In-situ thermal remediation: ecological and economic advantages of the TUBA and THERIS methods

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1 Introduction

The reuse of former commercially or industrially used areas by new investors is often only possible if there is no contamination on the site to avoid danger by liability for the new site owner. Therefore investors frequently prefer a rapid and complete remediation of such contaminated areas. Until recently, soil excavation was usually seen as the only option to remediate a site within a few months. In comparison to this procedure, the operation times of conventional remediation techniques such as 'cold' soil vapour extraction (SVE) or pump and treat methods can take several years to clean up a property, and the result is often still uncertain.
Using the in-situ thermal remediation methods TUBA (steam- (air-) injection) or THERIS (thermal well application) (Fig. 1) a sustainable cleaning of soil and groundwater within a few months can be achieved. These techniques were developed in research- and development projects at *VEGAS*, the research facility for subsurface remediation located at the Universität Stuttgart.
In addition, by removing the contaminants in the soil and groundwater, converse to the excavation method, the impairment of the surrounding area is minimized and an economical advantage is gained.

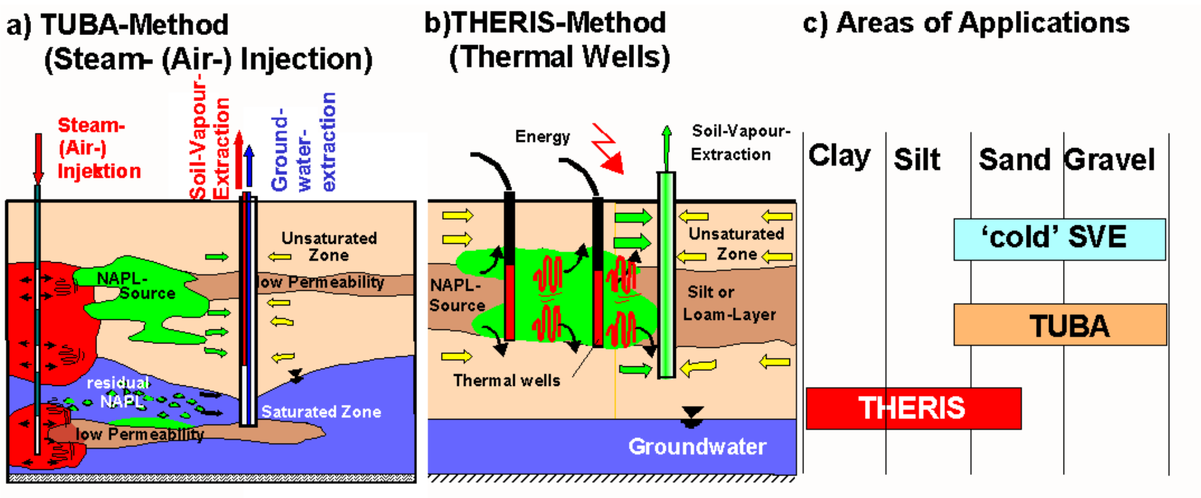

Fig. 1: Sketch of the thermal in-situ-remediation methods a) TUBA, b) THERIS and c) their fields of application

2 Method description

Under natural conditions in the subsurface (approx. 10°C) liquid organic pollutants (NAPL) evaporate only in a small degree due to their low vapour pressure. A higher temperature in the subsurface accelerates the evaporation of the pollutants essentially. Therefore the extraction of the pollutants by the TUBA and THERIS method from the subsurface takes place considerably as gaseous phase by means of soil vapour extraction (SVE).
To heat up the subsurface, different methods can be used. In soil structures with sufficient permeability, the pore diameter enables effective steam- or steam-air-injection (TUBA method) to heat up the subsurface mainly by convective heat transport (Fig. 1). In the case of a cohesive soil layer (silt, loam, clay) from larger thickness a conductive heating by electrically driven thermal wells (THERIS method) is more efficient. Furthermore, this procedure provides a partial drying process of the cohesive soils, which causes an increase of the effective gaseous permeability [HIESTER et al. [3]]. Higher pollutant discharges are therefore attainable, and thus the total remediation time is reduced.

Tab. 1: Overview of Projects

Project	Method	Conta-minant	Depth [m b. surface]	Zone, Soil	Remediation Time	
					thermal	'cold' SVE
Gas Plant Plauen	TUBA	BTEX	up to 4,5 m	UZ[1]: loam	110 days	>8 years
Deposit Mühlacker	TUBA	CHC, BTEX	up to15 m	UZ[1]: marl- & claystone	15 month	>10 years
Chem. Cleaning Albstadt	TUBA	CHC	up to 6 m	UZ[1]+SZ[2]: fractured marl, claystone	110 days	>>3 years
Chem. Cleaning Field 1-a	THERIS	CHC	up to 7 m	UZ[1]: loam, marl, silt	90 days	>> 3 years

The technical feasibilities of the TUBA- and THERIS- methods had been shown by *VEGAS* by conducting pilot and demonstration remediation tests in the field (Tab. 1) (SCHMIDT & KOSCHITZKY [5], STEIDINGER [6], THEURER et al. [7], TROETSCHLER et al. [8], HIESTER et al. [3]). All remediation tests had been completed successfully within a few months. The pollutants were removed by both methods via steam distillation. Here, water and contaminants are boiled together. The partial vapour pressures are added and the boiling point of the water pollutant mixture at atmospheric pressure is always below 100°C.

3 Research method
3.1 Introduction

In the following, the results of the different sites are compared with one another. Before starting the thermally enhanced in-situ-remediation, at each location a conventional 'cold' SVE was operated. With the measured values, the determination of the expenditures for an overall conventional remediation method in terms of remediation time, power requirement and costs, can be predicted. In order to make a comparison of the two remediation methods, functional units are formulated, as they are common in the field of life cycle assessment (HIESTER & SCHRENK [2]). For this investigation, specific values per recovered mass of contaminant must be calculated. Site specific conditions like subsurface characteristics (e.g. geology, contamination, distribution) and the type of the remediation installation (e.g. location of injection and extraction wells, injected heat flux) are cumulatively represented. For a site independent comparison, the absolute values however, have only limited usefulness, because they can vary over a large range on case by case basis. For example, in the case of prices, fluctuations are not unusual around the factor 3 to 4 [€/m³, €/t]. However, relative comparisons of different remediation methods are more meaningful. For this, the specific values of the predicted conventional 'cold' SVE are set into relation to the thermal method for every examined location.

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[1] UZ = unsaturated zone
[2] SZ = saturated zone, below ground-water table

3.2 Calculation of the potential environmental impacts of the soil vapour extraction

For the calculation of potential environmental impacts in different field cases of the thermally enhanced soil vapour extraction projects the method of life cycle assessment (LCA) was used. This method is defined as a DIN EN ISO standard [1].
The comparison of different remediation options is possible if they refer to the same specific value. In the case of the comparison of different remediation methods, the mass of contaminant to be extracted from the subsurface must be similar. For the calculation of the LCA the software tool 'Environmental Balancing of Soil Remediation Measures' [4] was used. This tool enables the balancing of all usual remediation methods and the most common innovative methods through combinations of 60 so called 'modules' (e.g. transportation, soil washing plant, excavation, etc.).
Based on the *input-data* (e.g., transportation-distances, operation time of the SVE, consumption of material etc.), the *consumption-data* (water, fuel, electricity, etc.) and the *life cycle inventory assessment* (e.g. total amount of energy, emissions) are calculated by the software. Finally, more than 100 inventory categories are summarised in the *life cycle impact assessment*, covering 19 different impact categories, none of which are comparable to each other. Examples for the impact categories are cumulative energy demand, global warming, fossil resource consumption, waste, summer-smog, acidification and human toxicity.
In principle, a comparison of different remediation options per site is only possible within the equal impact category. The results from different categories must be evaluated together to get a summarised interpretation of the expected environmental impacts caused by the different remediation options.

4 Results
4.1 Remediation time

The forecasted operation times for the 'cold' SVE are systematically too short due to an overestimation contaminant recovery over the time. Reasons are difficulties in predicting the limitation by diffusion limitation. Therefore, the thermodynamic equilibrium is calculated very optimistic for the 'cold' SVE. For example, at the THERIS site, no decrease of the extraction concentration for the 'cold' SVE is calculated, so the forecast scenario for the 'cold' SVE is based on a linear pollutant discharge, which is a well known overestimation.
Based on these optimistic operation times, the results of the prognosis calculations for the 'cold' SVE are always minimum values, because the 'real' extraction concentrations would decrease. Despite this over-estimation of the 'cold' SVE, the in-situ thermal remediation methods TUBA and THERIS were about an order of magnitude faster (Fig. 2). Moreover the procedures TUBA and THERIS offer more guarantee for the remediation of a site, because the contaminants can be removed completely from the subsurface.

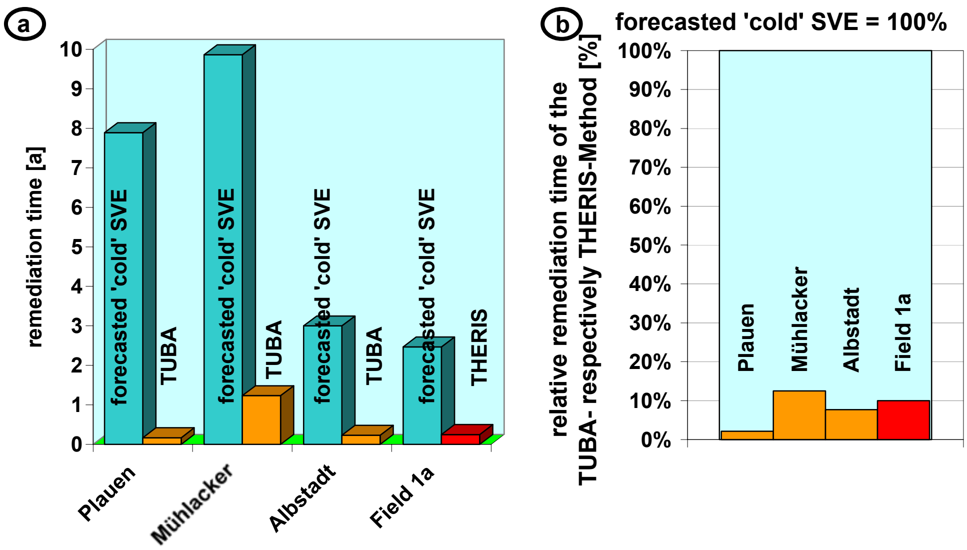

Fig. 2: Comparison of the remediation times of a forecasted 'cold' SVE-application and the thermal in-situ-methods TUBA and THERIS: a) absolute values, b) relative values (forecasted 'cold' SVE-application equals 100%)

4.2 Energy consumption and other impact categories of the LCA-method

The method of life cycle assessment is expanded to estimate the potential environmental impacts by the remediation processes with a variety of different impact categories. The benefit of this approach is the benchmarking of the complete remediation procedure including impacts from air and waste-water treatment.

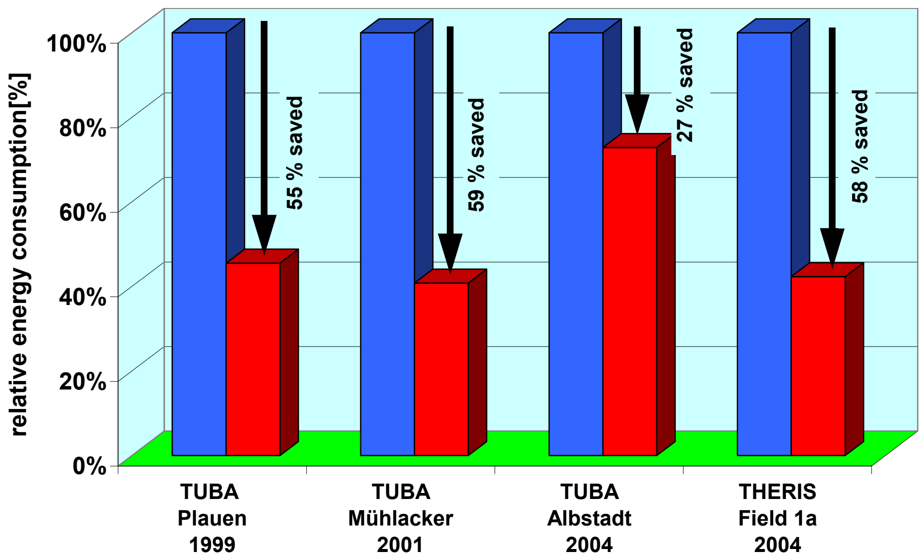

Fig. 3: Comparison of the total energy consumption of forecasted 'cold' SVE-application (=100%) and the energy consumption of the thermal in-situ-methods TUBA and THERIS

The total energy demand is one of the most important criteria. Again, the total energy consumption for LCA of the forecasted 'cold' SVE equals 100%. Compared to that, the thermally enhanced methods TUBA and THERIS needed only a maximum of 42 - 45% of the energy required by the conventional method (Fig. 3). This is almost a bisection of the energy consumption. However, in one case, the Albstadt site, the energy consumption was only reduced by about a quarter of the energy consumption by the conventional method. The energy was injected in the groundwater to clean the pollutant's source in the saturated zone. At the same time a substantial quantity of the warmed water was removed due to the site specific needs of groundwater pumping.

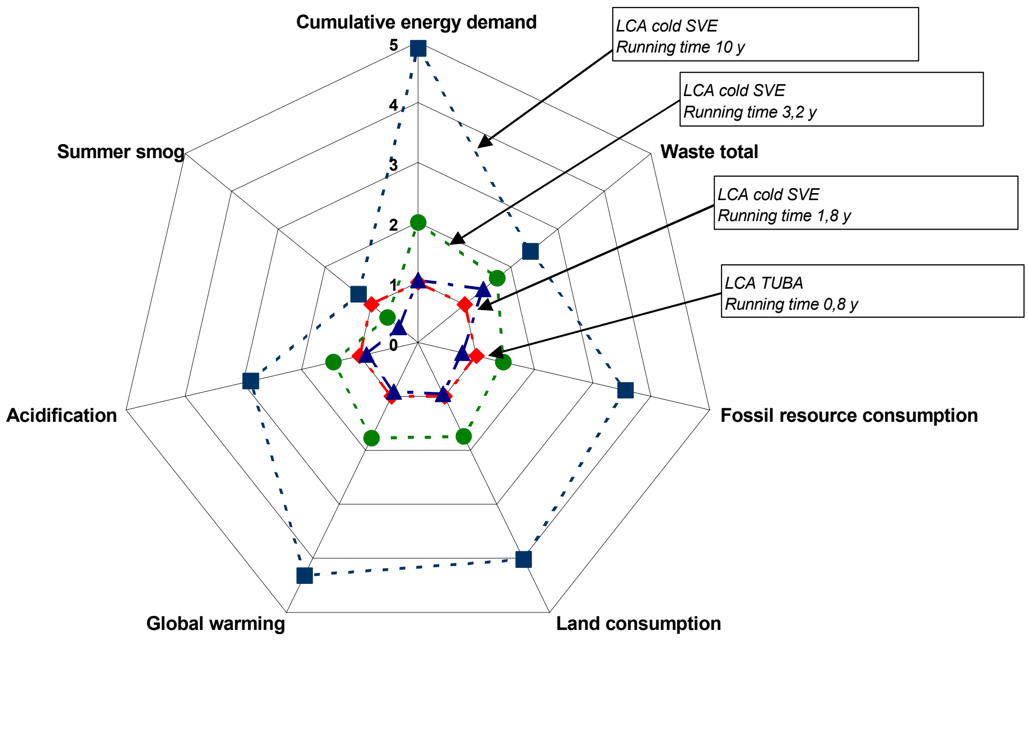

Fig. 4: Comparison of the 'cold' SVE and the thermally enhanced method TUBA (example taken from Mühlacker site)

Additionally, in other impact categories of the life cycle assessment, like the disposal of waste, the land consumption or the global warming, the TUBA and THERIS method cause less emissions than the conventional 'cold' SVE. In the following a comparison of the TUBA-application and the conventional 'cold' SVE is shown for one field site. The direct comparison of both procedures is based on an equal amount of removed contaminant (functional unit).
In only 280 days, one of the examined TUBA plant had extracted 1222 kg of PCE. Based on field data, for the extraction of an equal quantity of the contaminant, the remediation time for the 'cold' SVE is estimated with at least 660 days (scenario 1,8 y)(Fig. 4). The assumption of a constant contaminant concentration in the extracted vapour strongly favours the SVE. The scenario with 3,2 years of remediation time is still a very optimistic, but the SVE's performance is approximated in a non-linear manner. In this scenario, the SVE would require 1160 days of operation to extract the same amount of contaminant as the TSVE did. After approx. 3.8 years (1400 d) of operation, the energy consumption of the conventional system is twice as large as that of the TUBA system, and thus, significantly worse. Finally, a realistic operation time of the 'cold' SVE is calculated by 10 years [THEURER [7]]. In all shown impact categories, the environmental impacts are larger than in the thermally enhanced technique. Nevertheless, a pre-requisite for these results was qualified planning and realisation of the two remediation methods.

4.3 Cost distribution during thermal in-situ-remediation with TUBA and THERIS

For the monetary evaluation of the remediation, the cost-analyses were done for the thermal and the pneumatic components of the plants, including the associated measuring and all control equipment. The costs for the installation of the pneumatic components at the sites including its operating costs for the 'cold' SVE was approx. half of the total costs. The other half of the costs was due to the thermal components (Fig. 5).

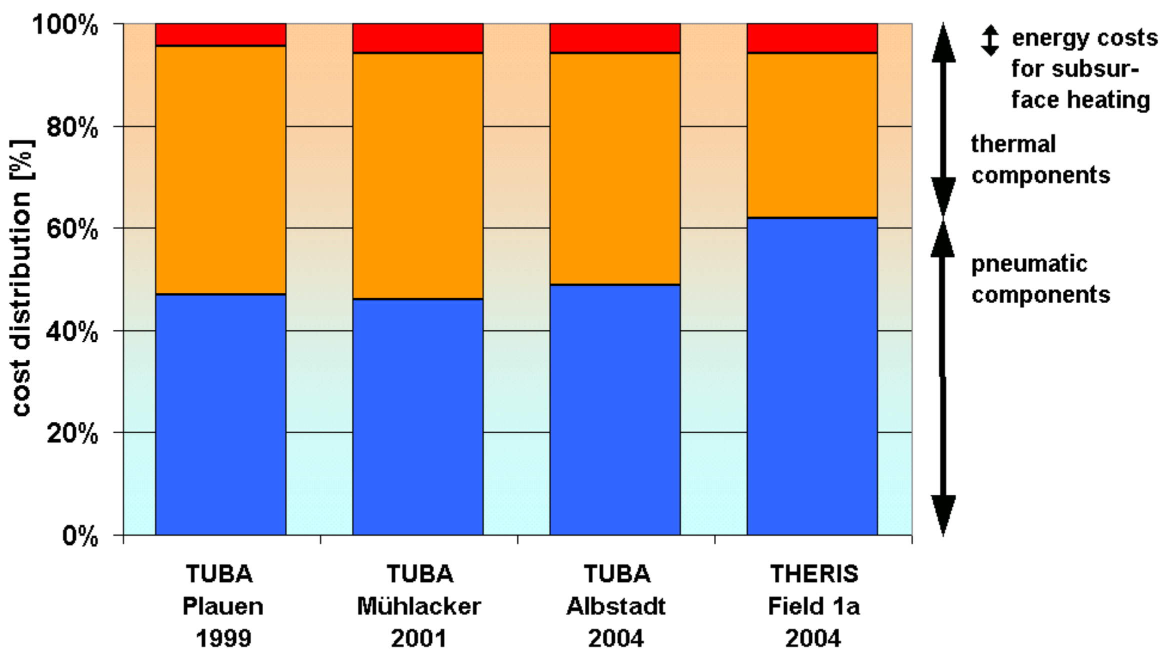

Fig. 5: Cost distribution for the thermally enhanced remediation methods TUBA and THERIS

The energy costs for heating up the soil in the examined cases were about 5% of the project costs (Fig. 5), the costs for the total energy consumption (incl. SVE and air treatment) were less than 10% of the project costs.
These results are clearly below the results of the investigations of the US-EPA. They calculated that the energy costs were lower than 30% of the total project costs [9].

4.4 Comparison of remediation costs with conventional in-situ-methods

For the overall project cost, a clear reduction of the remediation costs is proved by these investigations (Fig. 6) of TUBA and THERIS. The site-specific cost reduction potentials are between 1/3 and 3/4 of the forecasted costs of the 'cold' SVE.

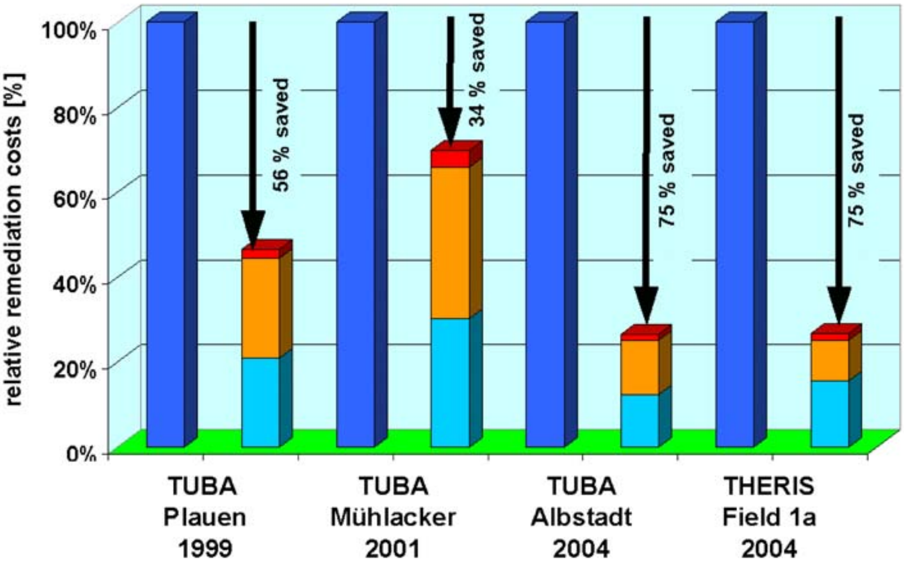

Fig. 6: Reduction of the remediation costs by using the TUBA - or THERIS-method

The results show impressively, that the thermally enhanced in-situ-remediation methods TUBA and THERIS reduce the remediation costs due to significant shorter remediation times.

5 Summary and outlook

The investigations show that the thermally enhanced in-situ remediation methods TUBA and THERIS are both ecologically and economically more efficient than conventional 'cold' SVE. The cost, time and energy consuming disadvantage of the conventional SVE, which are mainly the limitation by diffusion processes, can be overcome by using TUBA or THERIS. Economical in-situ-remediation within some weeks or month is possible.
The *VEGAS*-spin-off reconsite – TTI GmbH is mainly working in the field of revitalisation concepts for brownfields, sites and urban areas. Part of reconsite – TTI GmbH's remediation management is the planning and realisation of the TUBA- and THERIS-method for field applications.

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