compartment was reduced linearly by 18%, 69% and 98% for the target temperature levels of 100°C, 200°C and 325°C respectively. As for the contaminant concentration for the C compartment, it reduced linearly as well by 33%, 59% and 99,9% for the target temperature levels of 100°C, 200°C and 325°C respectively.

In conclusion, the remediation was effective at most locations of the container at a rate of contamination reduction superior to 95% for all types of hydrocarbons.

7. Additional information

7.1 Lesson learnt

More heat resistant materials (no plywood) need to be used to ensure safety of the installation throughout the entire treatment and some further design optimisations can be made to induce a more homogenous heating and a better demobilization (insulation and dust issue).

7.2 Additional information

1) Soil temperatures:

Most of the curves of the soil temperature follow the normally observed three phases of heating:

- Linear rising from ambient temperature to 100°C
- Stabilization at 100°C for a few days (depending on water content)
- Linear rising from 100°C to the Target Temperature (TT)

The stabilization at 100°C is due to the evaporation of the water into the soil. The temperature stays at 100°C if water is not fully evaporated.

2) LECA temperatures:

The empty space between the sheet piles and the plywood all around the container is filled with LECA, acting as an insulation layer. Several thermocouples were placed in the LECA to measure the evolution of temperature in the insulation layer, to evaluate the energy loss. The location of these thermocouples is shown on the figure 7.

LECA temperatures never exceeded 100°C, except for locations T1 and T12, which respectively reached 110°C and 158°C. As described for soil temperatures before, the C compartment heated faster as it had more direct power income from the first meters of the heating wells from the 4 burners (temperature gradient along the heating wells), which explains the higher temperatures in the insulating layer. The temperatures show that the insulation had a positive effect in keeping the energy inside the container on its sides.

3) Temperatures under each compartment:

Thermocouple tubes were placed under each compartment, to follow the loss of energy from the bottom of the container, where no insulation is installed, as the metal was in contact with the ground. The temperatures under each compartment show that the

energy is not well kept inside the container at the bottom.
Finding ways to insulate the bottom of the container should be a subject of optimization.

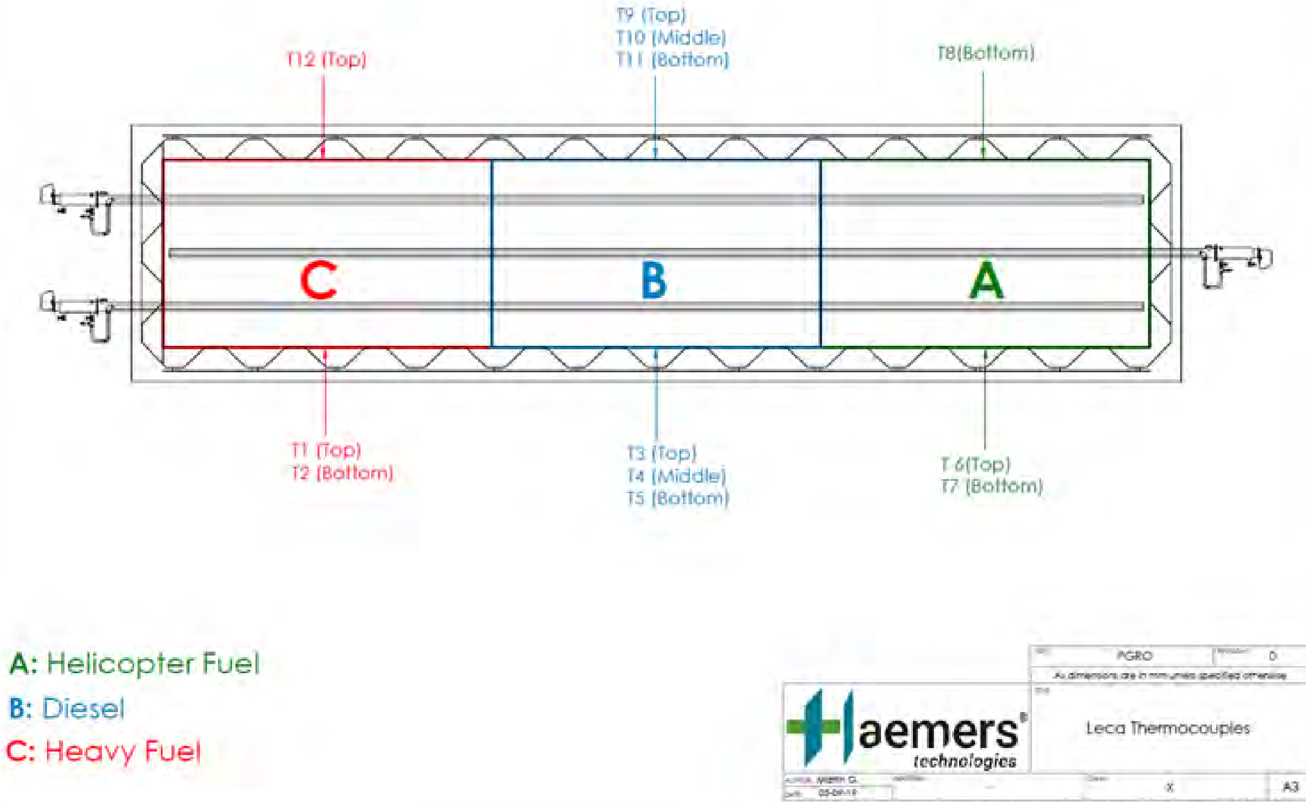


Figure 7 - Container design and dimensions

4) Soil pressure:
It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P<P_{atm}$), which will consequently avoid fugitive emissions during the treatment. The constant vacuum created in the soil also improves the decontamination. The treatment was started with a satisfactory slight vacuum in the container, but the pressure increased over the first days, to get close to 0 mbar. This is mainly due to the reaching of the 100°C plateau, with all the water vapor bringing positive pressure in the soil. Once the plateau was past, the measured pressures started to go towards more negative values again.

5) Emissions control:
Various parameters (O_2, CO_2, CO, SO_2) were manually monitored with a gas analyser (MRU Optima7) at the exhaust of the vent to control emissions to the ambient air, making sure that these emissions respect the local norms. The emissions at the vent are shown in the figure below.

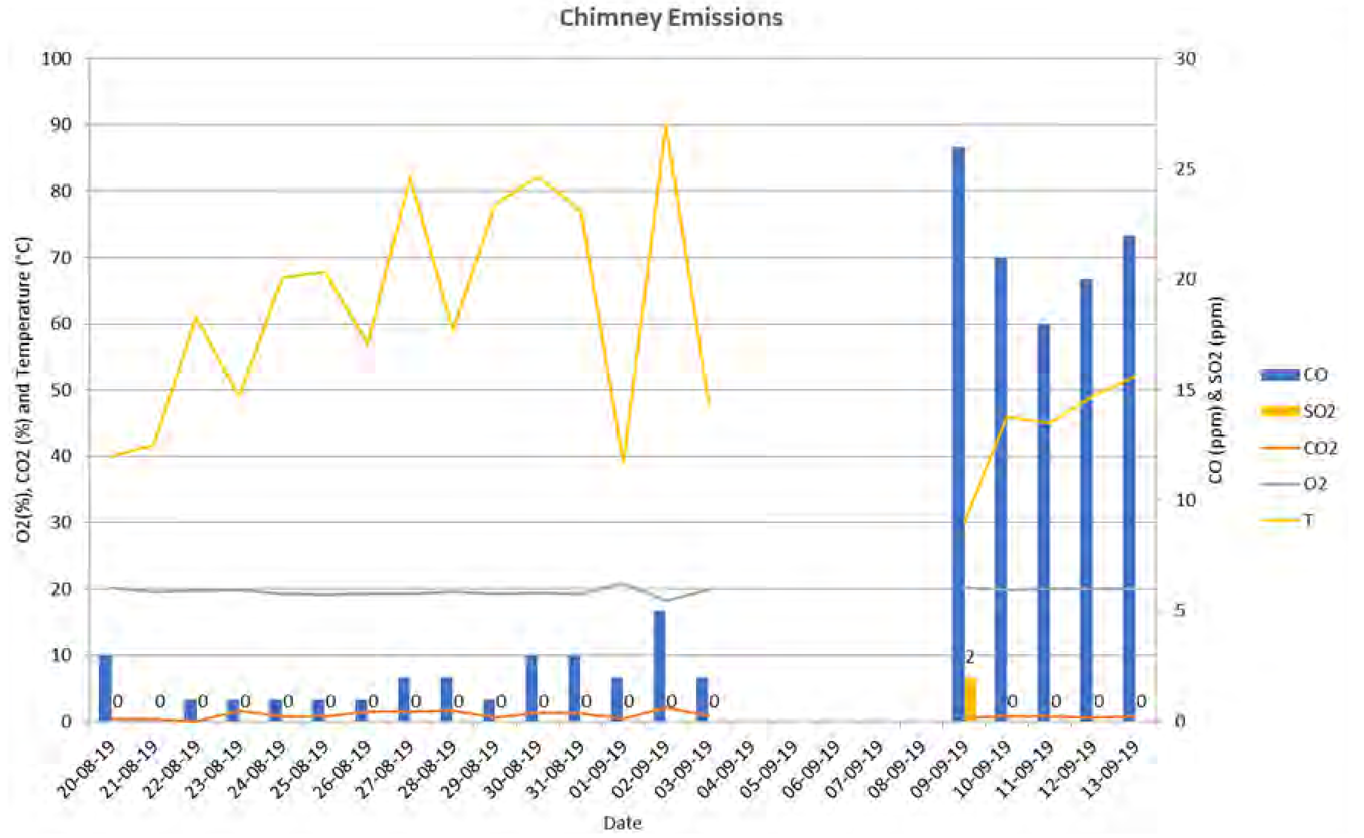


Figure 8 - Chimney emissions evolution during treatment

Before the shutdown on the 4th of September for maintenance, emissions have always been very low. The increase of CO concentration afterwards is mainly due to the decreased power of the burners and therefore less efficient reburn and catalyst actions.

7.4 Additional remarks

The ex-situ pilot project demonstrated to be a fast and reliable approach for the remediation of contaminated soil with hydrocarbons. Such technology and the way it is applied does not need much equipment to mobilize with a relatively low fuel consumption to heat the soil.

Glossary of Terms

Term **(alphabetical order)**	**Definition**
VTU	Vapor treatment unit

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.13

1.1 Name and Surname	Willian Felipe Do Prado
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	willian.doprado@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The project is in Poland at the city of Świętochłowice.

The contamination on site was due to leaks of waste from the chemical industry nearby. The sludges were highly contaminated by Phenol, BTEX, PAHs (mainly Naphthalene). The sludges were dredged and dewatered up to 50% of dried mass, followed by a thermal desorption treatment (ESTD) on site.

Figure 1 – Site overview

2.2 Geological setting

The soil treated was dewatered sludges as illustrated below. The bottom of the pond was dredged then the sludge was passed through a press to obtain the dewatered soil “cakes” used during the thermal desorption phase.

Figure 2 - Dewatered sludge

2.3 Contaminants of concern

Regarding the pile, different pollutant concentrations have been observed as shown in the tables below:

Contaminants Pilot	Average Conc. In Soil [mg/kg d.m]	Max Conc. In Soil [mg/kg d.m]	Target [mg/kg d.m]
BTEX	349	414	20
PAHs	14.200	15.800	20
Phenol	1.049	1.740	20
C_5-C_{35}	10.670	16.250	N.A.

Table 1 – Contaminant in the pilot

Contaminant Pile 1	Average Conc. In Soil [mg/kg d.m]	Max Conc. In Soil [mg/kg d.m]	Target [mg/kg d.m]
BTEX	-	-	20
PAHs	6.900	11.200	20
Phenol	-	-	20
C_5-C_{35}	7.777	10.500	N.A.

Table 2 – Contaminant in Pile 1

Contaminant Pile 2	Average Conc. In Soil [mg/kg d.m]	Max Conc. In Soil [mg/kg d.m]	Target [mg/kg d.m]
BTEX	-	-	20
PAHs	7.065	12.500	20
Phenol	-	-	20
C_5-C_{35}	6.985	12.500	N.A.

Table 3 – Contaminant in Pile 2

2.4 Regulatory framework

The target concentration for each pollutant was set at 20 ppm.

3. Pilot Scale

3.2 Treatment unit (pilot scale)

The ex-situ Smart Burner^{TM} Technology developed by Haemers Technologies, shown in the figure below, heat polluted soil using thermal desorption process after excavation. More precisely, a soil pile is built with steel tubes inserted to remediate. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} (in the case of hydrocarbons pollution).

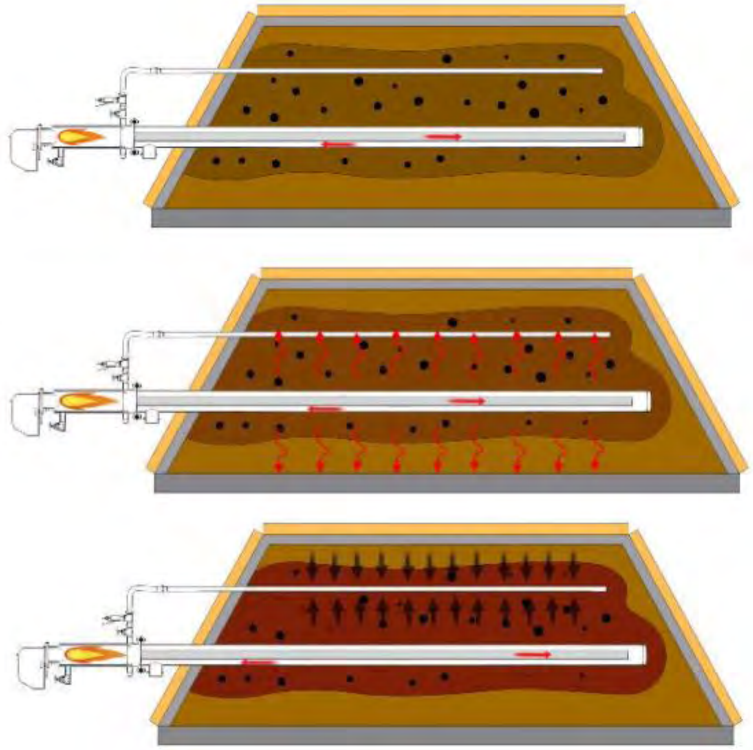


Figure 3 - Ex-situ Smart Burner^{TM} technology with reburn

To respect timelines, it was concurrently decided that the pile would be of 168m³ instead of 250m³ and would be in reburn mode.

Figure 3 shows the as-built design layout of the pilot pile and table below summarizes the characteristics of the final pilot pile installation.

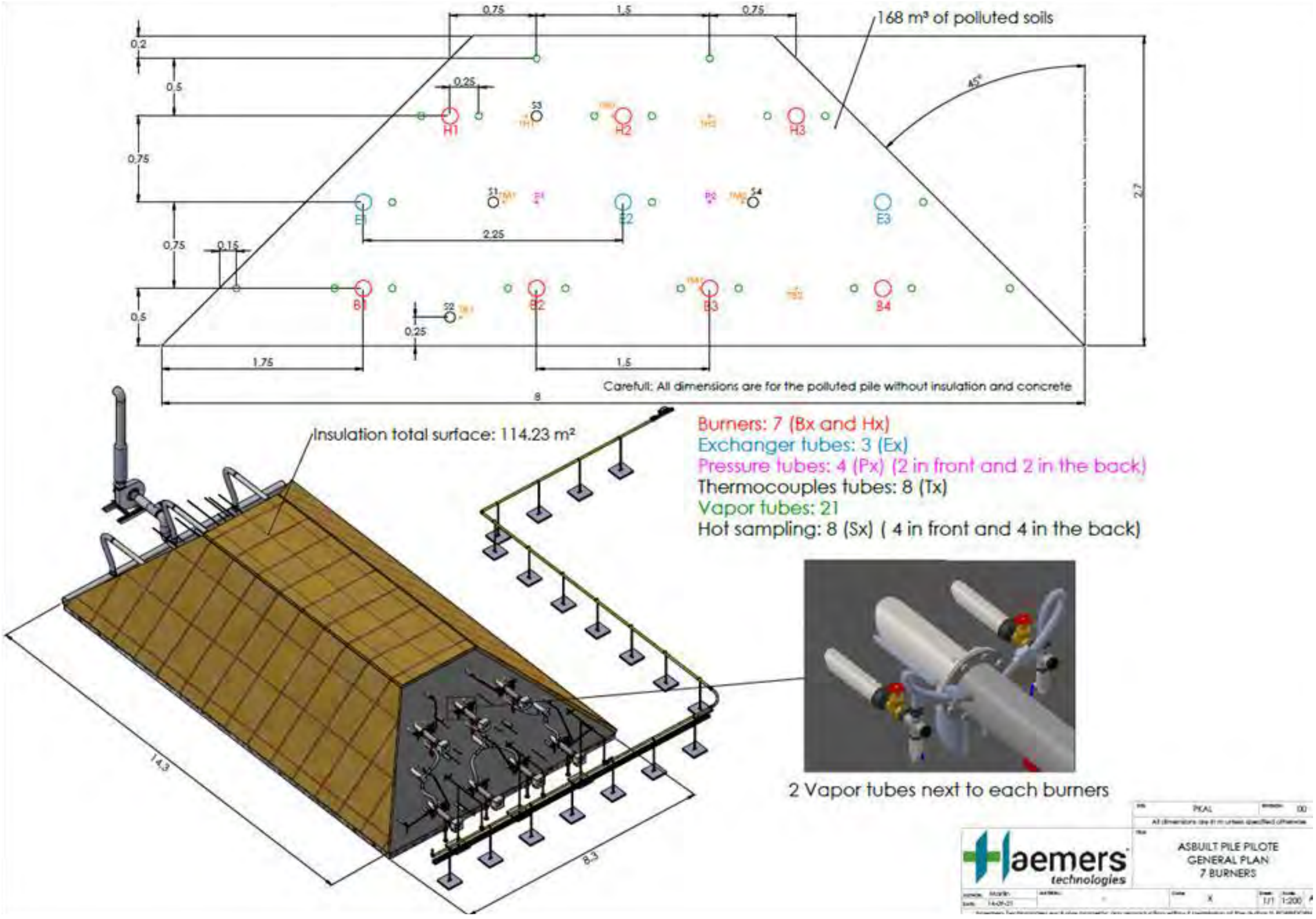


Figure 4 – Pilot as-built layout

ESTD Installation	
Number of heating tubes	7
Number of extraction pipes (vapour)	21
Fuel used	Propane
Vapor treatment	Reburn

Table 4 – Characteristics of ESTD installation

3.4 Post Treatment for effluent (pilot scale)

The post treatment for effluent was based on the reburn technology. The vapours from the soil are extracted through the steam tubes. The negative pressure in the tubes is created by the fans, and the vapours (water and hydrocarbons) exit through the steam tubes. The vapours and gases are directly reinjected into the burners to undergo different degradation mechanisms: hydrolysis, partial oxidation and total oxidation.

The main mechanism expected from the treatment after recovery is a complete oxidation in the burners. The products of combustion are then drawn off and sent to the chimney.

3.5 Post Treatment for effluent (pilot scale)

A condensate trap has been installed to collect the liquid coming from the condensation of the polluted vapor in the vapor network.

Figure 5 - Condensate trap

3.6 Control parameters (pilot scale)

The different parameters to follow-up the trial treatment is divided into 6 parts:

- Soil temperature at 3 different depths at 6 different locations
- Pressure monitoring at 4 locations
- Emission control at the venting
- Fuel consumption
- Hot Sampling

Connected monitoring boxes were installed to monitor during the treatment and the cooling phase the soil temperature at different points in the pile. It allowed HT team to keep a close eye on the heating profile evolution of the soil.

Atmosphere emissions of CO2, CO and CxHy were also monitored manually every day to ensure a good quality of the treatment.

4. Full-scale application

4.1 Main treatment unit

The main treatment unit for the next two piles was also a ESTD (ex-situ thermal desorption) with a reburn mode as explained for the pilot but slightly modified as a Vapor treatment Unit was added to capture the condensate coming from the polluted vapor flow the reburn mode to ensure pollutants capture and good environmental release. The idea of the implementation of a VTU with a reburn mode was to extract produced vapours from the soil through collectors to a condensation vapor treatment unit. The vapours will go through a series of elements such as a heat exchanger and knock outs, to promote water condensation, and then will be sent back to the combustion chambers of the burners of the heating tubes for final contaminant oxidation. Condensate would be then collected through a series of tanks and a separator for final disposal or treatment. In this way, it allowed HT team to have a better control on the water vapor produced by the thermal desorption treatment.

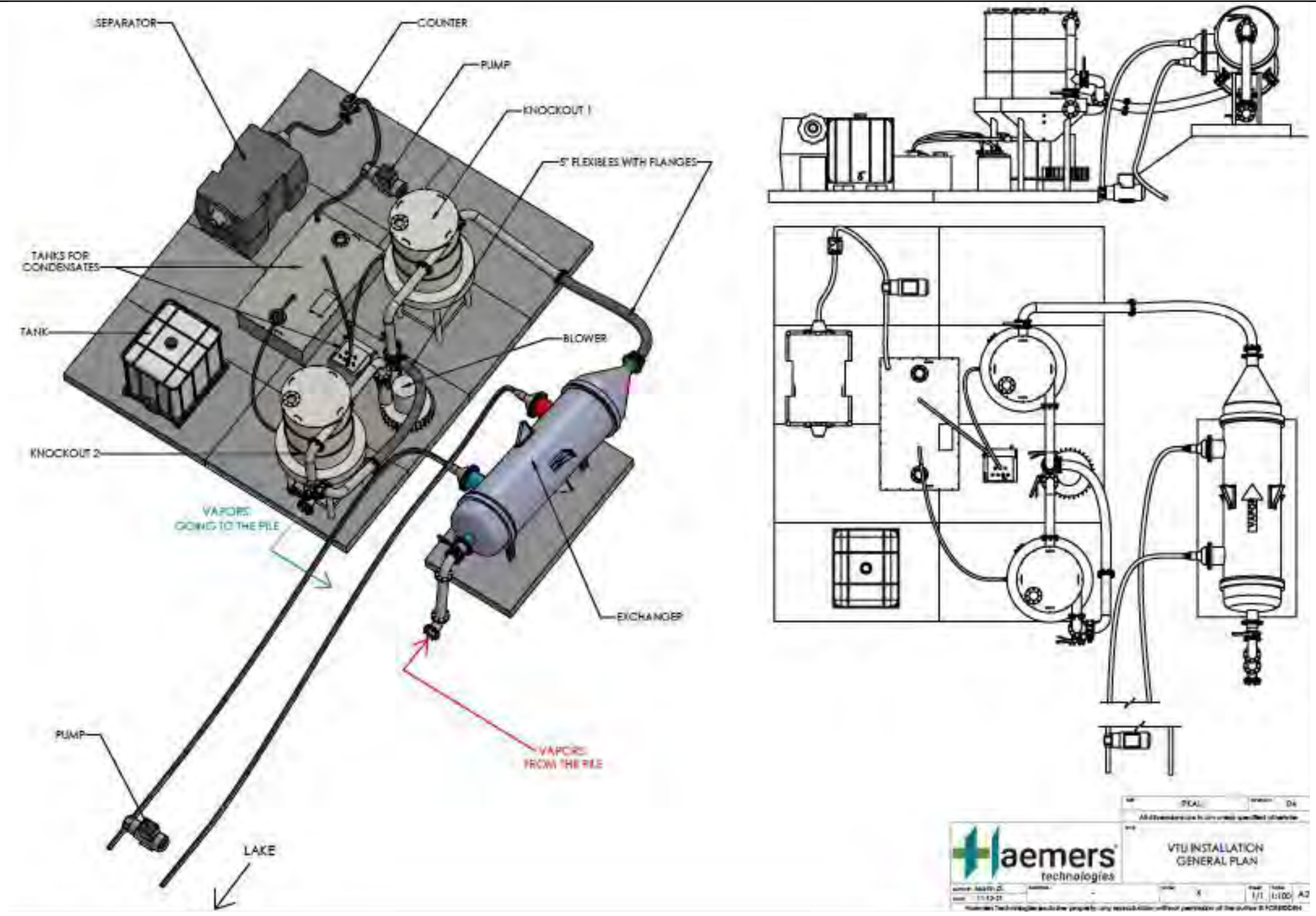


Figure 6 – Vapor treatment unit

To optimize the amount of soil that could be treated in one single pile, and based on the experience of the pilot, the height of the pile has increased up to 3m when compared to the pilot (2.7m). The table below present the sizing characteristics of pile 1.

Length (m)	Distance between heating pipes (m)	Width (m)	Height (m)	Volume (m³)	Payload (tons)
14.3	1.5	35	3	1051.62	1472.3

Table 5 - Sizing characteristics of pile 1

Figure 7 shows the as-built design layout of the pile 1 and the table below summarizes the characteristics of the final pile 1 installation.

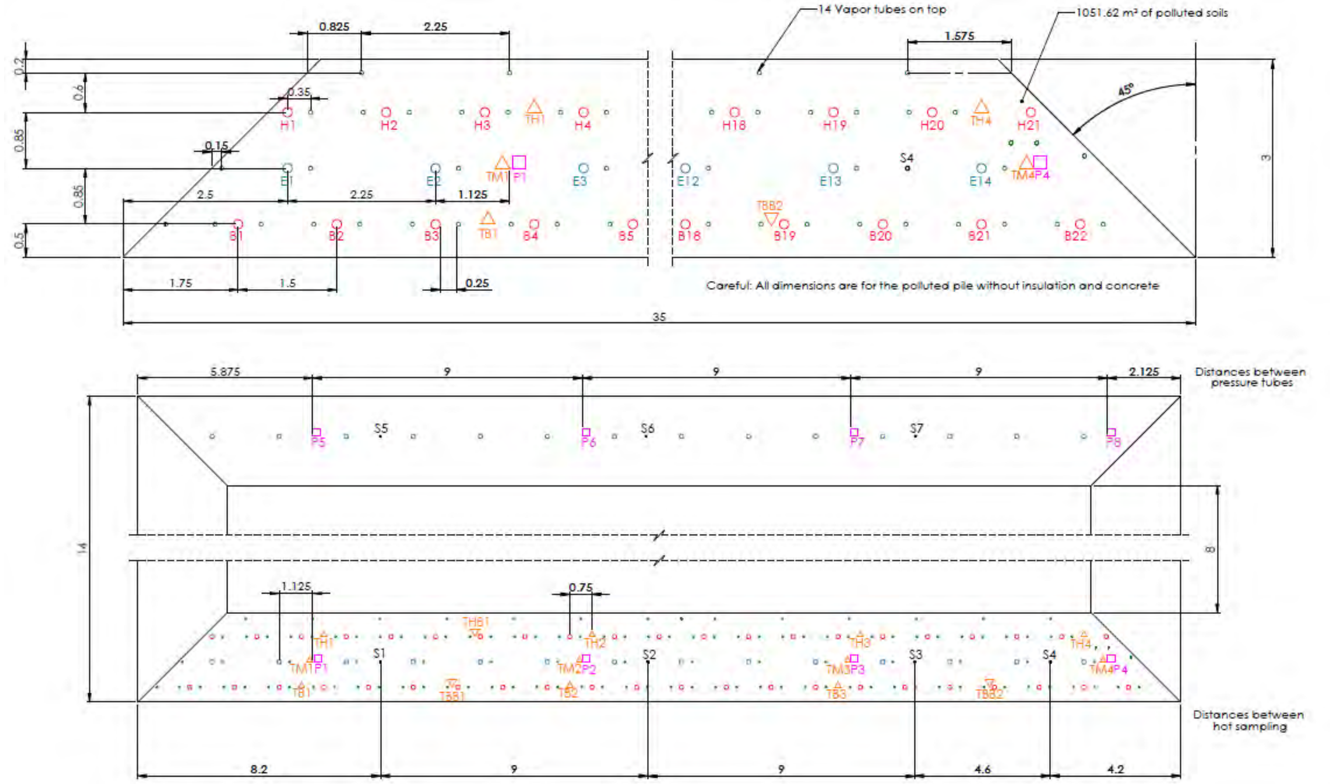


Figure 7 – Pile 1 as-built layout

ESTD Installation Pile 1	
Number of burners	43
Number of heating tubes	43
Number of extraction pipes (vapour)	119
Fuel	Propane
Vapor treatment	Hybrid: VTU and Reburn

Table 6 - Characteristics of the final pile 1 installation

Some modifications regarding the concrete have been made for pile 2 to increase its stability and ensure a good integrity to the pile for the entire treatment but it kept the same profile as pile 1.

ESTD Installation Pile 2	
Number of burners	56
Number of heating tubes	56
Fuel	Propane
Vapor treatment	Hybrid: VTU and Reburn

Table 7 – Characteristics of the final pile 2 installation

4.3 Post treatment for effluent

The post treatment for effluent was based on the reburn technology. The vapours from the soil are extracted through the steam tubes. The negative pressure in the tubes is created by the fans, and the vapours (water and hydrocarbons) exit through the steam tubes. The vapours and gases are directly reinjected into the burners to undergo different degradation mechanisms: hydrolysis, partial oxidation and total oxidation.
The main mechanism expected from the treatment after recovery is a complete oxidation in the burners. The products of combustion are then drawn off and sent to the chimney.

4.4 Post treatment for water

Once collected by the vapor network and the vapor treatment unit, the condensates were sent to settling tanks to separate the water from the pollutants. Afterward, the polluted supernatant was collected and sent to an appropriate waste management site.

4.5 Control parameters

The different parameters to follow-up the treatment is divided into 6 parts:

- Soil temperature at 3 different depths at 11 different locations
- Pressure monitoring at 8 locations
- Emission control at the venting
- Fuel consumption
- Hot Sampling

Connected monitoring boxes were installed to monitor during the treatment and the cooling phase the soil temperature at different points in the pile. It allowed HT team to keep a close eye on the heating profile evolution of the soil.
Atmosphere emissions of CO_2, CO and C_xH_y were also monitored manually every day to ensure a good quality of the treatment.

5. Results

5.1 Removal rate

The official hot sampling was done after 101 days of treatment for pile 1. The COC(s) identified and analysed during the official sample are listed in the previous sections. This table shows that all the samples reached the target values for pile 1. All hydrocarbon related contaminants were effectively remediated

Contaminant Type	S2	S3	S7	S8	Targets
Phenol (mg/kg)	<0.2	<0.2	<0.2	<0.2	20
BTEX (mg/kg)	< 6.0	< 6.0	< 6.0	< 6.0	20
PAHs (mg/kg)	< 0.80	<0.8	1.01	2.83	20

Table 8 – Confirmation samples for Pile 1

The pollutant Mass Reduction was up to 99.86% for both piles.

7. Additional information

7.2 Additional information

The results presented in this section only concern Pile 1.

1) Soil temperature by height

The next graphs show the evolution of the temperature measurements at the bottom, middle and top of the pile during the entire treatment. The temperatures follow the same behaviour as the theorical temperature evolution and can be separated in the same three phases. During the first month, the temperature rose linearly up to about 100°C, when it reached the plateau. The temperatures of the pile 1 have been constant to 100°C for approximatively 45 days. However, the bottom temperatures seem to take about 2 weeks more than the rest of the pile to rise above the plateau. Similar situation has been experienced during the pilot, reinforcing the hypothesis of the higher amount of water to the bottom of the pile. When all the water was vaporized and extracted, the temperatures rose again.

The third phase of the treatment has been extremely fast. A phenomenon of auto combustion has been experienced in most part of the pile. This phenomenon has a great potential in thermal desorption and allows great optimization of energy expenses. However, the trigger for this phenomenon was easier achievable during the pilot when compared to the Pile 1.

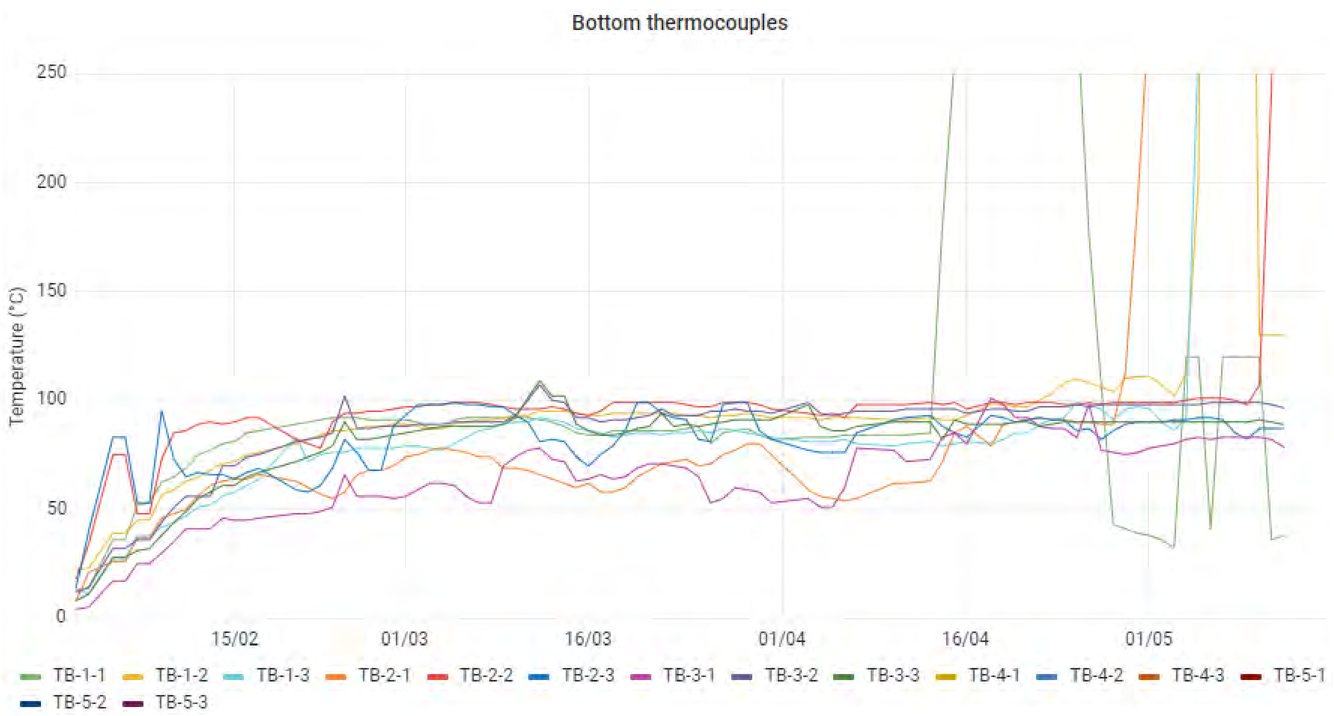


Figure 8 - Bottom temperatures during the treatment

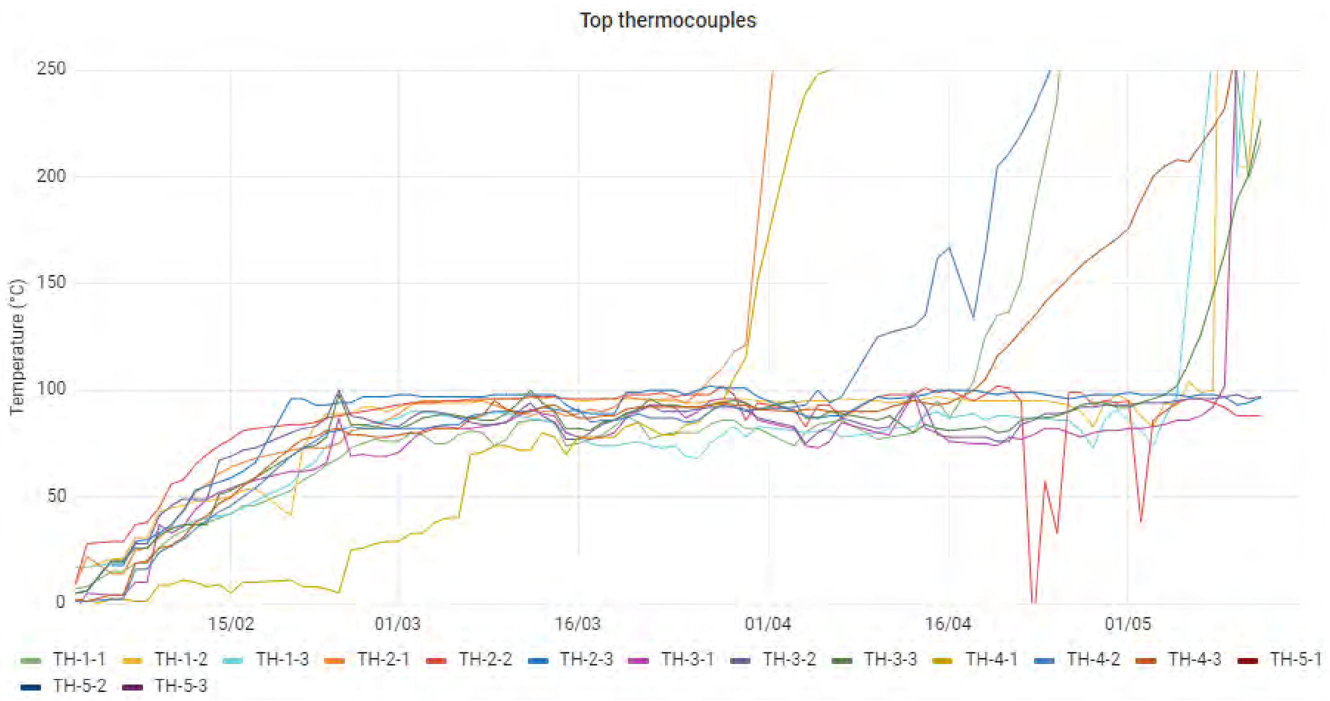


Figure 9 - Top temperatures during the treatment

2) Soil temperature by depth:

The next graphs show the evolution of the temperature measurements at the front, center and back of the pile during the entire treatment. The temperatures follow the same behaviour as the theorical temperature evolution and can be separated in the same three phases.

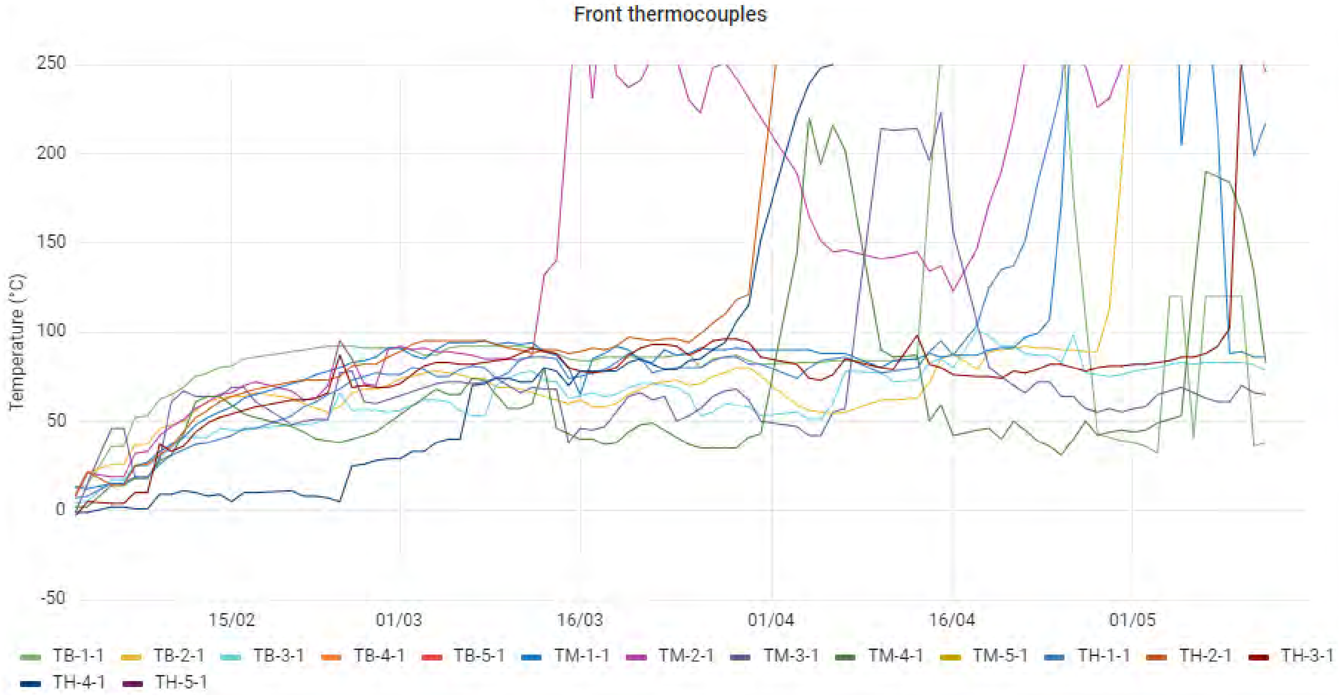


Figure 10 - Front temperatures during the treatment

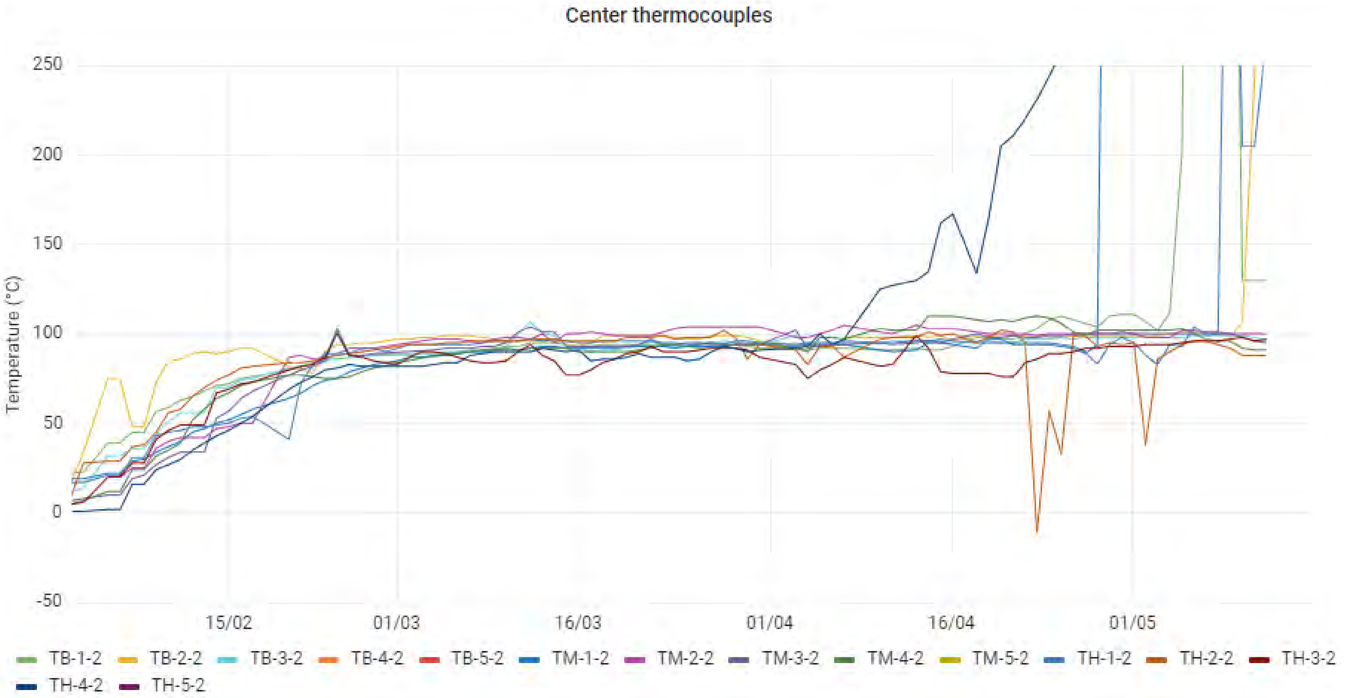


Figure 11 - Center temperatures during the treatment

The temperatures to the front of the pile rise faster than the middle and the back of the pile. This is given by the fact that the vapor extraction is done by the front of the pile.

Considering that in presence of liquid water the temperature cannot overcome the 100°C, the zone of the pile where the vapor extraction is better is the earliest to rise in temperature.

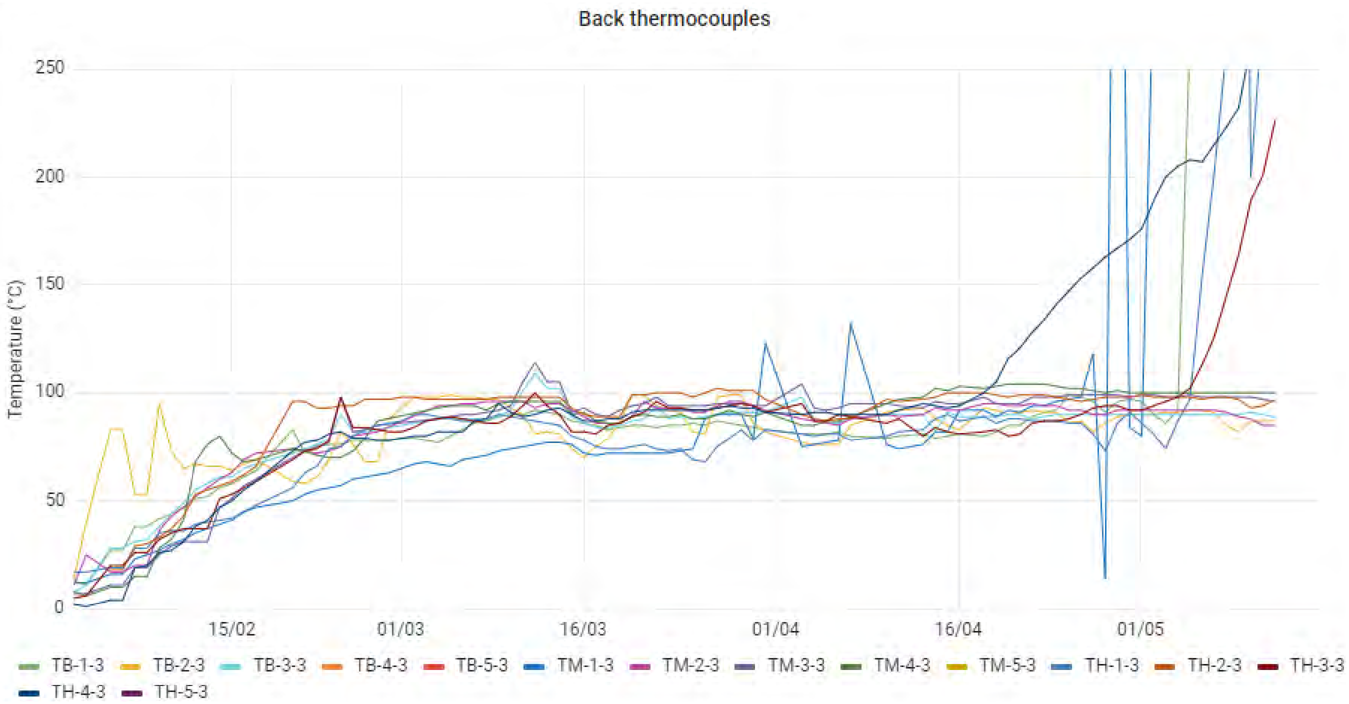
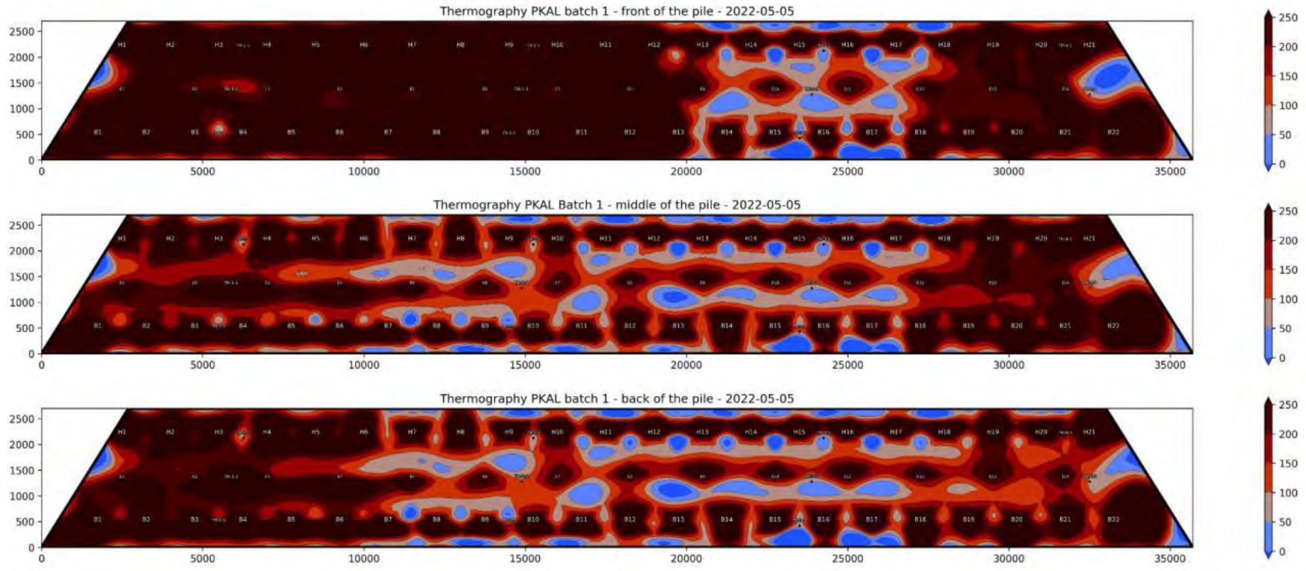


Figure 12 - Back temperatures during the treatment

3) Thermographies:

A thermography has been produced by the end of the treatment to visualize the amount of soil that could be treated. Note that all temperatures above the target temperature are at the same colour because the goal of the model is to prevent non treated parts.


Thermography PKAL batch 1 - front of the pile - 2022-05-05

Thermography PKAL Batch 1 - middle of the pile - 2022-05-05

Thermography PKAL batch 1 - back of the pile - 2022-05-05

Figure 13 - Thermography of the pile at the end of the treatment

The thermography shows the zones of the pile where the target temperature was reached. It seems that the left side of the pile has been better heated than the right one. Also, the thermography reinforces the idea that the treatment has not been totally homogenous. The main hypothesis is that the left part, which was built and protected from rainwater earlier in the project was dryer, when compared to the right part, built during the wintertime when water was probably frozen, hindering the drainage of the water before treatment.

4) Pressure monitoring:

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P<P_{atm}$), which will consequently avoid fugitive emissions during the treatment. The constant vacuum created in the soil also improves treatment.

The pressures inside the pile remained generally negative during the entire treatment. A big difference on the vacuum can be seen during the first stage of the treatment before the pile reaches 100°C and the rest of the treatment, when the vacuum is lower because of the big number of vapours produced.

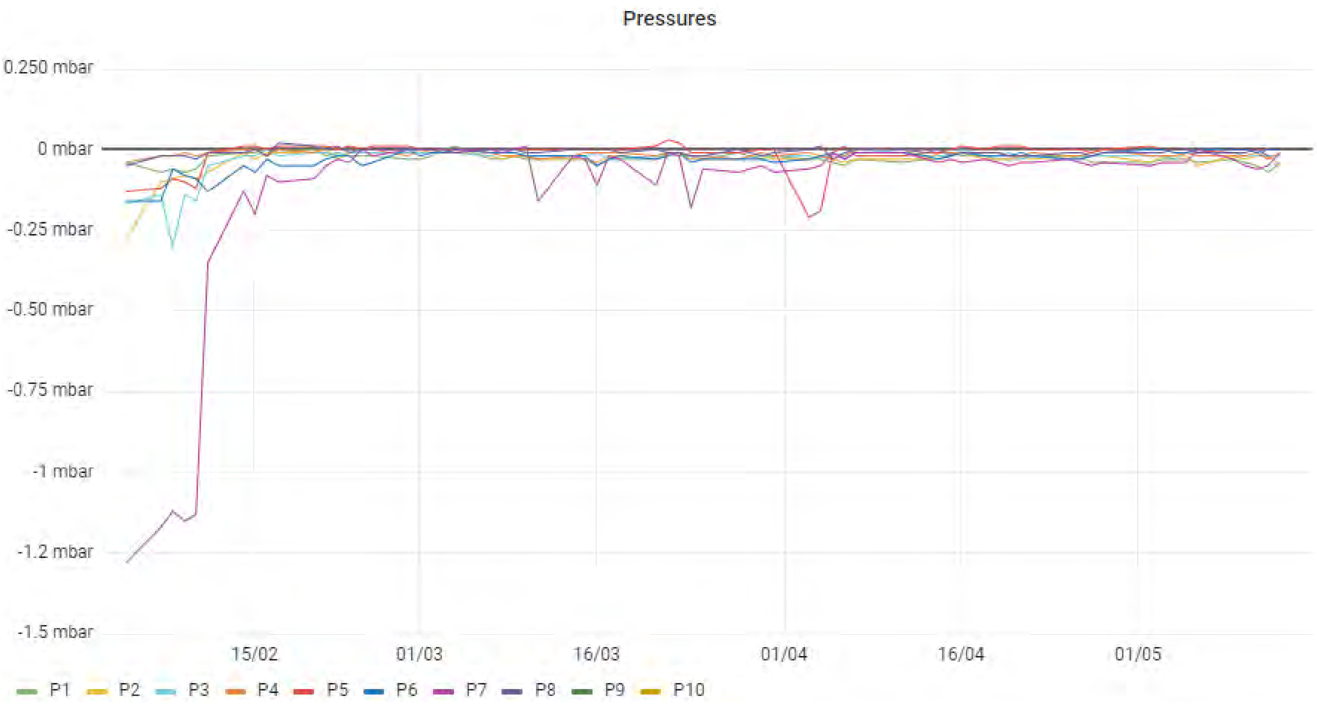


Figure 14 - Pressure monitoring during treatment

5) Emission control:

Various parameters (CO, C_xH_y, NO, NO_x SO_2) were manually monitored with a gas analyser (MRU Optima7 & MRU Vario Luxx) at the exhaust of the vent to control emissions to the ambient air, making sure that these emissions respect the local norms.

Figure 15 and Figure 16 show the evolution of the monitored parameters during the treatment.

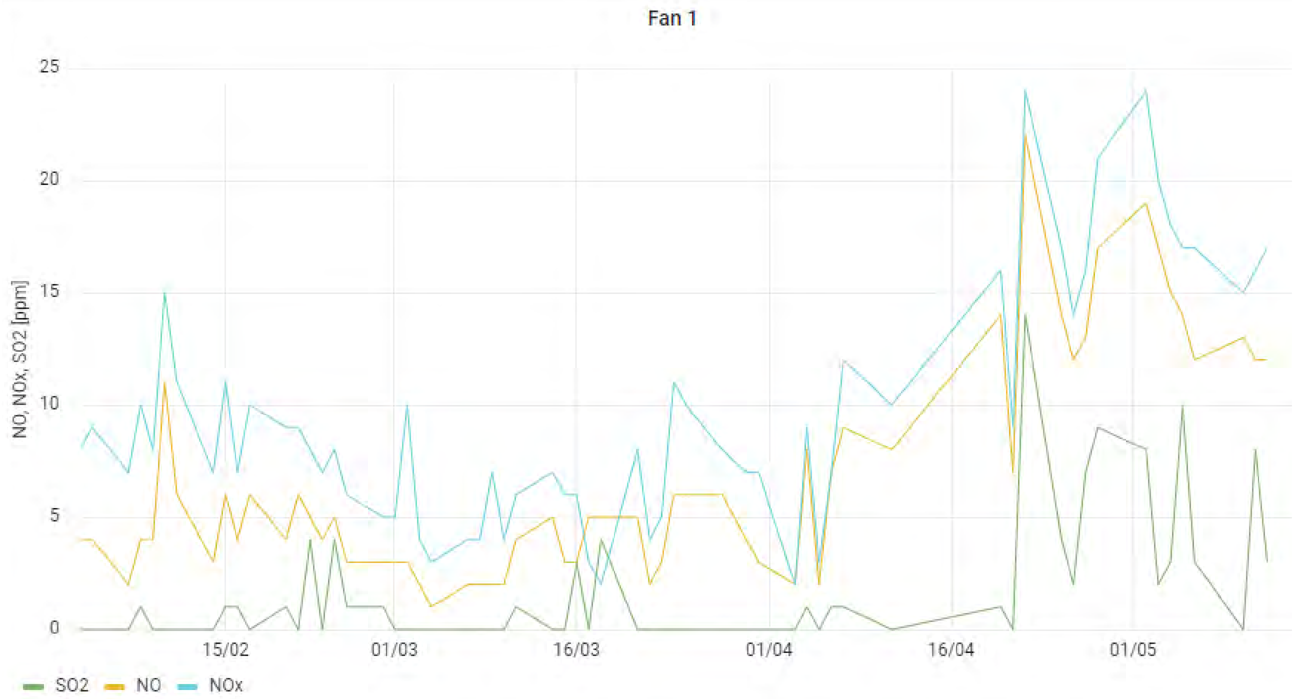


Figure 15 - Emission evolution at the chimney of Fan1

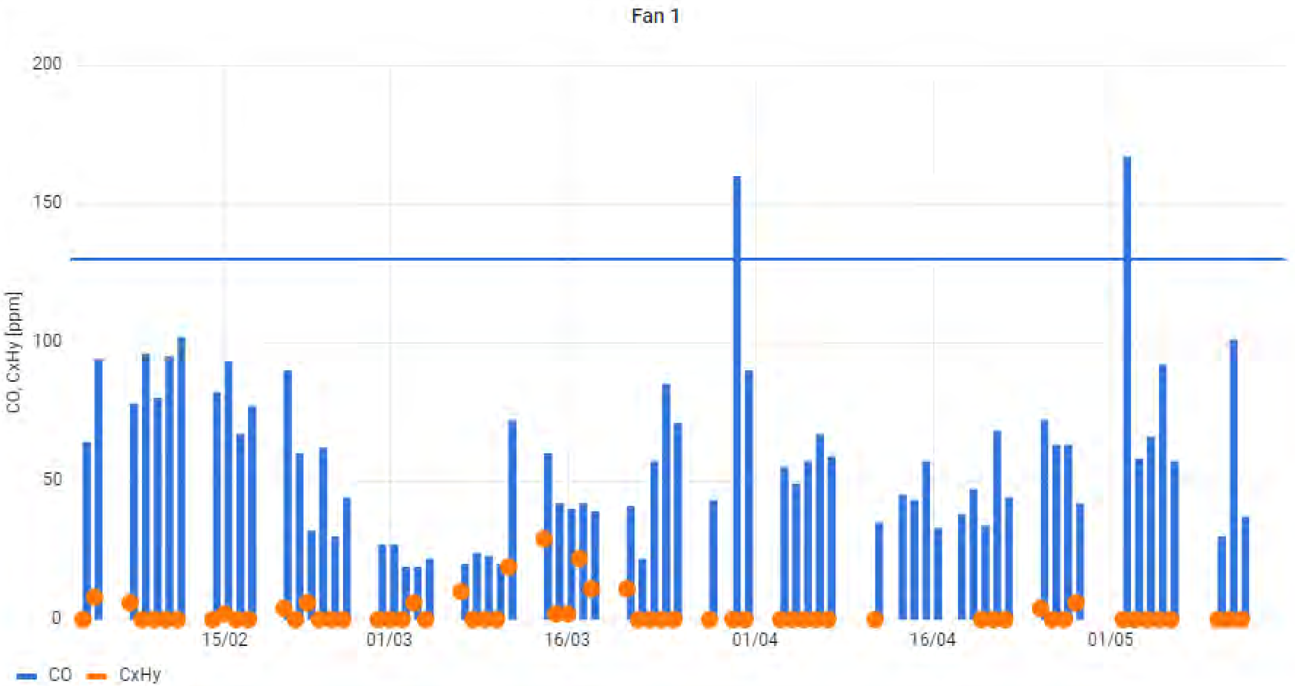


Figure 16 - CO and CxHy emission evolution at the chimney of Fan 1

These measures have been taken for each fan every day but here only the emissions of Fan 1 are presented as an example.

6) Condensate:

The collection of the contaminated condensate has also been monitored as it gives a vision of the treatment progression. A total of more than 250m3 have been collected with an average of 6m^3 a day.

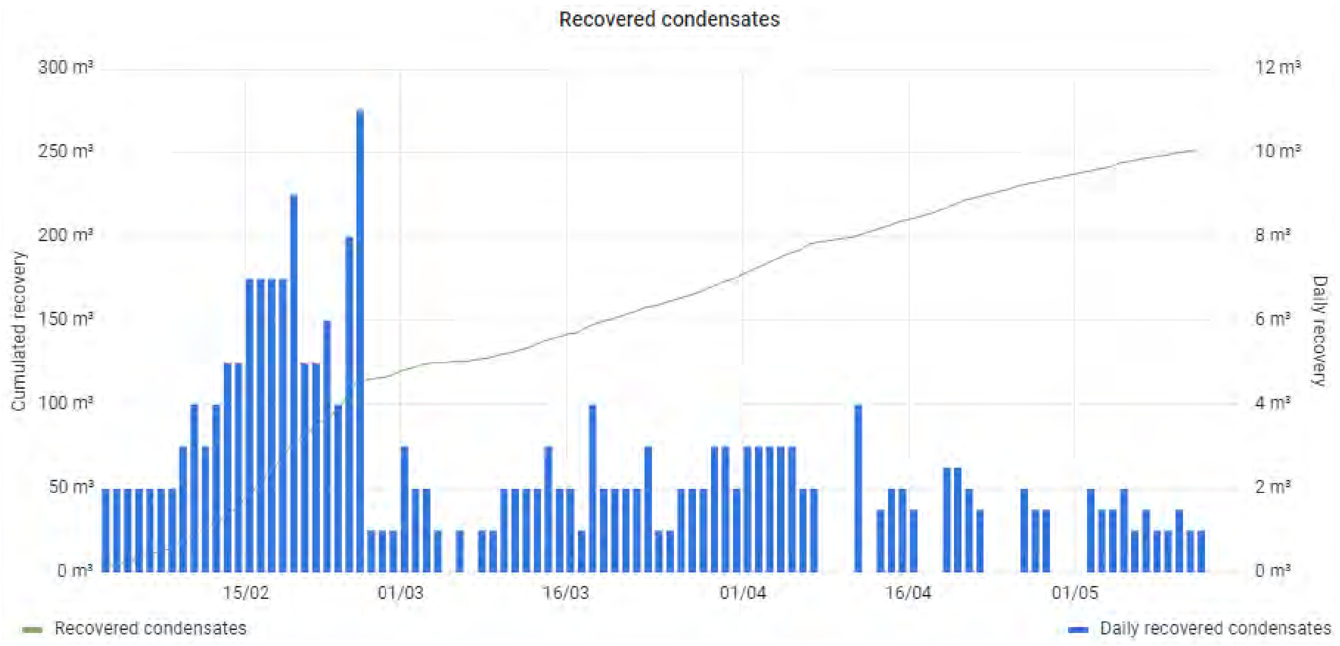


Figure 17 - Collected condensate during treatment for pile 1

7.4 Additional remarks

The reduction of volume due to the water in the soil is a predicted phenomenon and happened in other projects. However, for ESTD treatment of dewatered sludges the water content is much higher. For ESTD, a thicker layer of concrete may help to fix the issue of cracking but an additional solution from a structural point of view needs to be addressed. For this purpose, the use of reinforced concrete on some sections and "mobile" slabs inside the pile below the main layer have been done on the second pile.

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.14

1.1 Name and Surname	Rabih Jenadri
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	rabih.jenadri@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The project is in Westwood Margate, Kent, UK.

The site is contaminated over 35 meters deep (unsaturated zone, saturated zone, water table). The partner (Ecologia) decided to apply several remediation techniques simultaneously to accelerate soil decontamination: Steam Injection, Thermal Desorption, Groundwater Extraction and Air Sparging.

To improve their treatment method efficiency (steam injection), the partner decided to work conjointly with Haemers Technologies Smart Burners to favour the VOCs collection in their vapor treatment unit already on the site to treat the contaminated vapours.

Figure 1 – Site view from above

2.3 Contaminants of concern

The site is contaminated over 35 meters deep (unsaturated zone, saturated zone, water table). Contaminants of concern are not well documented because pollution is located at deep depth.

The maximum concentrations could be found at 5m to 25m below ground level and two main pollutants of concern were found:

- Benzene: 0,05 mg/kg soil
- Trimethylbenzene: 20 mg/kg soil

Mercury was also present as a soil contaminant, but at shallower depths and much less spread in the batch. Since it was not an objective, the partner requested to keep soil temperatures at these depths as low as possible to avoid mercury vapor generation.

2.4 Regulatory framework

Haemers Technologies remediation objectives were not set in treatment target residual concentration but in temperatures which was: batch “cold points” at 90°C for 10 days.

The cold points being the part of the soil in the treatment area that are the farthest from the heating source.

4. Full-scale application

4.1 Main treatment unit

Figure 2 – ISTD installation on site

The in-situ Smart Burner^{TM} Technology developed by Haemers Technologies heats up polluted soil using thermal desorption process with no excavation involved. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burners, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes. These recovered vapours are then treated in a vapour treatment unit (VTU).

This ISTD project of 3875m³ (7000 tons) was treated with 16 propane gas Smart Burners^{TM} using remote flame technology (treatment from 9 to 29m bgl) and a small VTU managed by the partner.

The remote flame (RF) technology is used when the pollution to treat is lower than ground level. The flame is directly brought to the soil level of interested to reduce heat loss and reduce fuel combustion during treatment. The combustion chamber, place where the flame is generated, is placed in the heating tubes at the desired depth and is made of a refractory component to resist to the heat of the flame.

The next figures show the principles and the different elements of the remote flame technology.

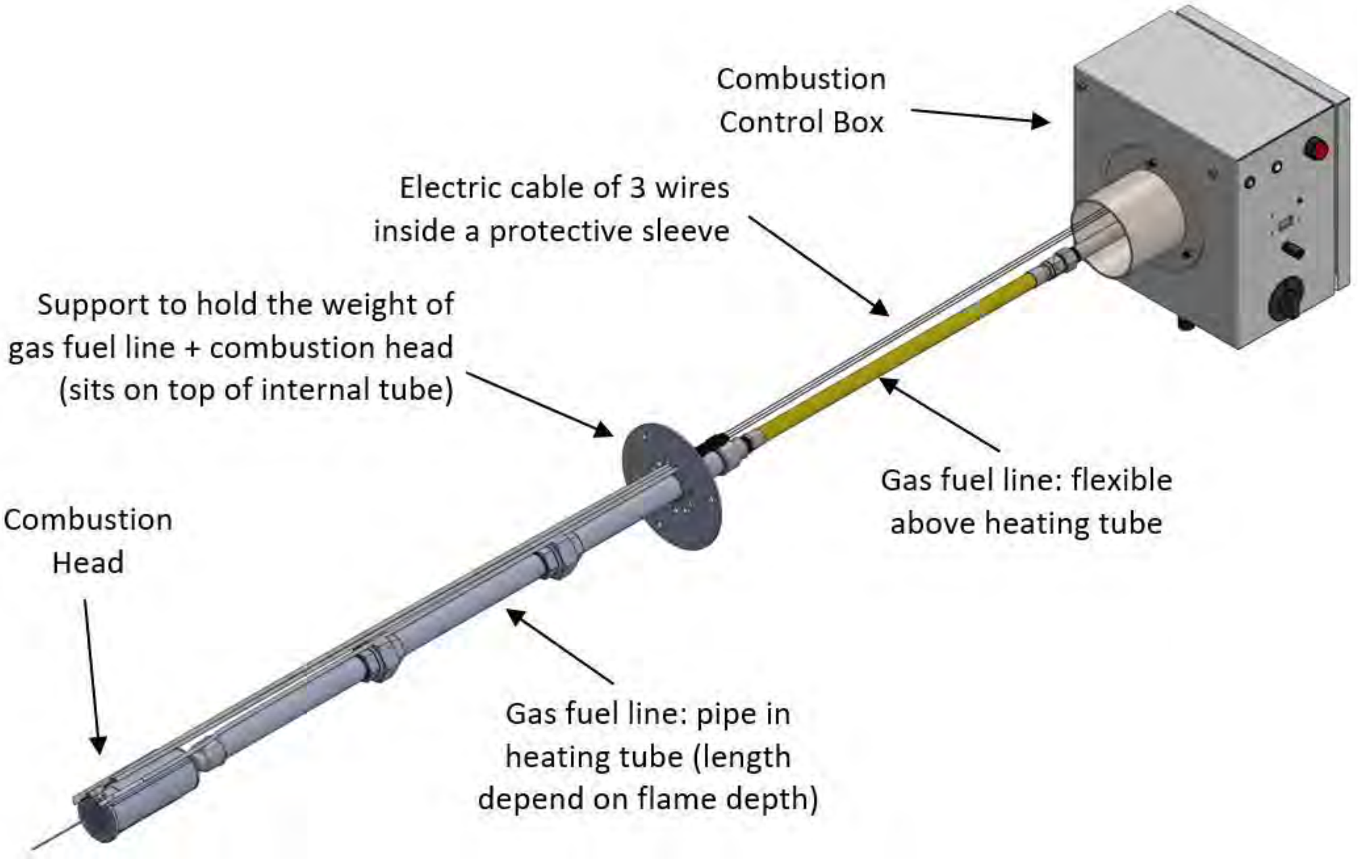


Figure 3 – Remote flame technology

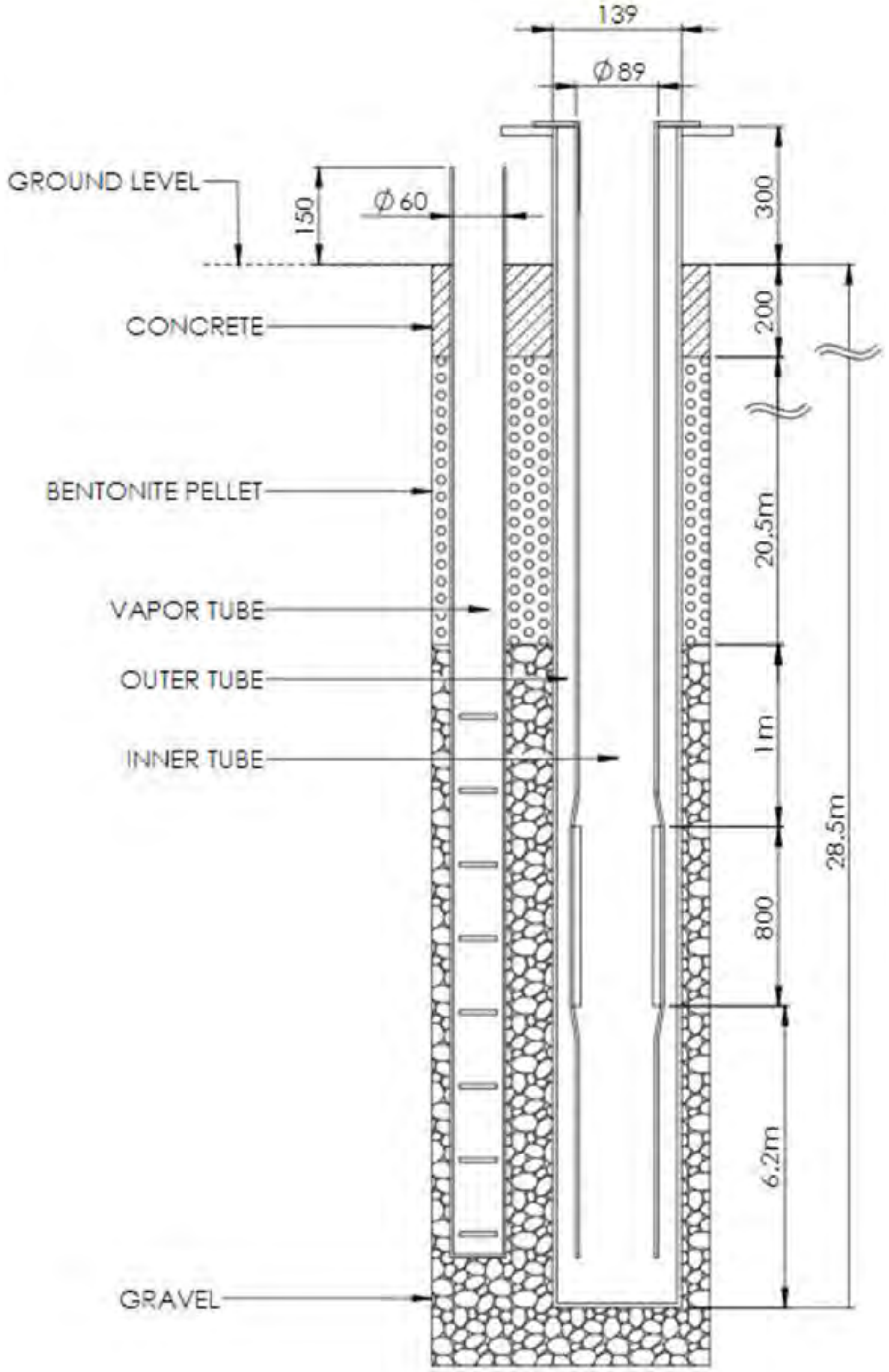


Figure 4 – Layout of the tubes

On site, wells interdistance was 5 meters. The batch was separated into 2 distinct areas: one with 3 wells of flame located at 9m below ground level (bgl) and the other with 13 wells of flame at 21,5m bgl (as shown in the figure below).

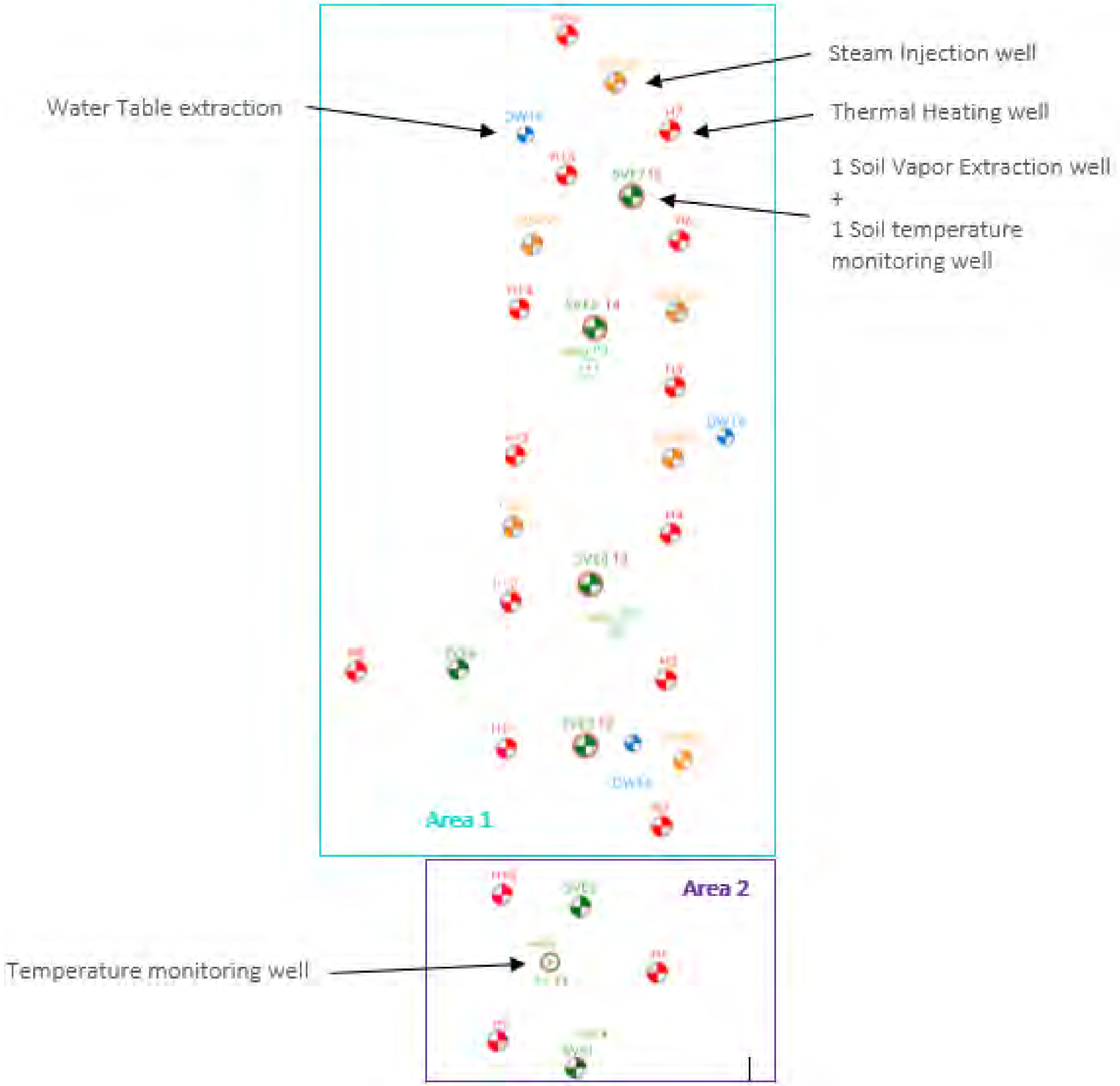


Figure 5 – Batch 2 distinct areas due to heating depth differences

4.3 Post treatment for effluent

No post treatment effluent was necessary as during this treatment HT team only extracted combustion gas and no contaminated gas. The contaminated vapours were extracted by the partner and treated with their vapor treatment unit.

4.4 Post treatment for water

Water table depth fluctuated naturally between 25m and 30m bgl. The partner was responsible for maintaining it deeper than 29m bgl by pumping water out from several wells to avoid immersing the heating wells and thus extending the treatment duration. Some pumping wells were out of service after 40 days of heating because the water in them and/or soil around them were above 90°C which caused the pump to fail. This caused the water table to rise occasionally to 26,8m bgl in the batch region contained between Heating well 4 and 16 which led to longer treatment time.

4.5 Control parameters

Five soil temperature monitoring wells were installed to continuously measure at the following depths:

- Monitoring well T1 had thermocouples at a depth of: 4m, 8m, 9m, 18m and 27m
- Monitoring wells T2, T3, T4 and T5 had thermocouples at a depth of: 15m, 20.5m, 21.5m, 24m and 27m.

Thermocouples were placed in soil at 4m and 15m bgl to monitor temperature at these depths to ensure that the temperature did not increase enough to evaporate the mercury present in some area on site.

In each heating well, 4 thermocouples were placed along the outer face of the internal tube. These measuring points allowed the HT operator on site to check if the produced energy is well distributed along the heating tube.

Six data acquisition boxes and a mini-PC were installed to manage all the data received from all the above thermocouples.

Figure 6 – Monitoring points

5. Results

5.1 Removal rate

There is no removal rate as such since the objective of the project was to enhance the Ecologia technology efficiency. No contaminated vapours were directly collected and treated by HT team. However, a target temperature was set and monitored.

All wells reached a temperature between 76°C and 90°C at all depths. The initially planned treatment time was exceeded by 36 days, so real total treatment was 146 days long rather than 110 days. Therefore, the propane consumption was also exceeded by 19,5%.

7. Additional information

7.1 Lesson learnt

During treatment and maintenance, it was found that the resistive igniter fix on the combustion head is more mechanically fragile than expected, a small force on its tip is sufficient to break it.

A new way to fix the heating head on the 1 inch gas pipe was study and applied to give more robustness to this part of the remote flame technology.

7.2 Additional information

1) Soil temperature

The soil temperature was monitored at 5 cold point locations (see Figure 6) with 5 different depths in each well. Almost all depths at all cold points reached the target temperature of 90°C as you can see on the two example graphs below.

Figure 7 – Temperatures evolution at cold point T1

Figure 8 – Temperatures evolution at cold point T2

2) Emission control:

Various parameters (O_2, CO_2, CO) were manually monitored twice per day at the exhaust fan stack in to control emissions released in the ambient air, making sure that these emissions respected the local norms. Figure 10 shows the emissions for CO during treatment, these values rarely exceeded the EU daily emission threshold of 50 ppm.

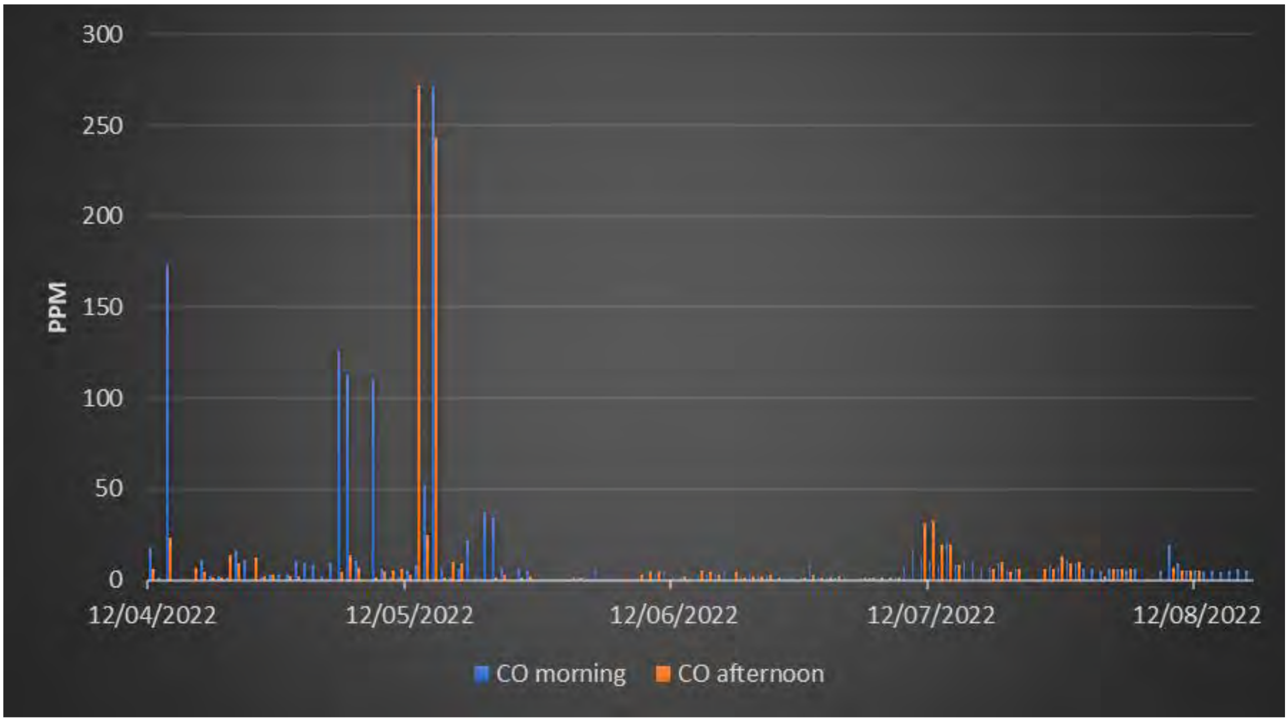


Figure 9 – CO emissions at stack due to combustion in all heating wells

Glossary of Terms

Term (alphabetical order)	**Definition**
ISTD	In-situ Thermal Desorption

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.15

1.1 Name and Surname	Jean Rhone
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	jean.rhone@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The site is in Rue Philip Lebon in the city of Saint-Nazaire, France. It is nowadays located at the city center of the city and is surrounded by apartments. It used to be a former gas plant.

The previous years, the site was occupied by a supermarket and a parking area. The remediation project took part of the "Restructuration de l'Ilot Lebon project" initiated by the SONADEV. The pollution is mainly PAH, naphthalene, TPH and BTEX. The water table was also contaminated.

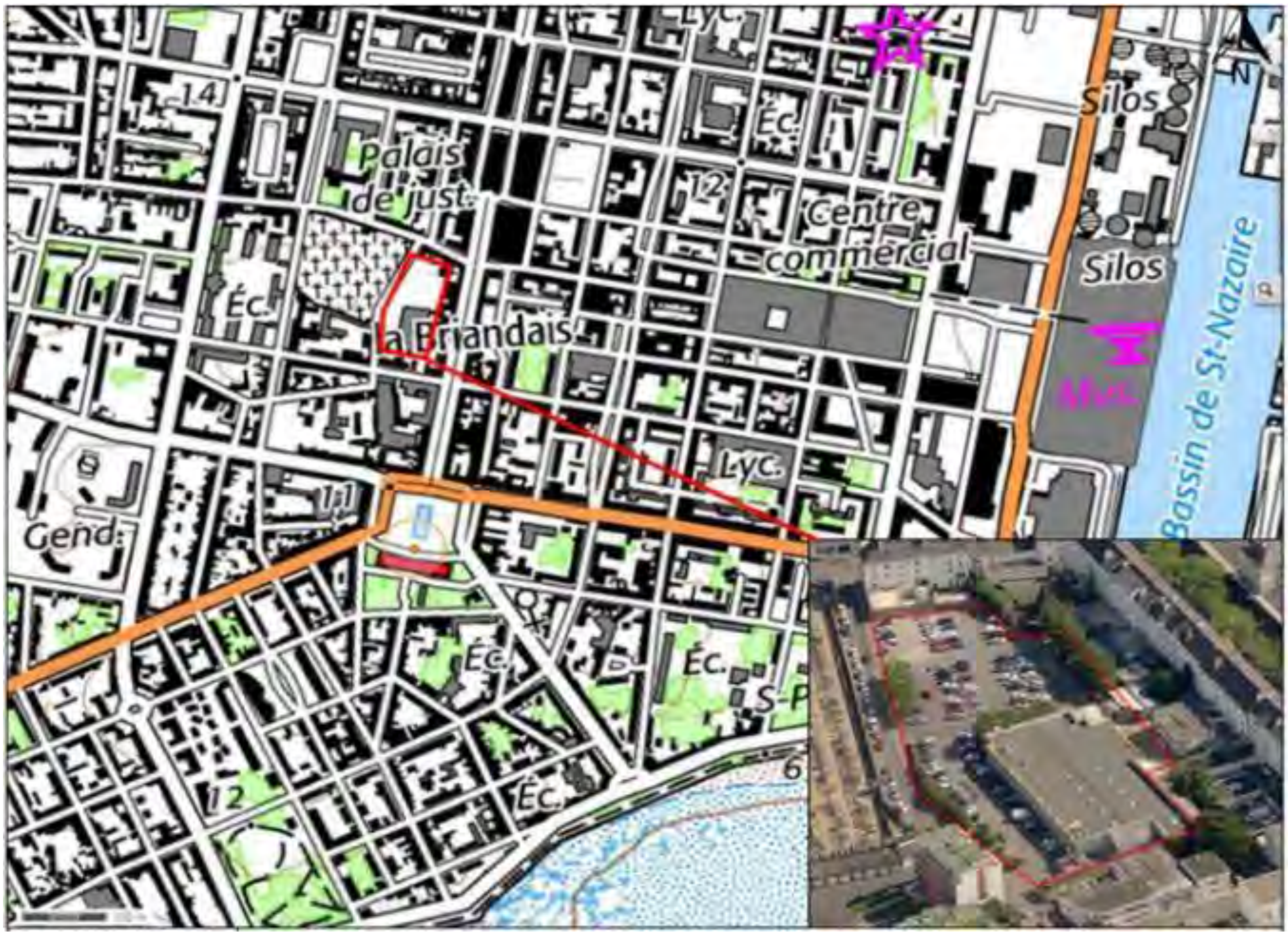


Figure 1 – Site localisation

2.3 Contaminants of concern

The average contaminants concentration identified were:

- TPH: 33.000 mg/kg DM
- BTEX: 20 mg/kg DM
- PAH: 12.000 mg/kg DM

2.4 Regulatory framework

The pollutant concentration limits after treatment have been defined at:

- PAH: 500 mg/kg DM
- Naphthalene: 12 mg/kg DM
- TPH: 2.250 mg/kg DM
- BTEX: 1,6 mg/kg DM

4. Full-scale application

4.1 Main treatment unit

The ex-situ Smart Burner^{TM} Technology developed by Haemers Technologies, heat polluted soil using thermal desorption process after excavation. More precisely, a soil pile is built with steel tubes inserted to remediate. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} to burn the hydrocarbons which reduced the fuel consumption and oxidized the pollutants.

In this case, two standard piles with reburn mode were made (see table below) with a total of 75 Smart Burners^{TM} for each one. The target treatment temperature was set at 250°C.

Pile n°	Length (m)	Distance between heating pipes (m)	Width (m)	Height (m)	Volume (m³)	Payload (tons)
1	14	1,5	45	3.2	1.500	2.880
2	14	1,5	60	3.2	2.000	3.840

Table 1 – Characteristics of the two piles

Figure 2 – Gas network and burner's distribution

4.5 Control parameters

Connected monitoring boxes were installed to monitor during the treatment and the cooling phase the soil temperature at different points in the pile. It allowed HT team to keep a close eye on the heating profile evolution of the soil.

The Pile 1 had 4 different monitoring points at 3 different heights which made a total of 36 thermocouples while Pile 2 had 45 different thermocouples.

Atmosphere emissions of CO_2, CO and C_xH_y were also monitored manually every day to ensure a good quality of the treatment.

5. Results

5.1 Removal rate

The purpose of hot sampling is to take a portion of material for which the volume is small enough to be easily transported, but sufficiently representative for its analysis to show the characteristics of all the materials from which the sample is extracted.

The sample must be manipulated in such a way that its composition is not altered during transport and must be taken every precaution to eliminate contamination or a change in the composition of the sample caused by temperature or inadequate manipulation.

To ensure that the treatment targets were achieved, a first internal hot sampling is done before the treatment stops and then an external sampling and a validation is done.

After treatment, a total of 18 samples for Pile 1 and 20 samples for Pile 2 were made to check the if the remediation goals were achieved.

All samples were below the remediation goals for Pile 1. Residual concentration for Pile 1 was:

- TPH: 320 mg/kg DM
- PAH: 146 mg/kg DM
- BTEX: below detection

Pile 2 was also satisfying with all the samples below the targets:

- TPH: 56 mg/kg DM
- PAH: 35 mg/kg DM
- BTEX: below detection

The removal rate was higher than 99%

7. Additional information

7.2 Additional information

1) Soil temperature by heights

For pile 1, the temperatures were followed at the top, in the middle and at the bottom of the pile in terms of vertical cross-section. With 8 days of treatment, most of the temperatures had reached the 100°C plateau. The 100°C stage lasted for most thermocouples for about 30 days. However, the temperatures of the back of the pile rose slower than the rest. At the bottom of the pile, only two temperatures reached the target at the end of the treatment. However, they all exceeded the 100°C stage. In the middle of the pile, the overall soil temperature at the cold points exceeded the 100°C stage, and several temperatures met the target of 250°C with a maximum at 365°C. At the top of the pile, all temperatures exceeded 100°C at the end of the treatment.

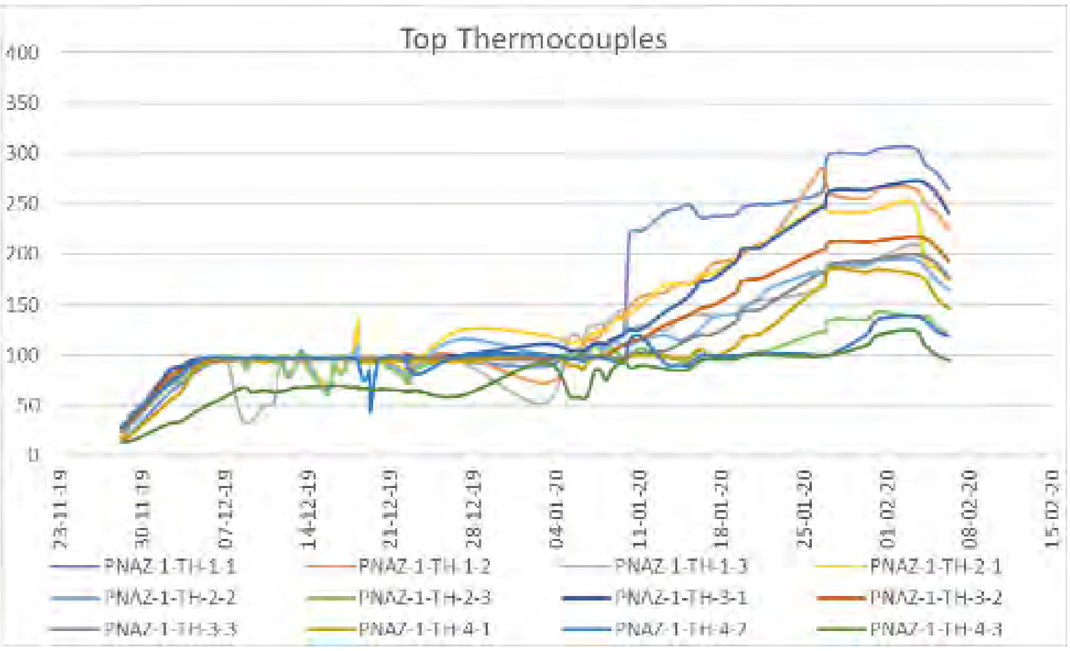


Figure 3 – Top temperature evolution pile 1

For pile 2,the temperatures at the front of the pile rose quicker than at the bottom and in the center but at the end of the treatment, most of the temperatures exceeded 100°C.

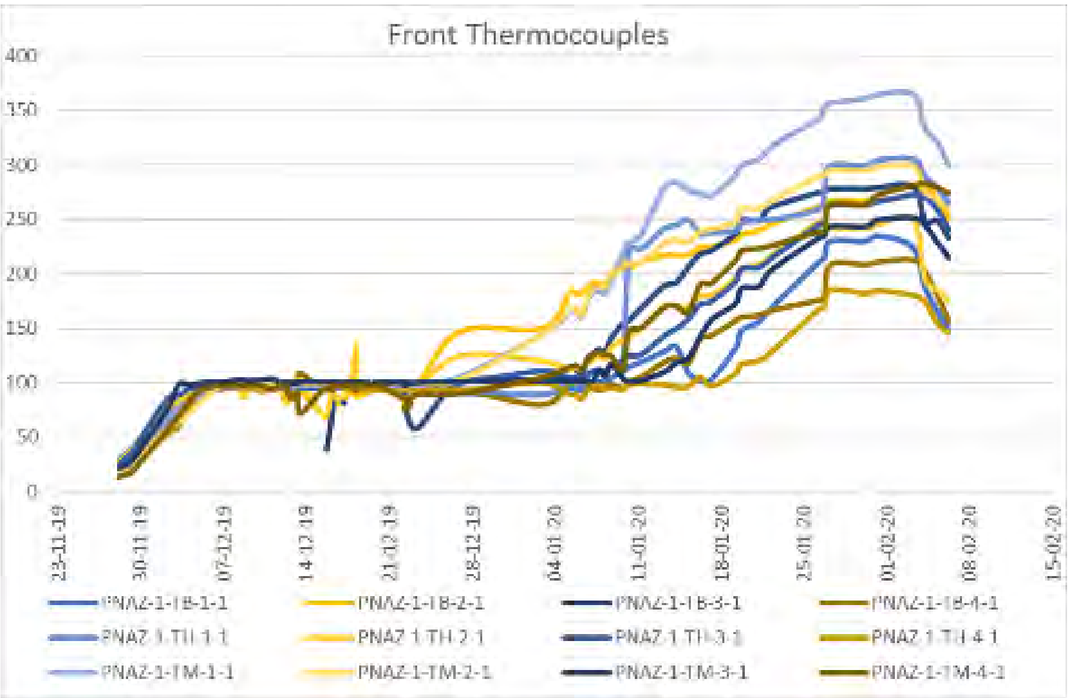


Figure 4 – Front temperature evolution pile 2

Both treatments lasted about the same time (68-69 days).

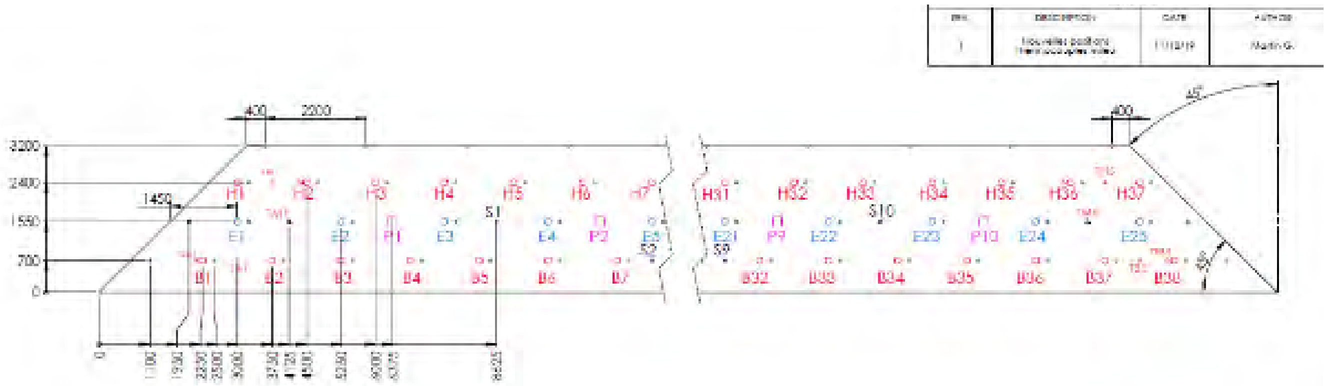


Figure 5 – Monitoring point overview

2) Pressure monitoring:

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P<P_{atm}$), which will consequently avoid fugitive emissions during the treatment. The constant vacuum created in the soil also improves the decontamination. Pile 2 showed a much better situation compared to Pile 1 during their respective treatment.

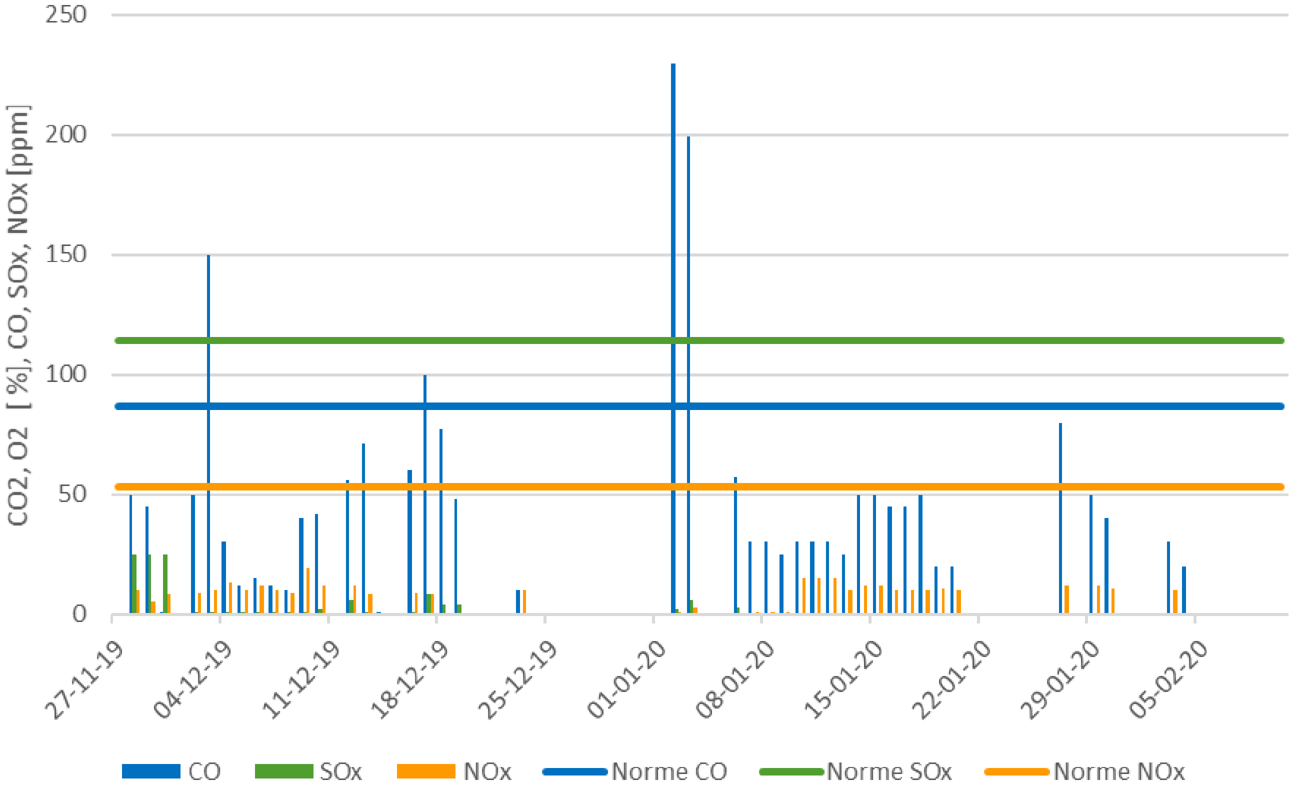


Figure 6 – Pile 1 emission at the chimney

3) Emission control:

Various parameters (O_2, CO_2, CO, SO_2, NO_x) were manually monitored with a gas analyser (MRU Vario +) at the exhaust of the vent to control emissions to the ambient air, making sure that these emissions respect the local emissions standards.

For pile 1, the emissions remained below the norms most of the time except for CO emissions on two punctual events on the third of December 2019 and early January 2020. The first of the two was solved the same day and the installation had been regulated back to normal conditions. The second one is probably due to the lack of manpower during holidays at the end of December 2019. CO emissions were back to the standards in the first week of 2021.

For pile 2, on the 8th of December 2020, one of the fans has stopped and the backup fan did not run as well. The two remaining fans were switched to drive the exhaust of the entire pile. In this case, the installation operated with only two fans until the arrival of the two other fans and regulation. This incident is noticeable thanks to the emissions peaks of CO and CxHy.

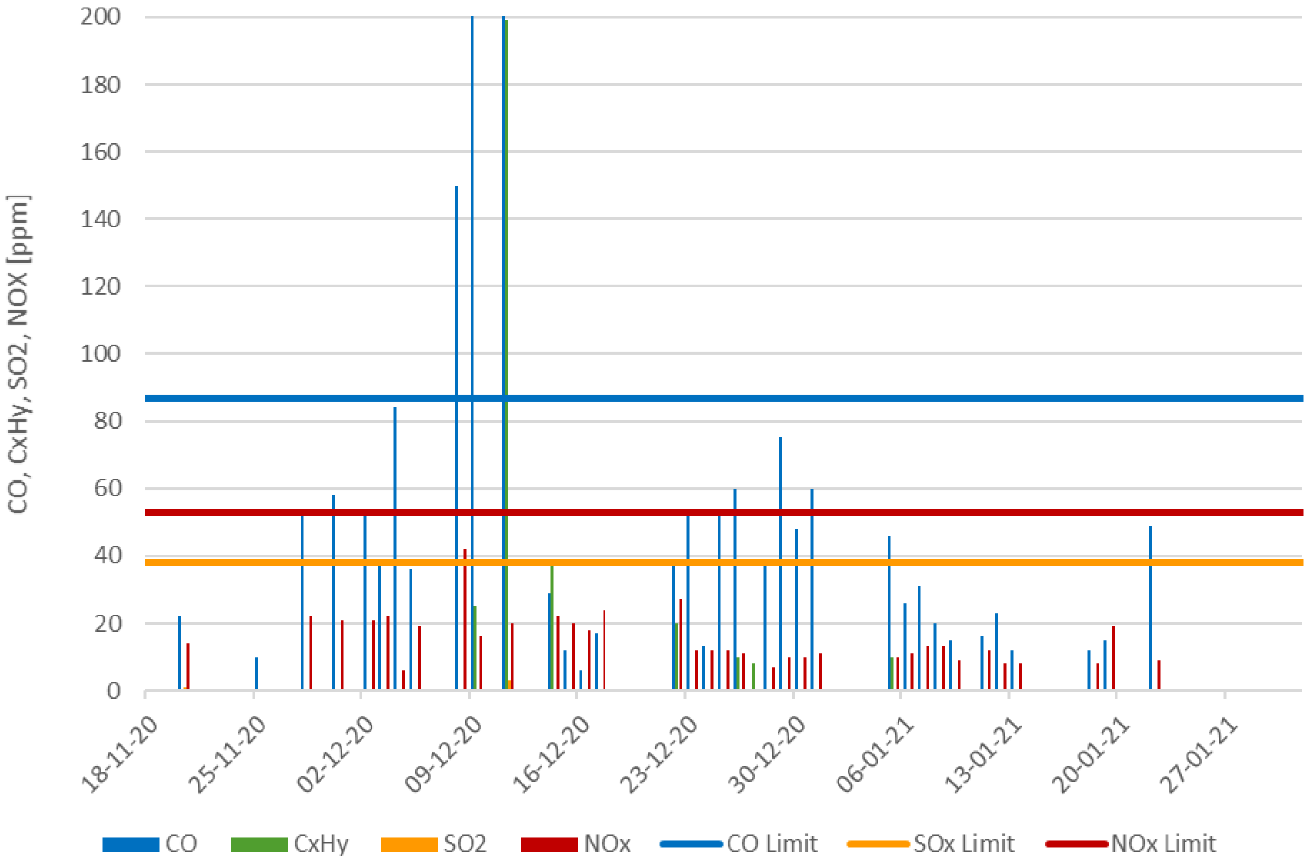


Figure 7 – Pile 2 emissions at the chimney

7.4 Additional remarks

For both Piles, the rising up to 100°C took approximatively 10 days. However, due to the presence of a GAC, the 100°C plateau was difficult to overpass. This stage could last up to 35 days. As the site operated between apartments, it was important to keep the batch under pressure to not worry the inhabitants

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.16

1.1 Name and Surname	Léa Deceuninck
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	lea.deceuninck@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The project is in Belgium, more precisely at Quaregnon, at the front of a habited house. The site has been polluted by a leak of the oil tank used to heat the house. The hydrocarbon leakage is essentially in the garden with a small area probed under the house. Moreover, the contaminated area is close to 2 staircases and a buried water pipe. The treated area is 10m². The house was inhabited during the works of depollution in cellar.

2.3 Contaminants of concern

The maximum pollutant concentrations (hydrocarbons) are detailed in the table below.

Contaminants	Average Conc. In soil	Max Conc. In Soil	Treatment Target Value
	mg/kg-dry soil	mg/kg-dry soil	mg/kg-dry soil
Fraction C5 -C8	45	54	4,8
Fraction C8-C10	480	770	16.8
Fraction C10-C12	990	1600	60
Fraction C12-C16	2000	4800	60
Fraction C16-C21	2000	5500	520
Fraction C21-C35	1100	3100	520

Table 1 – Maximum pollutant concentrations

2.4 Regulatory framework

The treatment targets were 520 mg/kg dry soil for the heavy hydrocarbons and 20mg/kg dry soil for the light hydrocarbons.

4. Full-scale application

4.1 Main treatment unit

The in-situ Smart Burner^{TM} Technology developed by Haemers Technologies, heat polluted soil using thermal desorption process with no excavation involved. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then either treated in a vapour treatment unit (VTU) or re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} (in the case of hydrocarbons pollution).

The batch of 40m³ (60 tons) was treated with 6 natural gas Smart Burners^{TM} in reburn mode to oxidize the hydrocarbons which also allowed HT team to reduce its fuel consumption for the treatment. The target treatment temperature was set at 220°C and it took around 60 days to reach this temperature and remediate the soil.

4.3 Post treatment for effluent

The post treatment for effluent was based on the reburn technology. The vapours from the soil are extracted through the steam tubes. The negative pressure in the tubes is created by the fans, and the vapours (water and hydrocarbons) exit through the steam tubes. The vapours and gases are directly reinjected into the burners to undergo different degradation mechanisms: hydrolysis, partial oxidation, and total oxidation.

The main mechanism expected from the treatment after recovery is a complete oxidation in the burners. The products of combustion are then drawn off and sent to the chimney.

4.5 Control parameters

A monitoring box was installed to monitor the six burners' temperatures. Four soil temperature points with measurement at 4 and 6 m below ground level were placed in the treated area. One soil pressure point measurement (in the cave) was also placed. It is important to check the vacuum in the soil to make sure that all the vapours are sucked into the vapor circuit.

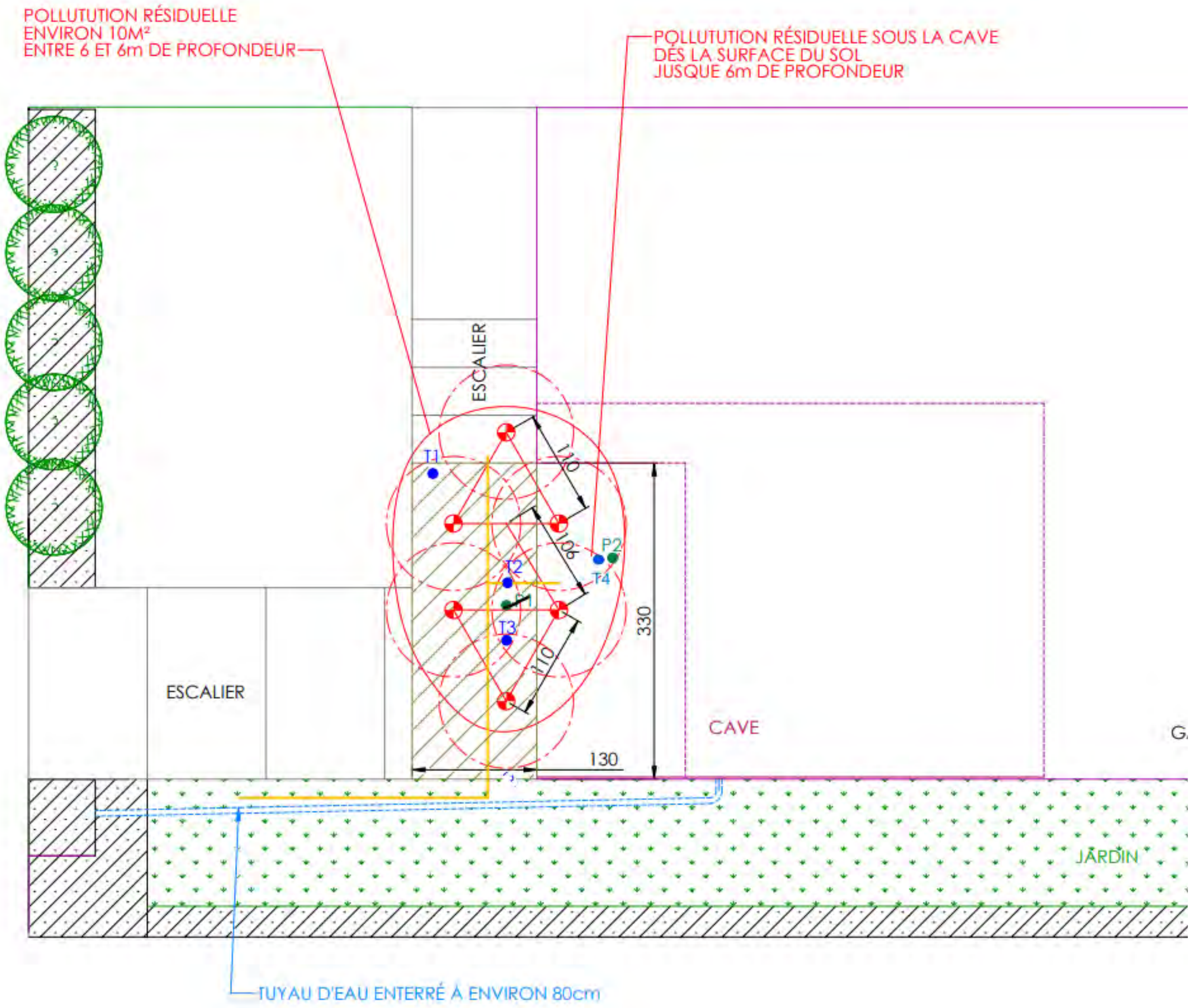


Fig. 1 – Monitoring point and site overview

Various parameters (O_2, CO_2, CO, T°, C_xH_y) were manually monitored at different points with a gas analyser (MRU Optima 7 and a VarioPlus).

5. Results

5.1 Removal rate

These samples are the closest of the state of the soil today because there were taken one month later, after cooling of the soil. These hot samplings were taken at the cold points. This corresponds to the place that has been heated the least during the treatment. HT team can conclude that if these samples are compliant, they will be on average on the site even better.

Contaminants	Conc. In soil	Treatment Target Value
	mg/kg-dry soil	mg/kg-dry soil
Fraction C5 -C8	4	4,8
Fraction C8-C10	2.1	16.8
Fraction C10-C12	< 2.5	60
Fraction C12-C16	< 15	60
Fraction C16-C21	< 15	520
Fraction C21-C35	18	520

Table 2 – Soil concentrations

The results obtained at 4m are below the detection level of the SGS laboratory as the heating was effective. The soil was heated uniformly over the entire area. If polluted vapours were still coming out of the 6m zone, higher values would have been found in the 4m zone due to rising vapours. The C16-C21 (which are the main fractions of the declared pollution from domestic fuel) results at 4m were 35 times below the target values.

7. Additional information

7.2 Additional information

1) Soil temperature

The soil temperature was monitored at four cold point locations (see Figure 2). The temperatures were divided by 2 meters depth and 4 meters depth under the excavation level as shown in the next two graphs. The 200°C temperature target was not fully reached everywhere but despite this fact, the final pollutant concentrations of 520 mg/kg dry soil for the heavy hydrocarbons and 20mg/kg dry soil for the light hydrocarbons were still reached.

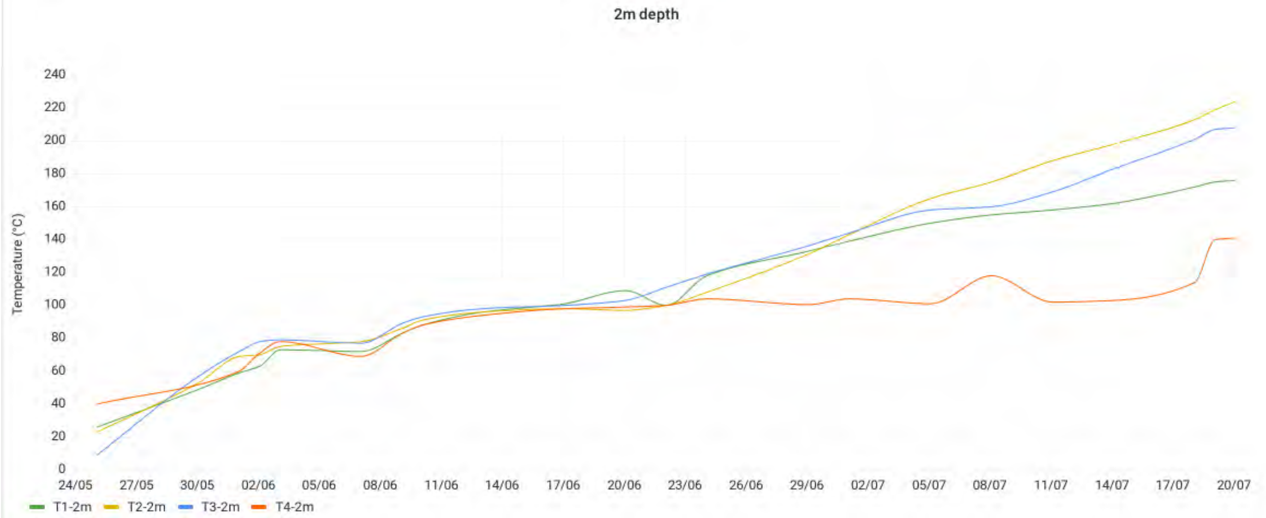


Figure 2 – Top temperature evolution pile 1

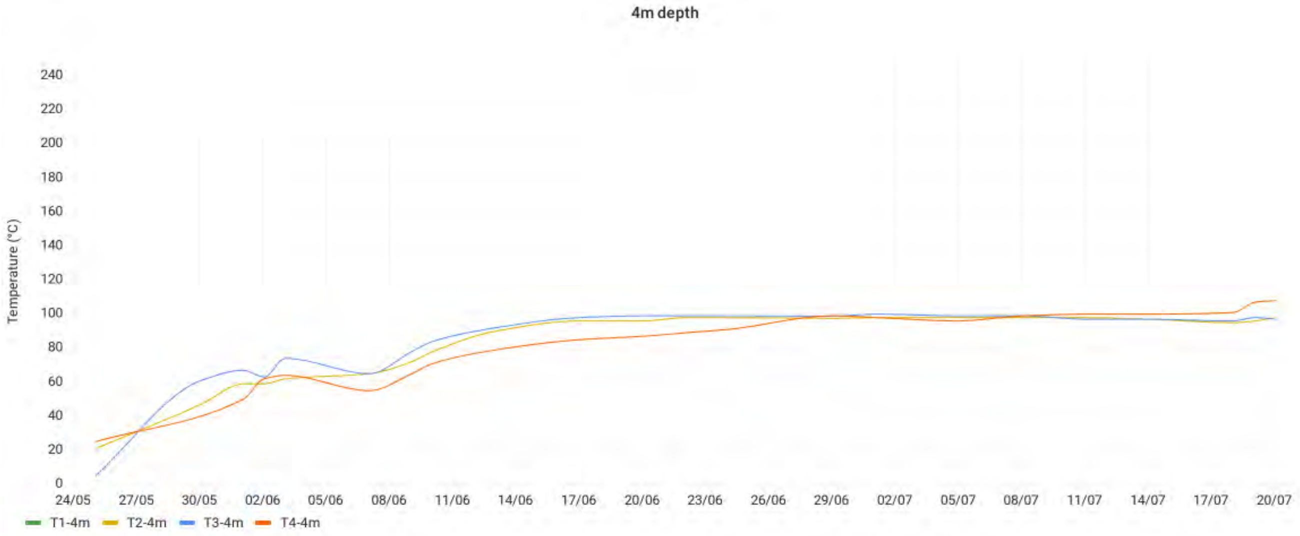


Figure 3 – Temperature evolution at 4m for each monitored localisation

2) Pressure monitoring

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P < P_{atm}$) which will consequently avoid fugitive emissions during the treatment. The constant vacuum created in the soil also improves the remediation. For this project, two pressure wells (P1, P2) were installed but only 1 could be used and measured manually every day. We were able to verify that no fugitive emission was possible inside the house.

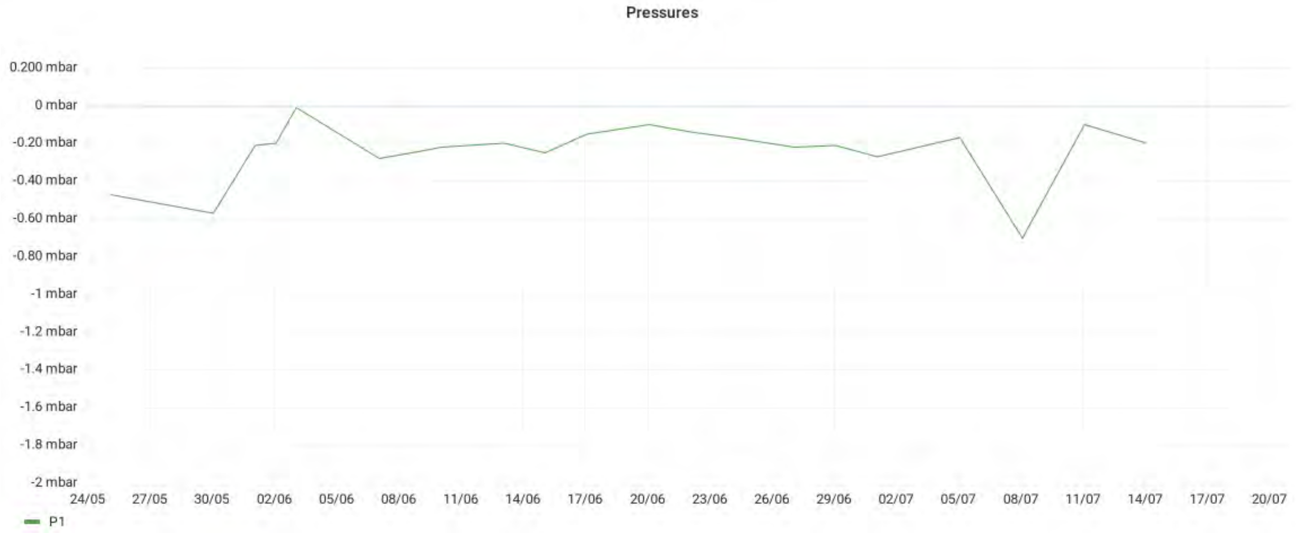


Figure 4 – Pressure evolution in the soil during treatment

3) Emission control:

Various parameters (O_2, CO_2, CO, C_xH_y) were manually monitored with relevant gas analysers at the chimney to control emissions to the ambient air, making sure that these emissions respected the local norms. For CO, the values never exceed the 35ppm (limit is at 150ppm) because catalysts were installed at the vapor outlet on each burner to avoid any release issue. This catalyst favours the oxidation and decreases the CO at the outlet. For CxHy it never exceeds 1 ppm (the limit is at 50ppm), this value is explained by the reburn mode where the CxHy are burned directly in the combustion chamber.

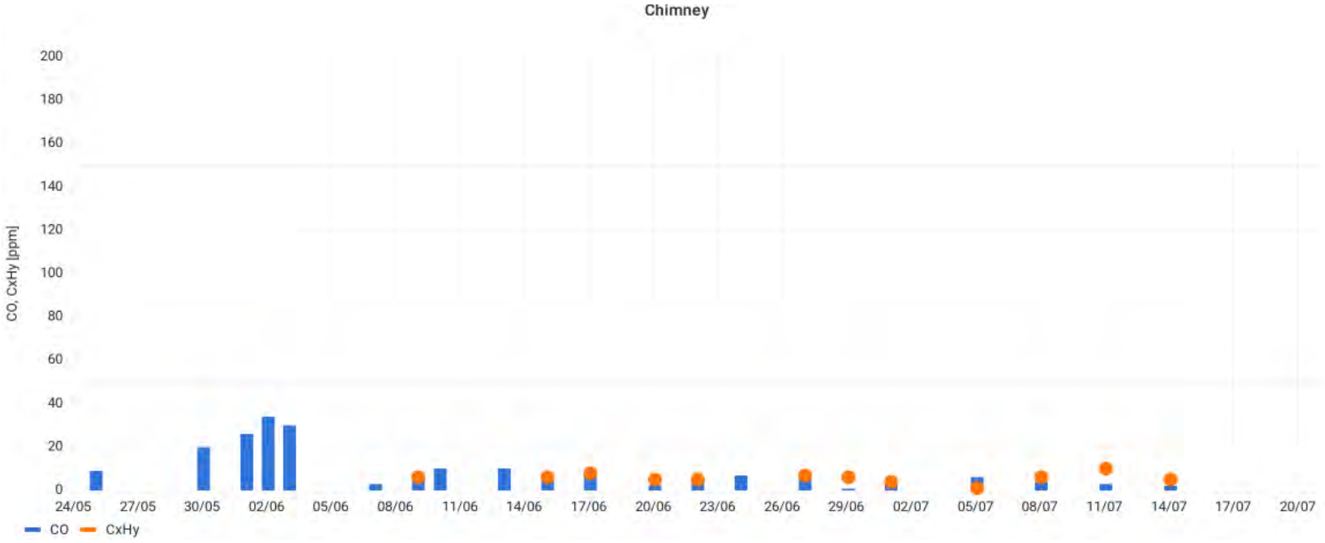


Figure 5 – Chimney emission

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.17

1.1 Name and Surname	Ysaline Depasse
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	ysaline.depasse@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The site is in Strasbourg, in the harbour area called "Les 2 Rives". This area is composed of different zones. This area used to be a former industrial area. The Mairie wanted to develop with new uses this area. Soils were investigated and various pollution were found: TPH, PAH, BTEX, Hg, etc.

The aim of this project was to remediate all the polluted soils onsite (biological, stabilization and thermal desorption (TD)). Different technics were used, especially TD to remediate soils polluted with TPH and PAH.

Soils came from the 4 different zones by barge to the TD site in order to realize ex-situ Thermal Desorption (ESTD). The soil was then reused directly onsite, and no trucks circulated in the areas during the entire process.

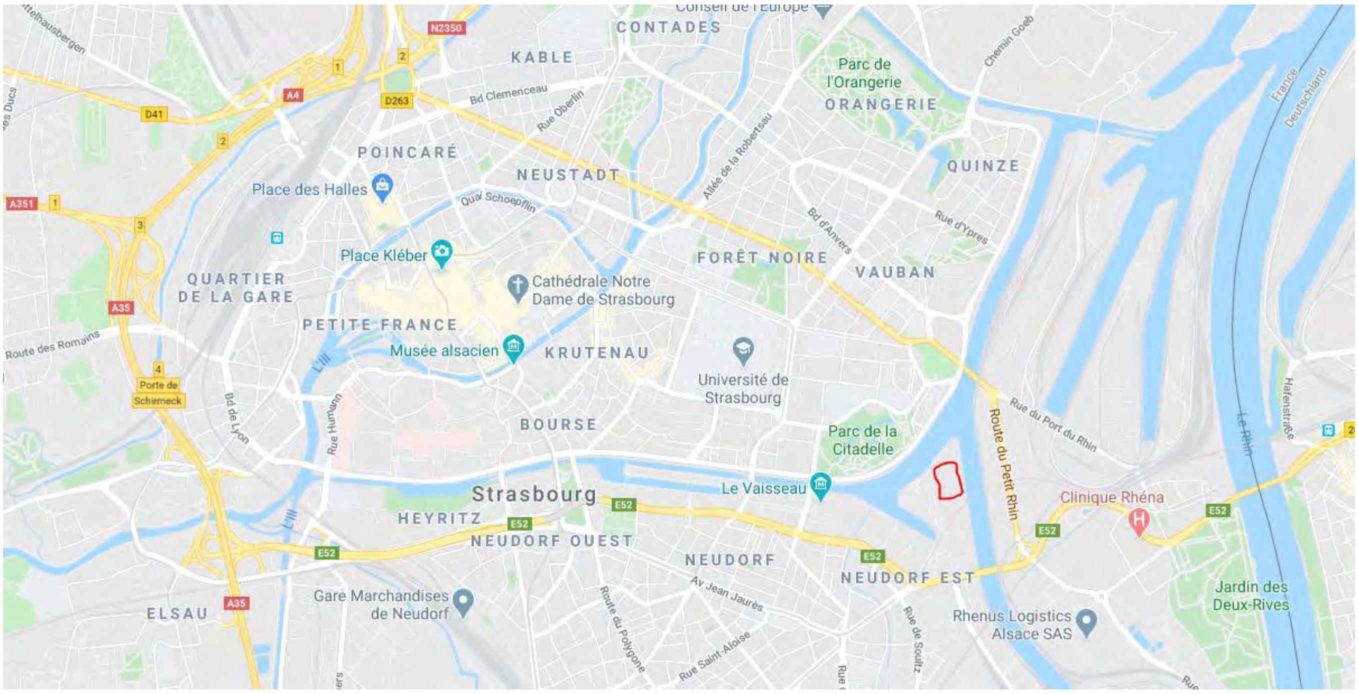


Figure 1 – Site localization

2.2 Geological setting

Mostly sandy soils.

2.3 Contaminants of concern

The COC(s) identified at the site are listed in the table below. The averages are calculated from the samples initial concentrations analysed before each of the 7 piles.

Contaminant Type	Average Concentration (mg/kg DM)	Max Concentration (mg/kg DM)
PAH	1.700	2.020
Hydrocarbons (C10-C40)	3.500	5.050

Table 1 – Contaminants of concern at the site

2.4 Regulatory framework

Regarding the pile, the target concentrations varied.

Contaminant Type	Average Concentration (mg/kg DM)	Max Concentration (mg/kg DM)	Targets (mg/kg DM)
PAH	1.400	2.020	136 (pile 1-4) 50 (pile 5-7)
Hydrocarbons (C10-C40)	3.100	4.102	640 (pile 1-4) 500 (pile 5-7)

Table 2 – Target concentrations

4. Full-scale application

4.1 Main treatment unit

The in-situ Smart Burner^{TM} Technology developed by Haemers Technologies, heat polluted soil using thermal desorption process with no excavation involved. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then either treated in a vapour treatment unit (VTU) or re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} (in the case of hydrocarbons pollution).

An Ex-Situ Thermal Desorption (ESTD) was selected by the client with a reburn technology. The treatment area was chosen to be able to run one pile, with a second one in mobilization/demobilization. The design of the different piles, made of 29 to 41 Smart Burners^{TM}, was a function of the soil available per zone as presented in the table below.

Pile	Length (m)	Distance between heating pipes (m)	Width (m)	Height (m)	Volume (m^3)	Payload (tons)
1	40	1,8	15	3,2	1.500	2.808
2	40	1,8	15	3,2	1.700	3.182
3	35	1,8	15	3,2	1.100	2.059
4	30	1,8	15	3,2	1.000	1.872
5	40	1,8	15	3,2	1.594	2.984
6	40	1,8	15	3,2	1.500	2.808
7	40	1,8	15	3,2	1.500	2.808

Table 3 – Design of the different piles

The target treatment temperature was 250°C and it took from 39 to 61 days to treat the pollution. Since Pile 4, a GAG is applied before the atmospheric releases of the vapours by order of the DREAL.

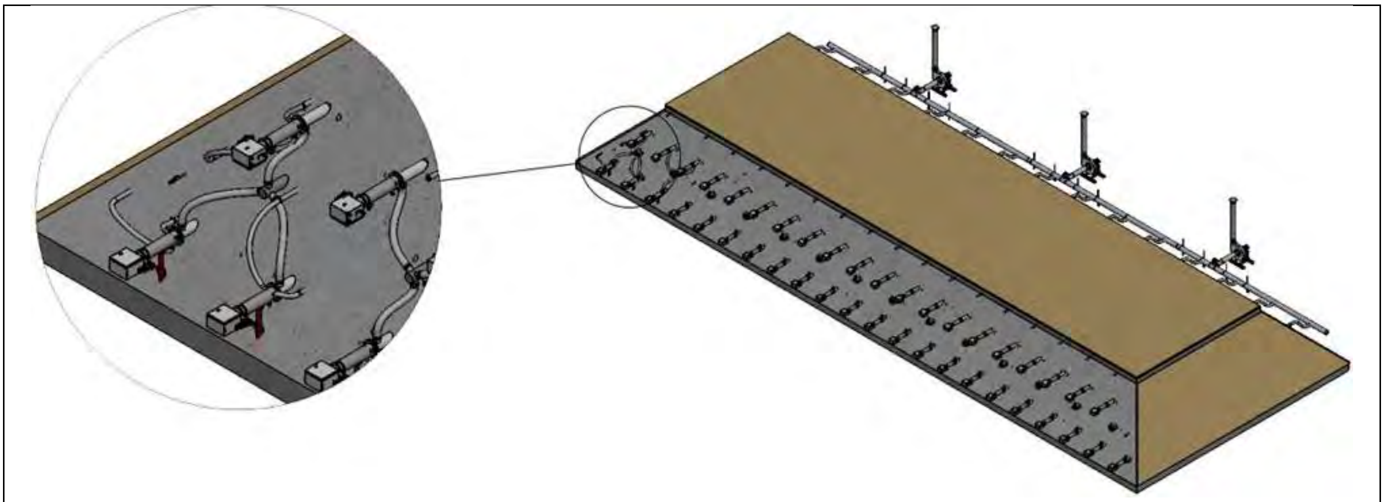


Figure 2 – ESTD pile design

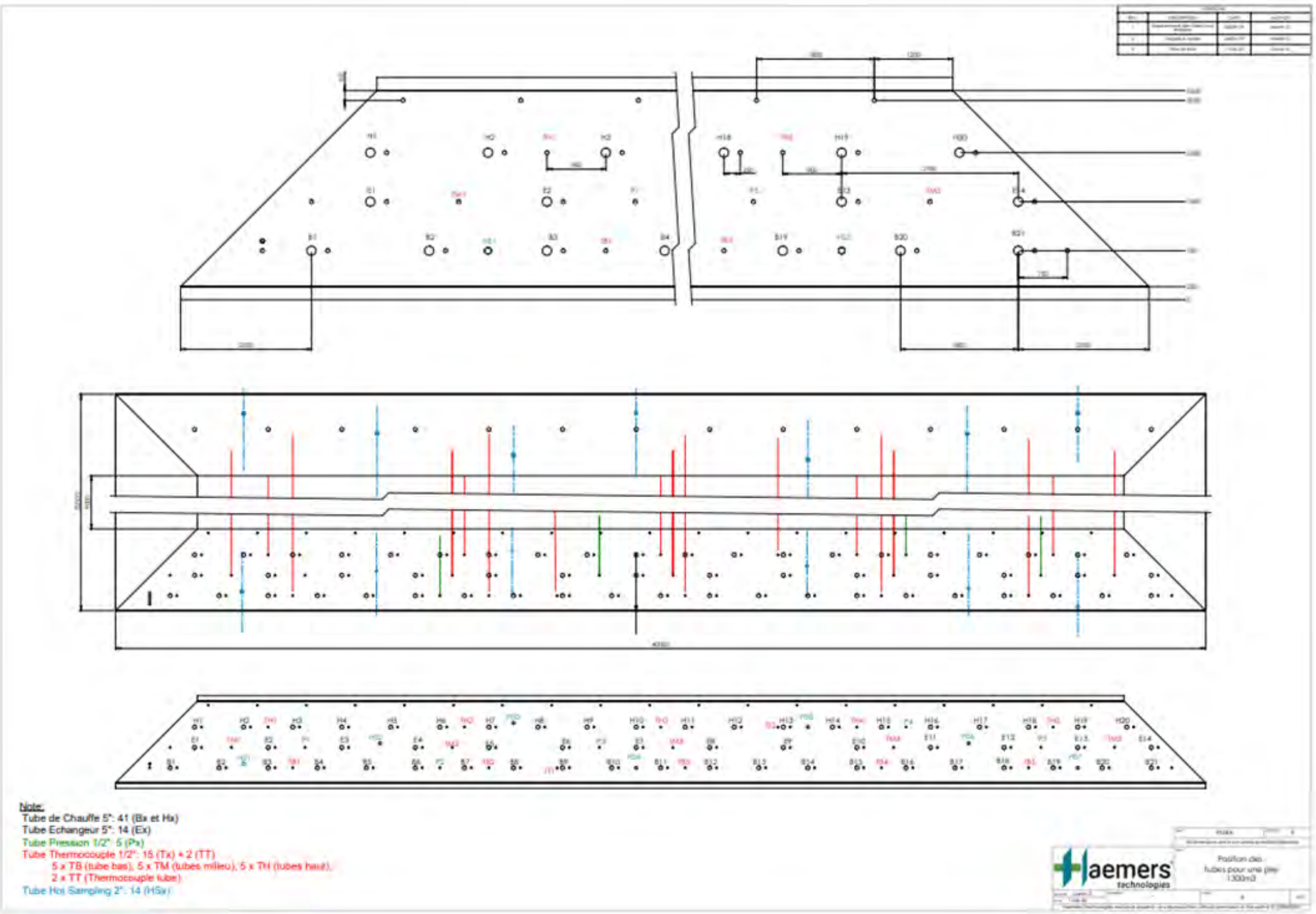


Figure 3 – ESTD installation schematic

Figure 4 – ESTD installation on site

4.3 Post treatment for effluent

The post treatment for effluent was based on the reburn technology. The vapours from the soil are extracted through the steam tubes. The negative pressure in the tubes is created by the fans, and the vapours (water and hydrocarbons) exit through the steam tubes. The vapours and gases are directly reinjected into the burners to undergo different degradation mechanisms: hydrolysis, partial oxidation and total oxidation.

The main mechanism expected from the treatment after recovery is a complete oxidation in the burners. The products of combustion are then drawn off and sent to the chimney.

4.5 Control parameters

Connected monitoring boxes were installed to monitor during the treatment and the cooling phase the soil temperature at different points in the pile. It allowed HT team to keep a close eye on the heating profile evolution of the soil.

Atmosphere emissions of CO_2, CO and C_xH_y were also monitored manually every day to ensure a good quality of the treatment.

with a gas analyser (MRU Optima 7 and a VarioPlus).

5. Results

5.1 Removal rate

To validate the stop of the heating as well as the treatment, several hot samples were taken. The number of hot samplings and the target concentrations varied from one pile to another depending on the size of the pile. The table below summarize the results

Pile	Hot sampling quantity	Final PAH residual concentration (mg/kg DM)	Final C10-C40 residual concentration (mg/kg DM)	Target PAH (mg/kg DM)	Target C10-C40 (mg/kg DM)
1	8	80	205	136	640
2	8	11	38	136	640
3	6	25	373	136	640
4	8	12	53	136	640
5	8	36	212	50	500
6	-	-	-	50	500
7	-	-	-	50	500

Table 4 – Results for each pile

7. Additional information

7.2 Additional information

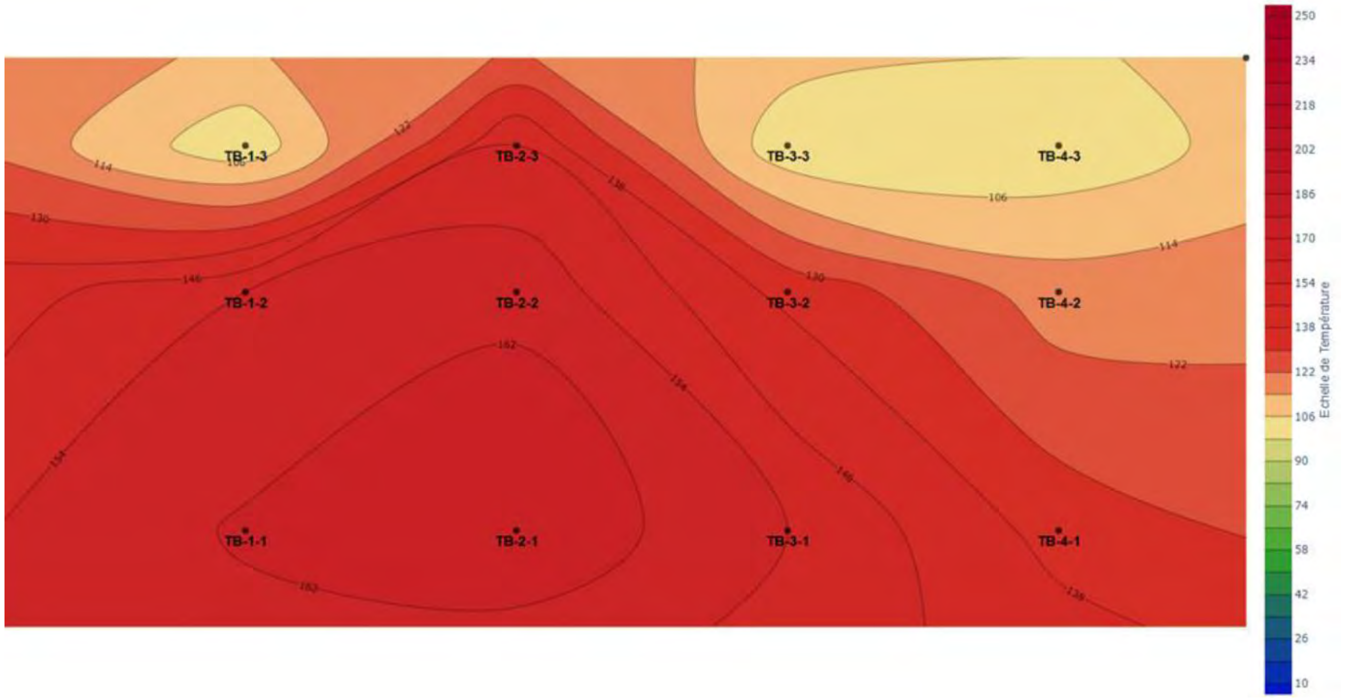


Figure 5 – Thermography of the upper part of pile 3 after 42 heating days

1) Temperature in the thermal pile

This section presents the thermographies generated at 42 days of treatment of Pile 3. Thermographies are heat maps representing the temperature distribution inside the thermal pile. Each thermography illustrates a vertical slice of the thermal pile: the bottom, the mi-height and the upper of the pile. The evolution of the thermographies enables to visualize the evolution of the heat front in the pile.

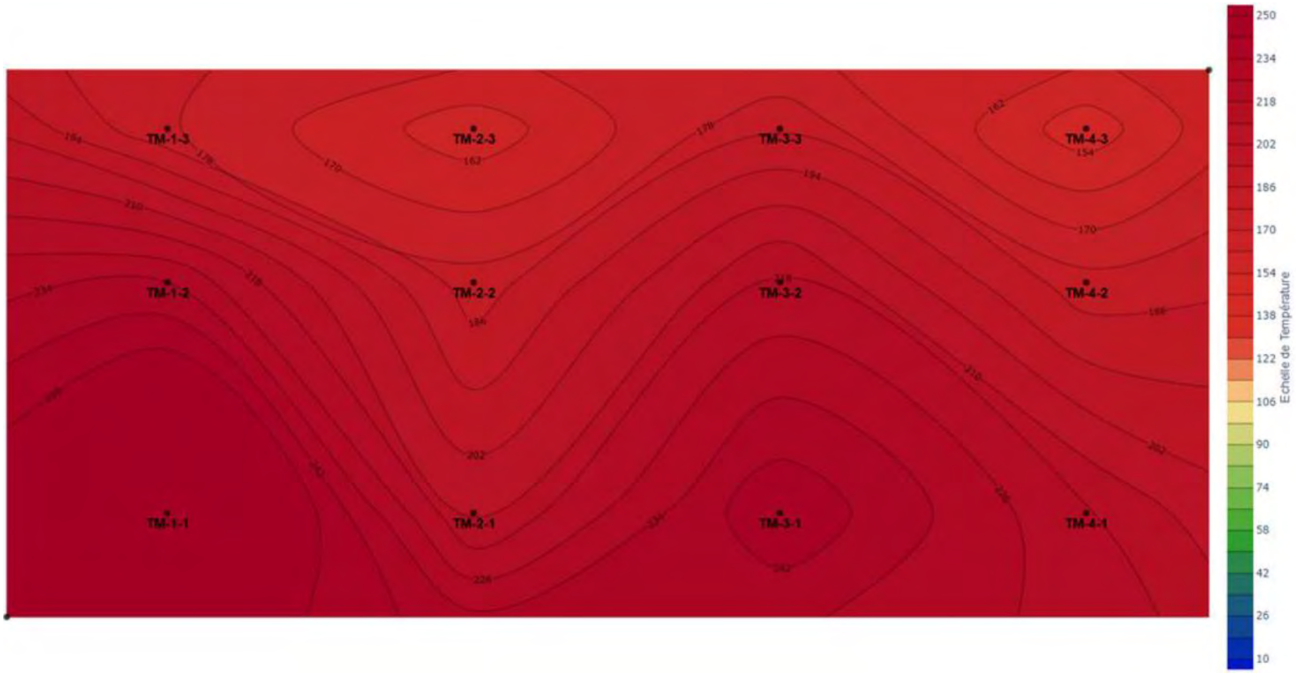


Figure 6 – Thermography of the mid-height part of Pile 3 after 42 heating days

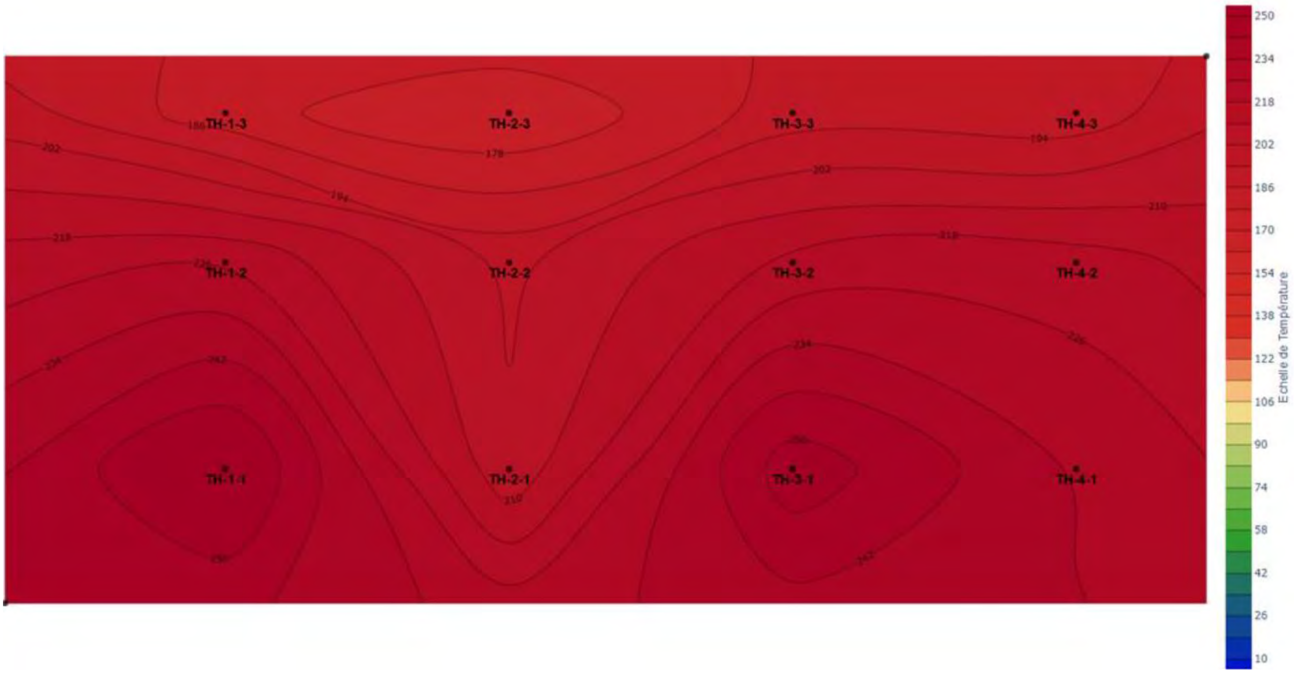


Figure 7 – Thermography of the bottom part of Pile 3 after 42 heating days

The thermographies show that the temperature was quite homogeneous in the pile except in the upper part where we can see that the back of the pile was less hot.
The next graph represents the average temperature at cold points (areas of the pile the furthest of the heat source) for every pile and during the entire treatment period.

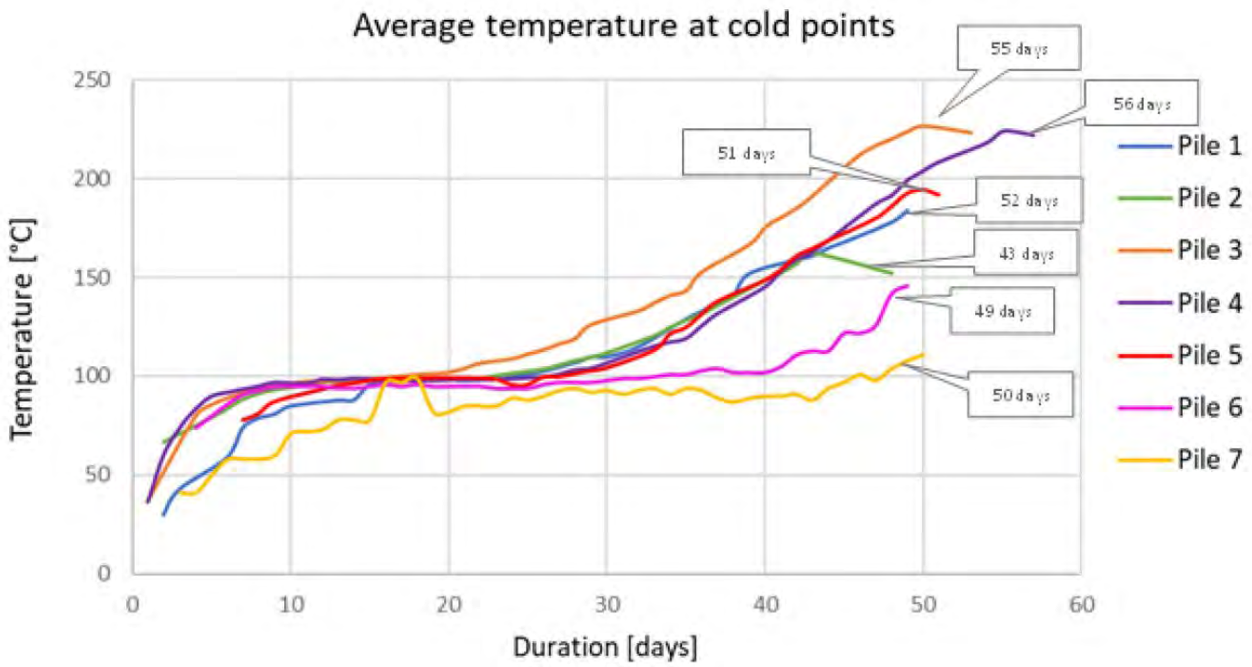


Figure 8 - Average temperature at cold points for the different piles

2) Pressure monitoring

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P<P_{atm}$), which will consequently prevent fugitive emissions during the treatment. The constant vacuum created in the soil also improves the decontamination. For this project, 5 pressure wells (P1-P2-P3-P4-P5) were installed and measurements were performed manually every day. The following figure presents the evolution of the soil pressure in Pile 1 following time. The graph shows that over time, the treatment got more and more stability.

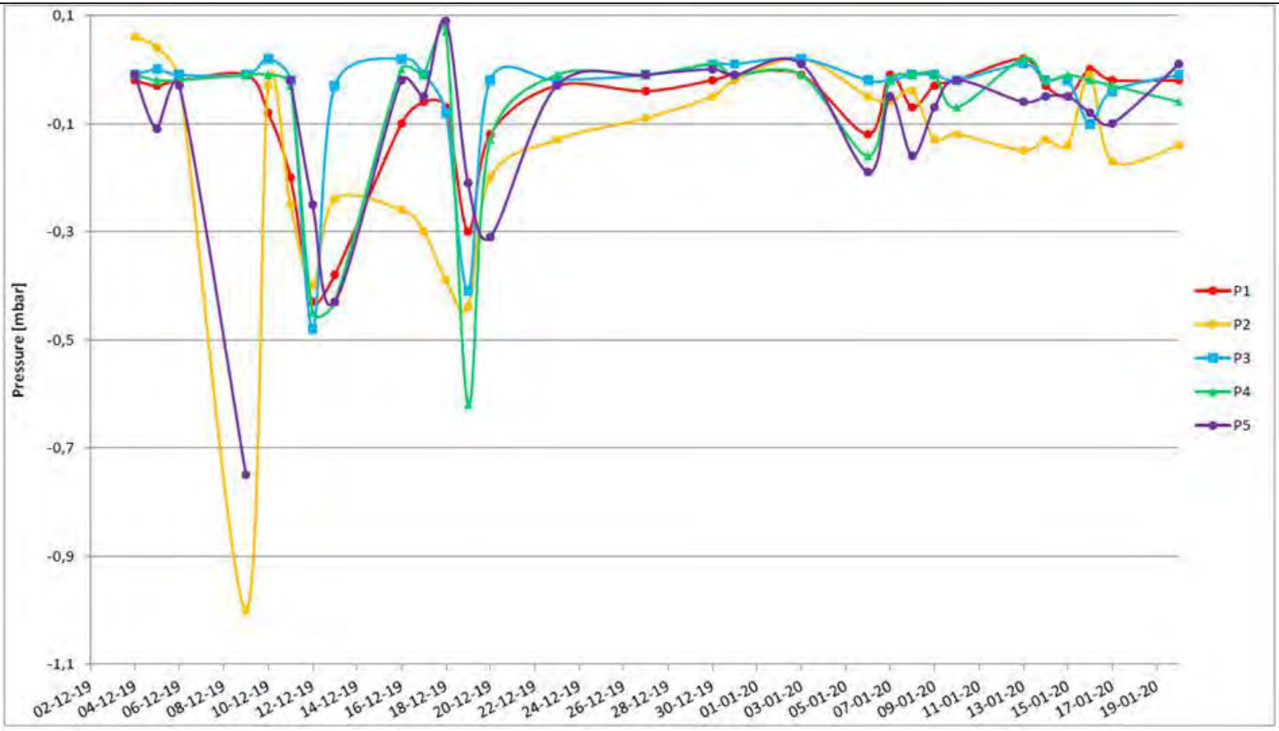


Figure 9 – Pressure evolution in the soil during treatment

3) Emission control

Daily measurements were taken at the 3 chimneys installed on the different piles. The graphs show that for all stacks the CO emissions stayed below 100ppm

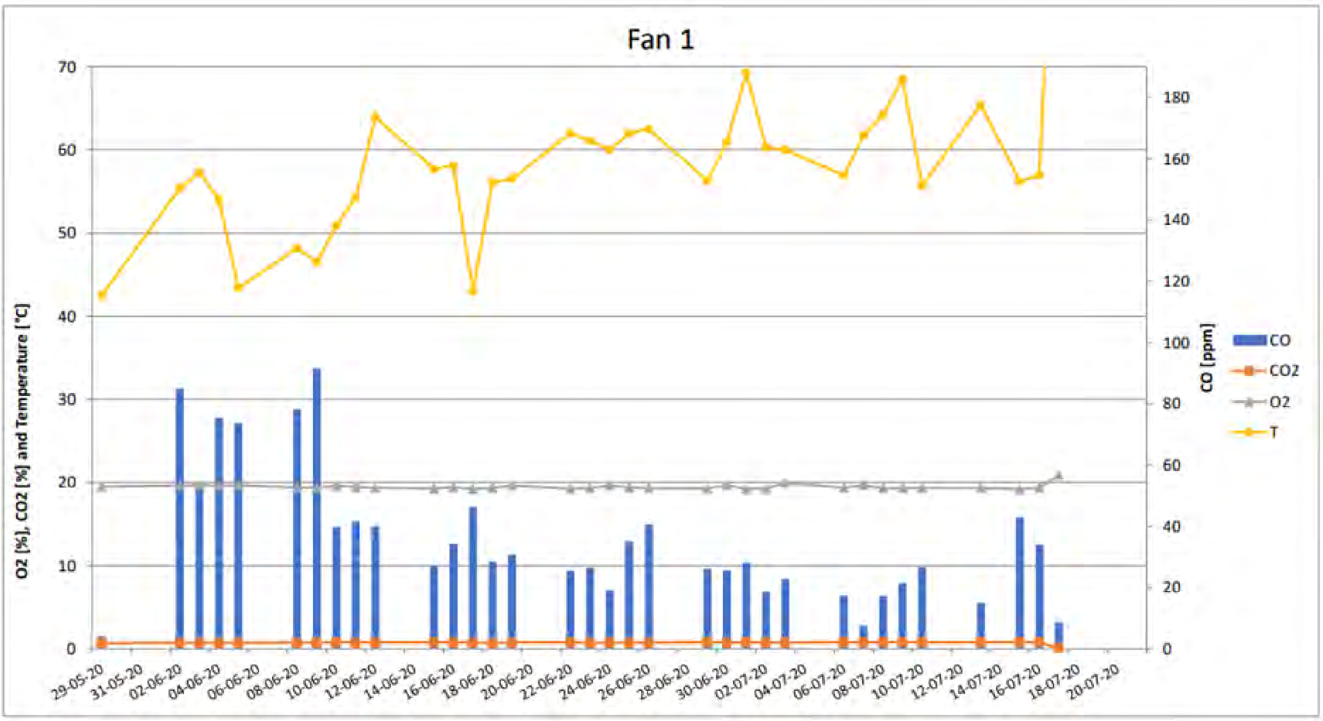


Figure 10 – Emission evolution at the chimney 1 of pile 3

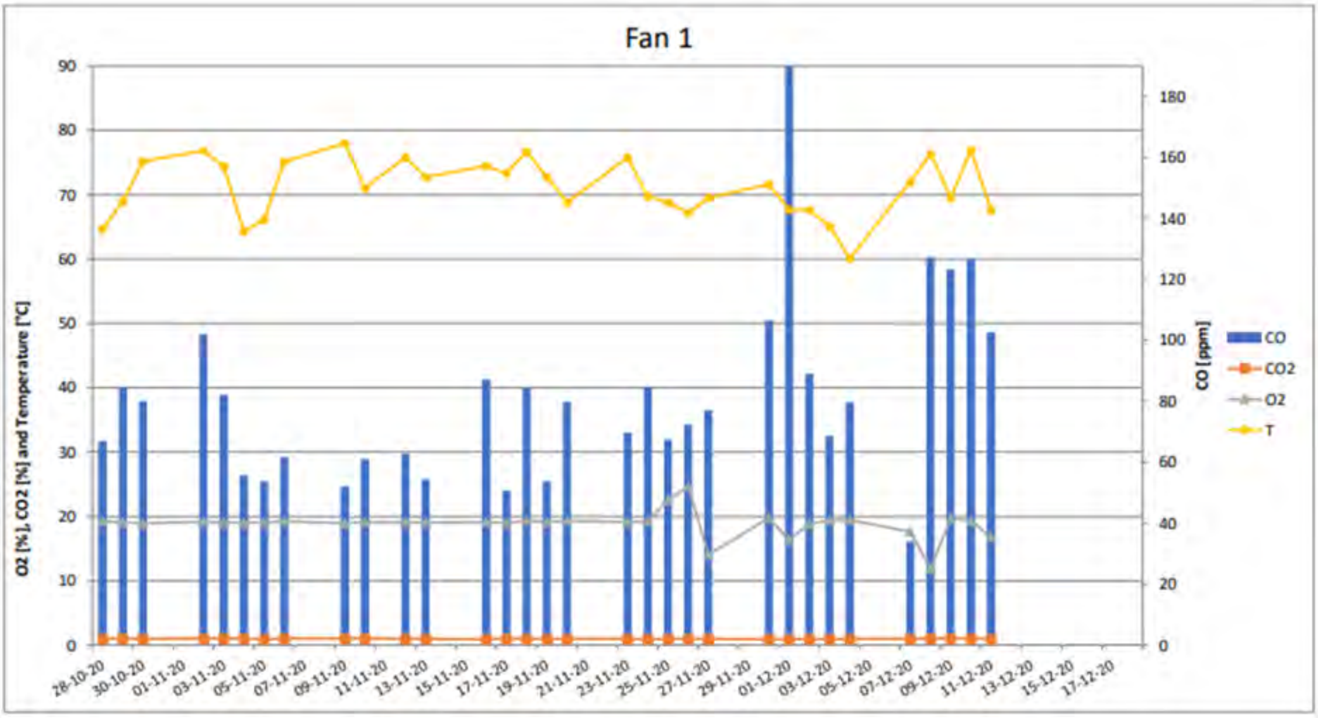


Figure 11 – Emission evolution at the chimney 1 of pile 5

7.4 Additional remarks

This project was made under a license mode which meant that HT team was not necessarily on-site during treatment as a client team has been trained in HT standards beforehand.

1. Contact details - CASE STUDY: In Situ Thermal Desorption n.18

1.1 Name and Surname	Yannick Lolivier
1.2 Country/Jurisdiction	Belgium
1.3 Organisation	Haemers Technologies
1.4 Position	Project manager
1.5 Duties	Operation
1.6 Email address	yannick.lolivier@haemers-tech.com
1.7 Phone number	+32 2 219 13 42

2. Site background

2.1 History of the site

The site is in Bonheiden, Belgium. It is a disused building whose faith is to be rebuild for housing. The contamination has been emitted by a former aluminium refining process.

2.2 Geological setting

No specific geological setting except that there is a groundwater table located at a depth of 3,5m.

2.3 Contaminants of concern

The contaminant of concern identified on site was the PCE (perchloroethylene) with a maximum concentration detected at 23 000 mg/kg of dry soil.

2.4 Regulatory framework

The soil concentration limit after treatment have been defined at 1mg/kg of dry soil; by the consulting firm (Veroeven) and OVAM (Public Agency in the Flanders region).

4. Full-scale application

4.1 Main treatment unit

The in-situ Smart Burner^{TM} Technology developed by Haemers Technologies, heat polluted soil using thermal desorption process with no excavation involved. More precisely, steel tubes are inserted into the soil to be remediated. Hot gases, generated by Smart Burner, circulate in the tubes to transfer heat to the soil. This results in the vaporisation of the pollutants when their boiling temperature is reached. The vapours emitted are then drawn through perforated steel tubes, called vapor tubes, surrounded by gravel acting as a draining medium preventing the clogging of the tube perforations (by fine particles, sludge, etc). These recovered vapours are then either treated in a vapour treatment unit (VTU) or re-injected (reburn mode) into the flame generated by the Smart Burners^{TM} (in the case of hydrocarbons pollution).

As the treatment was localised inside a building, the batch has been divided into three specific zone (one of the areas being almost no polluted), as shown in the next Figure, and some structural components had to be considered during the building and the demobilization phase to avoid any damage of the existing structure.

The batch of 250m³ (425 tons) was treated with 33 Smart Burners$_{TM}$ and a small VTU made of one activated carbon tank to treat the vapours.

The contaminant was located between 0 and 4m depth and it took 21 days to treat it at target temperature of treatment of 95°C.

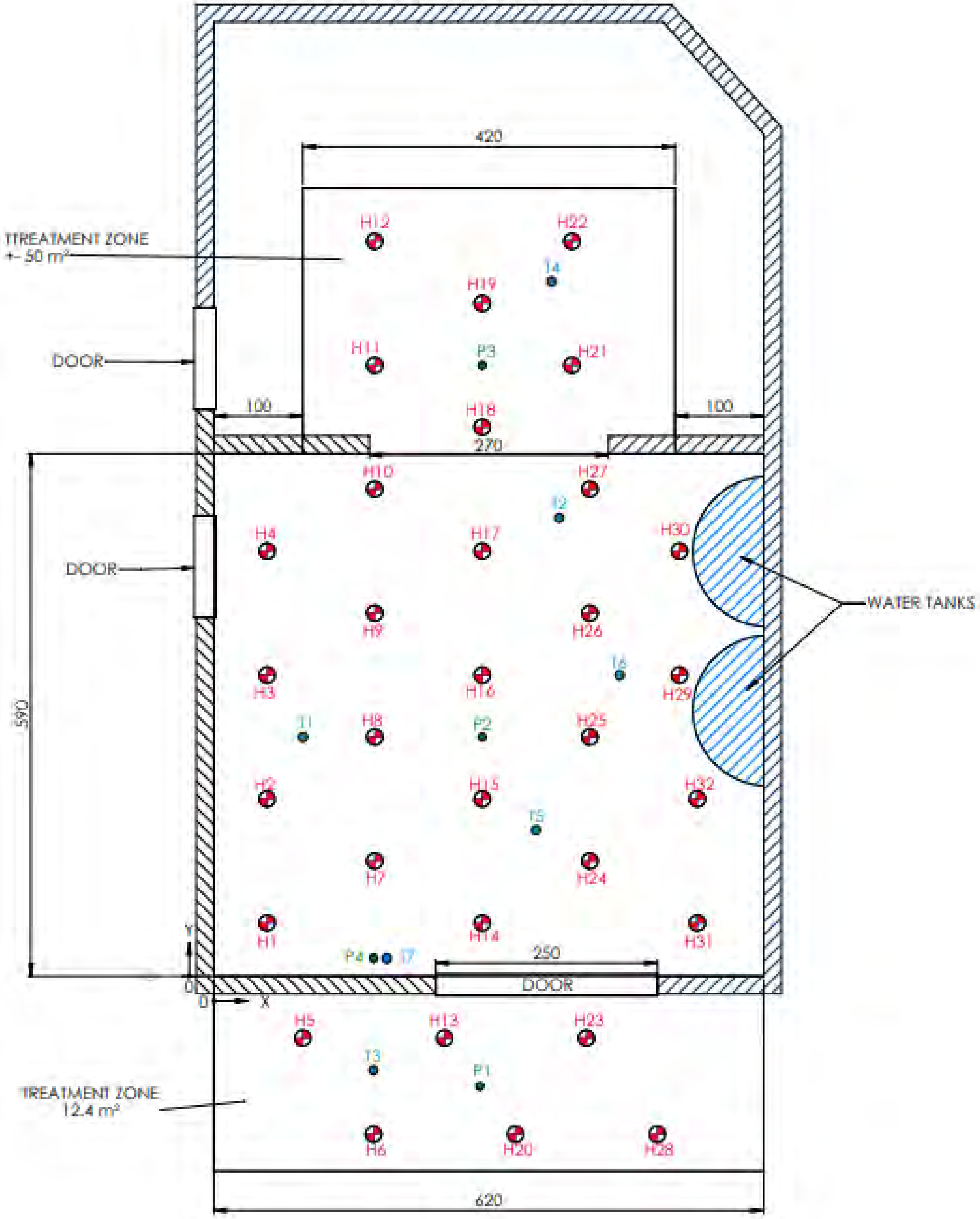


Figure 1 – Site overview

Figure 2 – Back area of the site with its Smart Burners^{TM}

4.3 Post treatment for effluent

Around the vapor tubes was placed an Haemers Technologies developed product: ThermoReact®. ThermoReact® is a mix of gravel and lime which reacts with the chlorine acid components that are coming out of the soil to form an environmentally friendly base. The contaminants are therefore captured before they even enter the vapor tube.

Then, before being released to the air, the exhaust gases and polluted vapours went through a granulated activated carbon filter (GAC). The GAC filtered the gases to capture the remaining chlorinated compounds that could be possibly find in the vapours.

4.4 Post Treatment for water

Groundwater was observed at a depth of 3.5 m from ground level. As pollution was also observed in the saturated zone, the consulting firm was charged to treat the saturated zone through injections after the Thermal Desorption treatment.

Haemers Technologies treated the unsaturated zone of the treatment areas (down to 4 m from the ground level as the target temperature was not above 100°C).

Due to the low target temperature (<100°C), no groundwater management was needed during the Thermal Desorption treatment phase.

4.5 Control parameters

Connected monitoring boxes were installed to monitor during the treatment and the cooling phase the soil temperature at different depth (2 and 4m). It allowed HT team to keep a close eye on the heating profile evolution of the soil. These devices were also used to monitor the 32 Smart Burner^{TM} temperatures.

Atmosphere emissions of CO2, CO and VOCs were also monitored manually every day to ensure a good quality of the treatment.

5. Results

5.1 Removal rate

The removal rate of PCE was higher than 98,5% on the entire surface treated.

7. Additional information

7.2 Additional information

1) Soil Temperature

The soil temperature was monitored at six cold point locations (point he furthest of the heat source) and at a depth of 2 and 4m.

At 2m depth, all the measurements followed the same temperature path and reached the target after 12-13 days except for T3 and T4 that reach both 81°C.

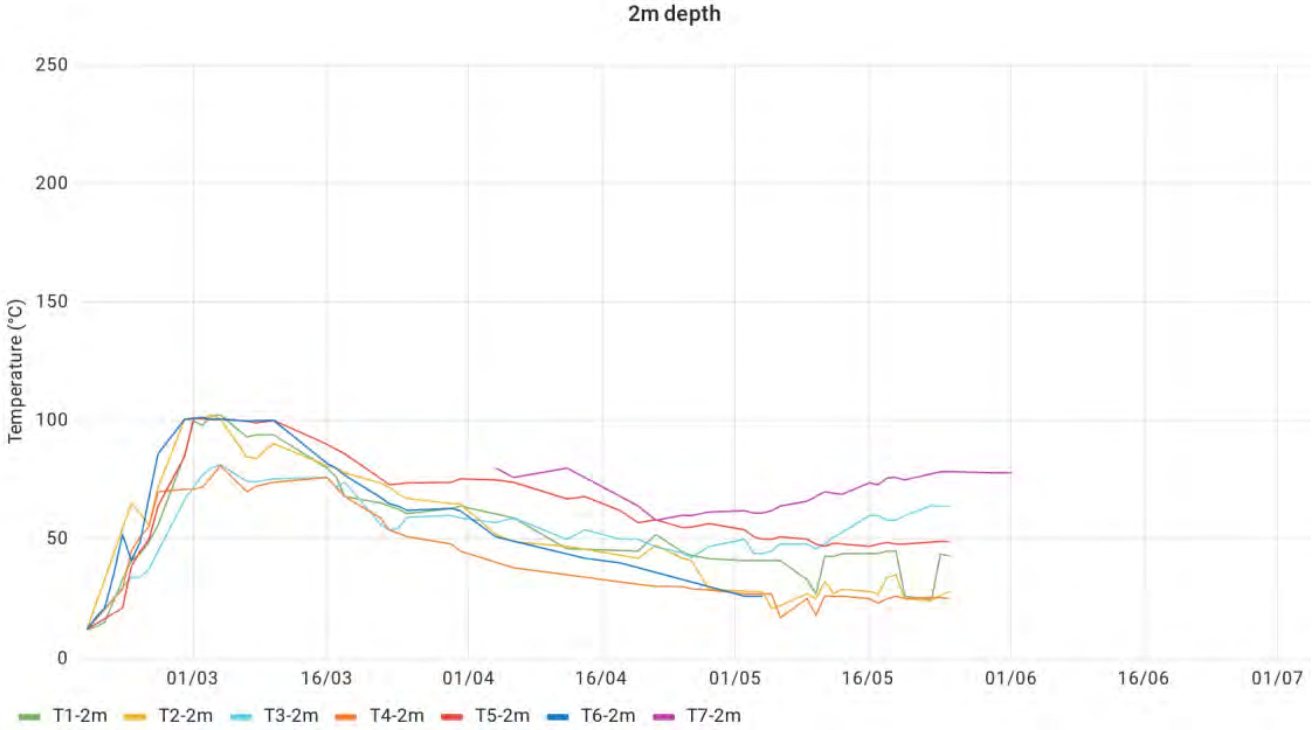


Figure 3 – Temperature evolution at 2m deep for each monitoring points

At 4m depth, all measurements reach the target except for T3 that reaches 84°C at the maximum

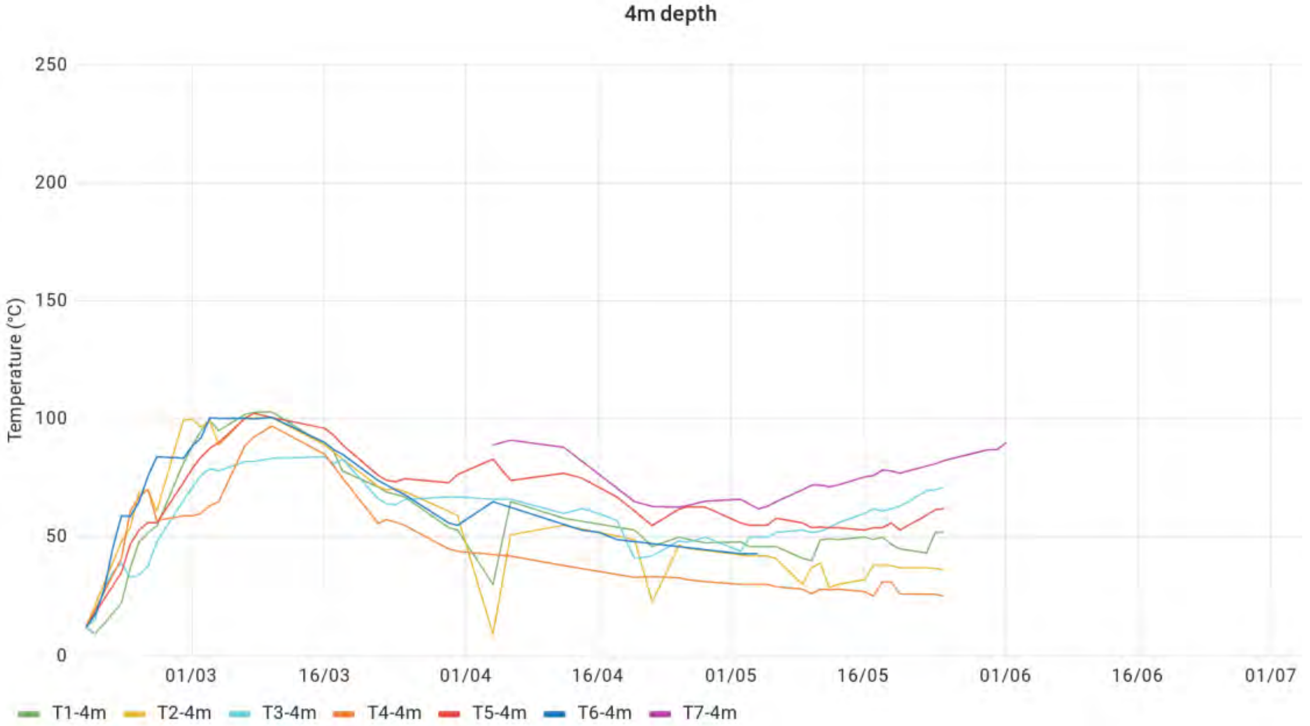


Figure 4 – Temperature evolution at 4m deep for each monitoring points

2) Pressure monitoring

It is fundamental to control and keep track of the soil pressure during the treatment. The aim of this monitoring is to maintain a negative relative pressure in the soil ($P < P_{atm}$) which will consequently avoid fugitive emissions during the treatment. The constant vacuum created in the soil also improves the remediation. For this project, 3 pressure wells (P1, P2 and P3) were installed and measures were done manually every day.

Figure 5 – Soil pressure evolution during treatment

It can be observed that the relative pressure always remains negative, at the location of the pressure measurement wells, throughout the entire treatment.

3) Emission control

Various parameters (O_2, CO_2, CO, T°) were manually monitored at different points with a gas analyser (MRU Optima 7) and the COVs were monitored using a PID with a 10.6eV lamp.

Regarding the emissions before the fan, as shown on Figure 7, the CO concentration always remained below the limit of 150mg/Nm³ (corresponding to 120ppm) and never exceeded 100ppm. The COV concentration before the fan were monitored only at the end of the treatment. The concentration of COV were between 100ppm and 300ppm before the activated carbon filter.

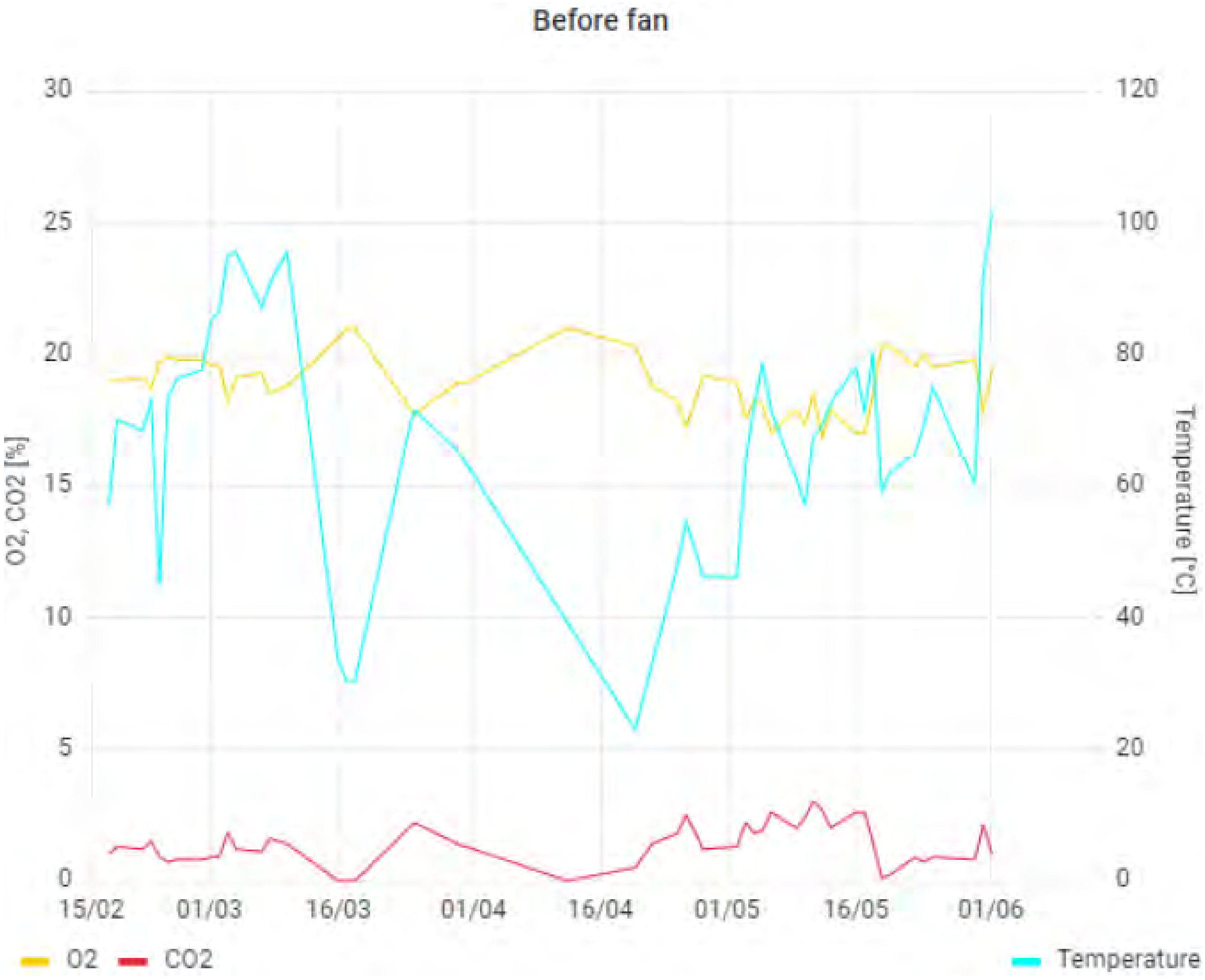


Figure 6 – Emissions O_2 and CO_2 before the fan

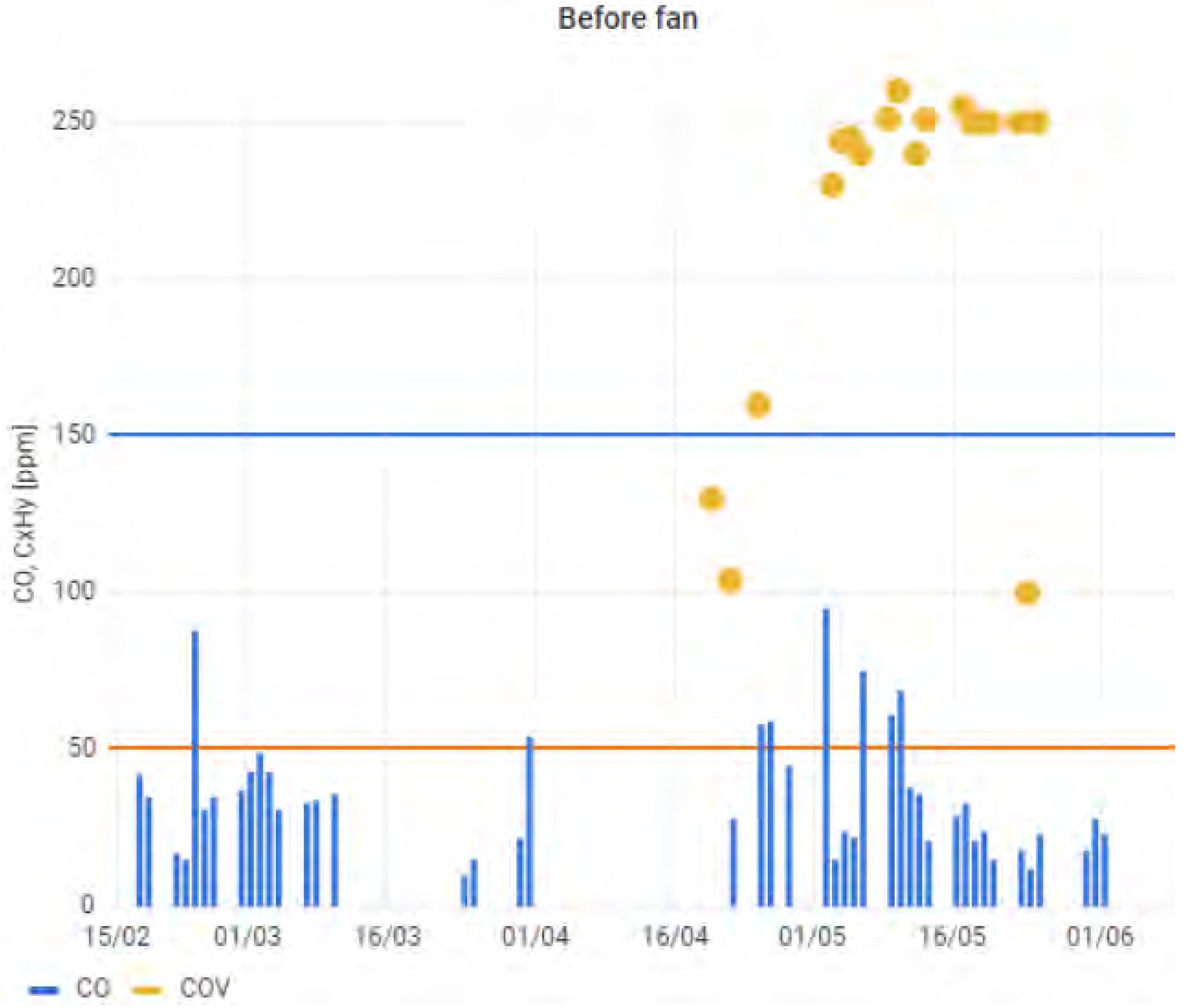


Figure 7 – Emissions CO and COV before the fan

For the chimney emissions, various parameters (O_2, CO_2, CO, COV) were manually monitored with relevant gas analysers at the chimney, after the activated carbon filter to control emissions to the ambient air, making sure that these emissions respected the local norms. For CO, the values never exceed the 80ppm. For COV, the limit is at 50ppm. One value was monitored at 100ppm due to problem in the GAC. The activated carbon was changed, and no emission problem were observed until the end of the project.

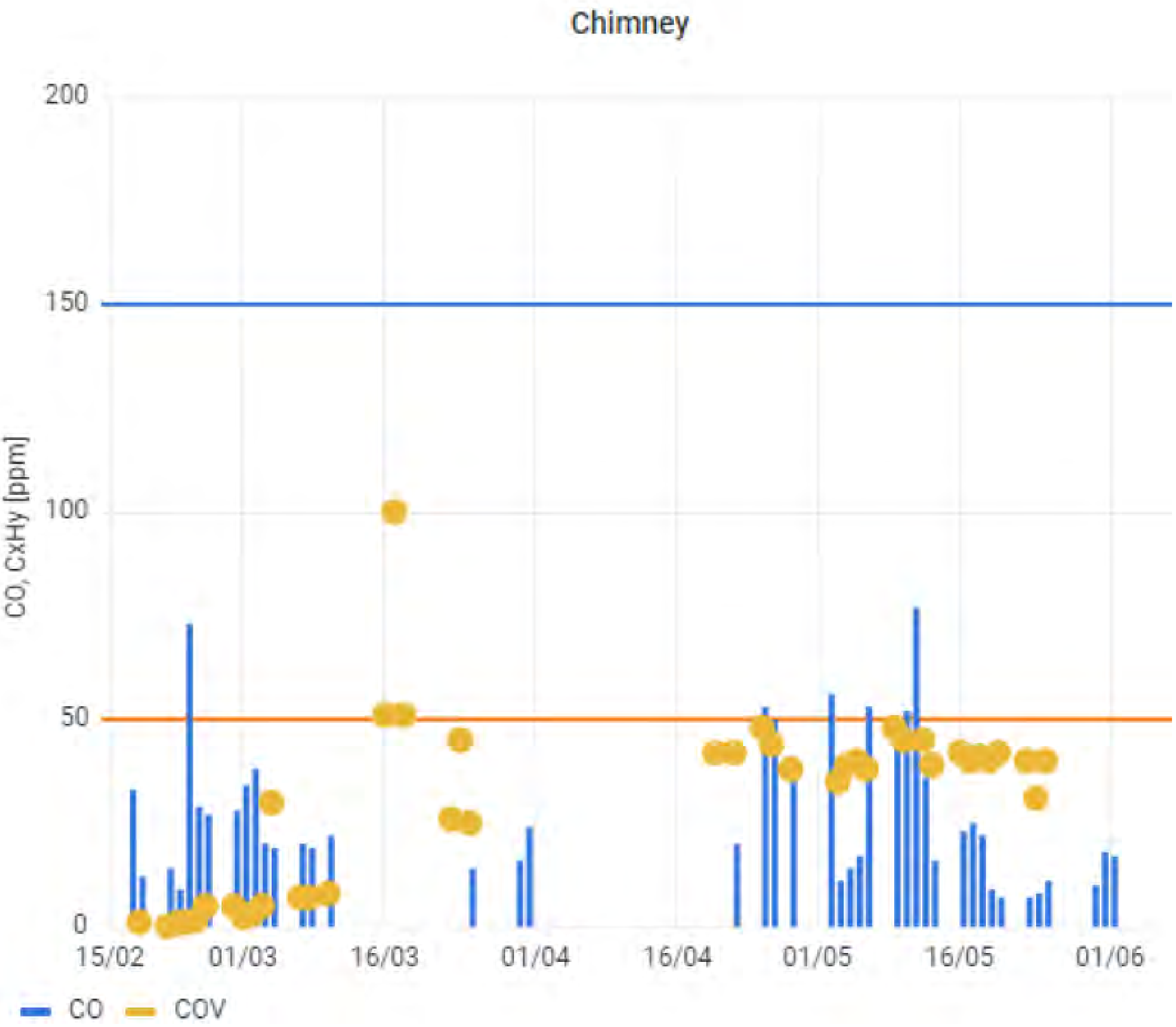


Figure 8 – Emission at the chimney

4) Emission and temperature before GAC

The temperature at the inlet of the GAC (Granulated Activated Carbon) is another critical parameter which must be monitored throughout the entire treatment. A too high temperature can lead to spontaneous combustion of the activated carbon. It was therefore important to keep the temperature around 65° at the inlet of the GAC. It can be observed on **Error! Reference source not found.** that the temperature remained around 60°C – 65°C throughout the process, with a maximum of 73°C on the 18th of May.

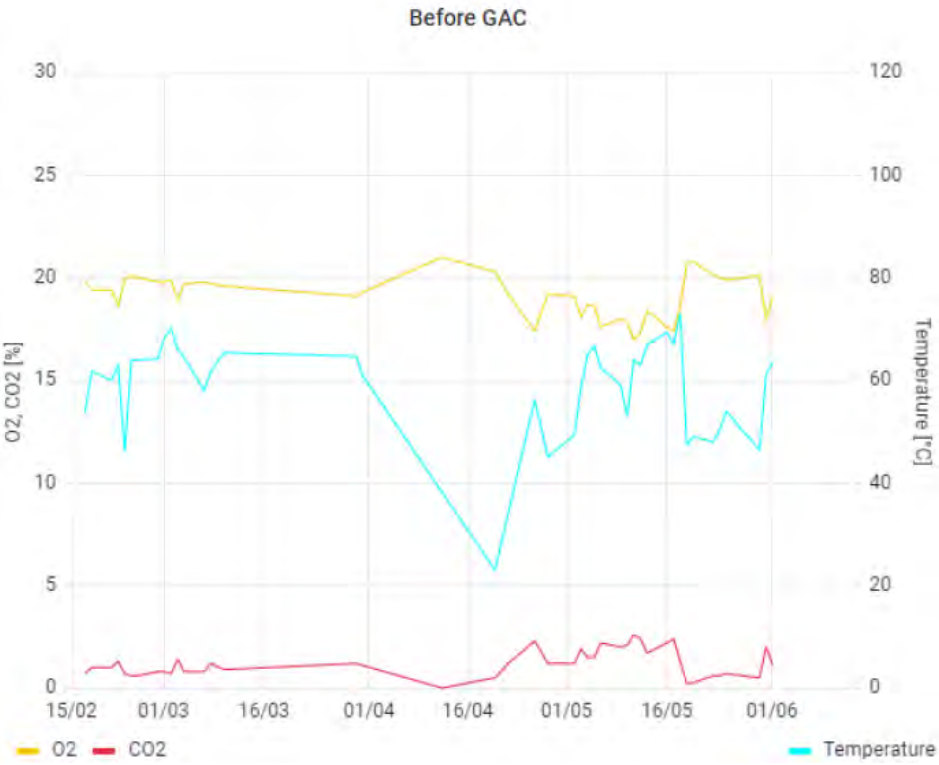


Figure 9 – Emission O_2 and CO_2 and temperature before GAC

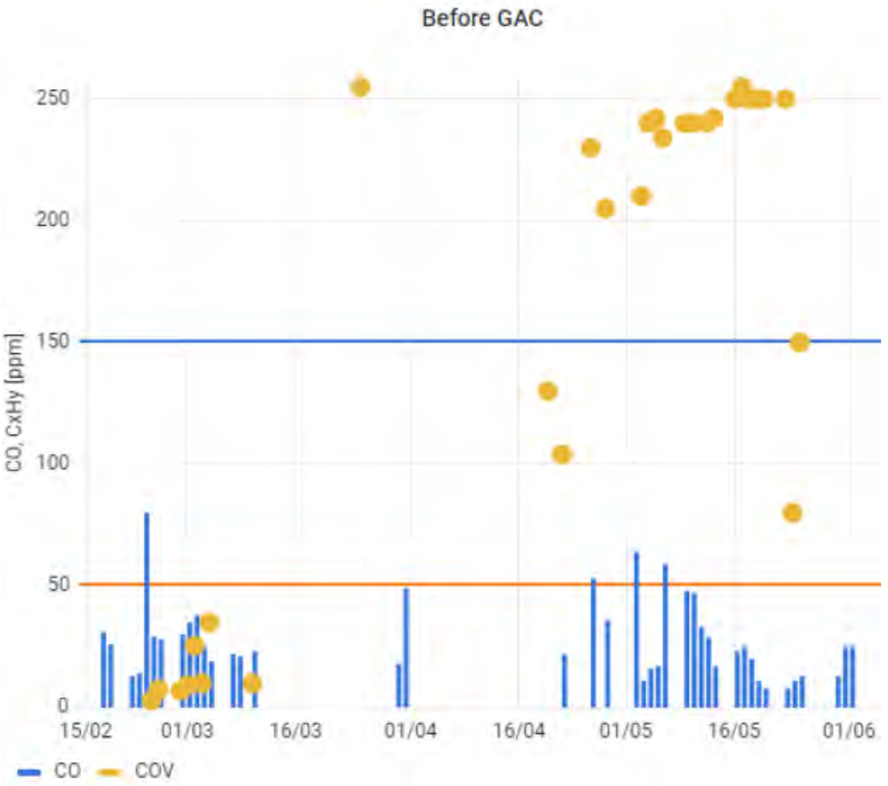


Figure 10 – Emission CO and COV and temperature before GAC