Thermally Enhanced
In Situ Source Zone Removal

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Thermally enhanced in situ source zone removal

Oilphase
Application of thermally enhanced in-situ remediation

- in-situ source removal
- organic contaminants boiling point up to app. 200°C
- LNAPL & DNAPL
- non cohesive & cohesive soil
- unsat. & satur. zone

Diagram showing the application of thermally enhanced in-situ remediation, including layers of soil (silt, loam, sand) and LNAPL and DNAPL regions with groundwater.
Comparison ‘cold‘ SVE with THERIS

![Graph showing CVOC mass flux from source zone 1 over time]
Comparison ‘cold‘ SVE with THERIS

CVOC-Mass Flux from Source Zone 1 [kg/d]

- 'cold' SVE Okt.1998 - Mar.1999
- 'cold' SVE June 2009
- THERIS (only SB26) June-Okt. 2009

Time [d]
Conventional ‘cold’ SVE

Conventional soil vapor extraction (SVE): usually several years of operation

**Continuous operation**

**Intermittent operation**

initial concentration $c_0$

$\text{Altenbockum et al. 1997}$

sand, filling

contamination

loam, marl, silt

sand

groundwater

$\text{SVE}$
Thermally enhanced in situ source zone removal

Thermally enhanced SVE

- soil vapor extraction (SVE)
- air treatment system

Target:
- liquid contaminant (10 °C) ⇒ gaseous phase
- short remediation time

THERIS = Thermally enhanced in-situ remediation with thermal wells

Schematic diagram:
- HE: Thermal enhancement
- SVE: Soil vapor extraction
- Contaminated groundwater, sand, filling, loam, marl, silt
- T_{HE}: 500°C
Boiling of water and contaminant phase

![Graph showing the boiling of water and contaminant phase. The graph plots temperature (°C) on the x-axis and steam pressure (mbar) on the y-axis. The graph includes curves for co-boiling PCE and water, water, and tetra-chloro-ethene (PCE).]
Thermally enhanced in-situ remediation

• convective heat supply into soil layer with good to high permeability e.g. sand
  ➢ Steam- (Air-) Injection (TUBA-method)

• direct heat generation e.g. in dry or humid sand
  ➢ Radio frequency

• conductive heat supply into soil layer moderate to low soil permeability, e.g. silt, loam, clay
  ➢ Thermal wells (THERIS-method)
Steam-Air Injection: Field of Application

**vadoze zone:**
high to medium permeability
(gravel to sandy silt)

**saturated zone:**
porous aquifers
$K: 5 \times 10^{-5} \text{ to } 1 \times 10^{-3} \text{ m/s}$
(sand -> silt) for

**thermal range in saturated zone:**

- $K: 0.5 - 5 \times 10^{-4} \text{ m/s}$
- radial steam propagation:
  3 - 5 m in radius for 150 kg/h steam (120 kW)
- the higher anisotropy the wider steam propagation
Zeitz - Impressions From The Pilot Field

Remediation goals of the pilot in-situ remediation

→ horizontal radial steam expansion > 2.5 m in the saturated zone

→ reduction of benzene concentration in soil vapor > 99%

→ removal of contaminant mass > 95%

→ to be achieved during six months (1600 m³ of soil)

injection well

test field during operation (June 2007)
Thermally enhanced in situ source zone removal

1. "cold" air-sparing
2. SVE
3. Steam-air-injection
4. Cooling (SVE)

Target: average temperature in subsurface > 75°C

Zeitz - Heating Of The Subsurface
**Zeitz - Heat Propagation**

**target → radial steam extension > 2.5 m in the saturated zone**

Injection UZ: I1 + I2 + I3 + EK3 day 44

Injection SZ: I1 + I2 day 50

- Injection in extraction well EK3 to steam the vadoze zone
- Symmetric steam propagation
- “thermal radius” ~ 5m
- Operation of two wells

*Zeitz - Heat Propagation*
Zeitz - Mass Extraction of Benzene by SVE

**target → reduction of benzene concentration in soil vapor > 99%**

- Phase 1: (SVE) 2130 kg
- Phase 2: (AS) 4050 kg
- Phase 3.1 (UZ): 6330 kg
- Phase 3.2 (SZ): 6630 kg
- Phase 3.3 (SZ+UZ): 6710 kg
- Phase 3.4 (UZ): 6766 kg
- Phase 4 (AS-AV): 6868 kg
Indication of Remediation Progress by SVE

- Reduction of benzene concentration in SVE by 99%
- Removal of more than 99% in soil (soil vapour-soil eq. K_{OC}-method)
  - 0.16 mg benzene / kg soil
- Soil sampling eight months after steam-air injection confirmed
  - 0.1 mg/kg for unsaturated zone and 0.5 mg/kg including saturated zone
Zeitz - Summary

Heating of Subsurface

- effective heating to exceed target temperature
- effective, fast & wide-ranging steam propagation in saturated zone

Remediation Progress

- mass extraction by „cold“ SVE and air-sparging (59% of total mass)
- remediation target achieved by SI (35% of total mass in 13 weeks)
- minor mass of Benzene in saturated zone: approximately 300 kg (~ 4%)

Remediation goals

- mass removal: more than 99% of Benzene extracted (6,75 to Benzene)
- groundwater: reduction of benzene concentrations by 75%
Thermally enhanced in situ source zone removal

**Applied electrode geometries**
- Parallel plate or net-shaped electrodes
- Arrays of rod-like electrodes
  *(optional: also used as extraction wells)*
- Radio-wave antenna

- **Similar to microwave oven**
- fast re-orientation of polar molecules (e.g. water) or other polar structures in the external electrical field
- interaction within the material
- heat formation

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**Set up and working principle of dielectric soil heating**

![Diagram of dielectric soil heating](image)
Arrangement for ISRFH project

- RF unit
  - Process control system
  - RF generator (15 kW, 13.56 MHz)
  - Fibre-optical sensors
  - PLF supply (12 kW, 50 Hz)
  - Power measurement
  - Cooling system
  - Gas analysis

- RF unit connections:
  - Flexible PE hose
  - Measuring section V, T, p, c
  - Manifold
  - Coaxial cable

- Electrode arrangement:
  - 3 m Electrode distance
  - 4 electrodes / extraction wells
  - Up to 50 temperature sensors
  - 9 points for vapour sampling

- Catalytic oxidation

- Sensors for p, T, V, c
- Shielding matchbox up to 50 temperature sensors
- 9 points for vapour sampling

ISRFH with a modular RF system
ISRFH – new electrode design

Site characterization

Soil: very inhomogeneous

Groundwater table: 8.5 m bgl.

Lignite: > 9 m bgl.

Treatment of the unsaturated zone between 3 and 7 m bgl.

Contamination:
mainly benzene < 3.5 g/kg
variety of aromatic and aliphatic VOC
ISRFH with a modular RF system

Temperature profile
Temperature distribution in a soil volume of about 300 m³ after 60 d RF heating with 15 kW

VOC concentration
Increase in VOC concentration by a factor of 4 to 8

Heat transport supported by SVE
Radius of influence up to 5 m
The demonstration project consisted of three stages:
1. „cold“ SVE (24 days),
2. RF heating alone (18 days)
3. combined SVE + RFH (36 days)

App. 300 m³ were heated to a mean temperature of 54°C.

The radius of influence for RF heating was about 5 m.

SVE supported heat transport in the soil.

Extraction of VOCs was significantly enhanced by heating although quantification was difficult due to interference with the soil around the demonstration site (1.3 tonnes were eliminated).
Site D: BTEX-petr. hydrocarbon remediation

filling

clayey finesand

THERIS-remediation

sand

groundwater
Site D: BTEX-petr. hydrocarbon remediation

- Surrounding SVE-wells
- Central SVE-wells
- Thermal wells

Thermally enhanced in situ source zone removal
Seite 23
Thermally enhanced in situ source zone removal (THERIS)

Factor 100 in mass recovery

Total site (14 SVE wells)

Thermally enhanced pilot test area (2 SVE wells)

Time [days]

Mass Flux via SVE [g BE/day]

THERIS-operation

Moderate heating

Cooling
THERIS BTEX-remediation

Monday, 30.07.2008:
min. 54 month (=4.5 years) further 'cold' SVE operation needed to recover the same mass from THERIS pilot test

additional costs for ‘cold‘ SVE to recover the same contaminant mass:
constant mass flux ~ 4.5 years ~ 120.000 £
half mass flux (av. over time) ~ 9 years ~ 300.000 £
Remediation Area
THERIS application

storeage

workshop
Treatment Container
Online Measurement Systems
Online Measurement Systems
Mass flux BL1 – BL5 [kg]

- Discharge [m³/h]
- Daily CHC-mass flux [kg/d]
- Time [d]
Soil Vapour Contamination [mg/m³]
Thermally enhanced in situ source zone removal

Before THERIS

2 month THERIS

4 month THERIS

6 month THERIS
TUBA-THERIS-TUBA combination @ industrial site

- Sand layer
- Aquifer 1: TUBA-remediation, steam-air-injection
- Clay layer
- Aquifer 2: TUBA-remediation, steam-air-injection
- Clay layer
- THERIS-remediation, thermal wells
Temperatures after 80 days

Deep

Intermediate

Shallow
Workshop usage during THERIS remediation

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Site</th>
<th>Specific Energy Consumption [kWh/kg]</th>
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<tbody>
<tr>
<td>CVOC</td>
<td>A</td>
<td>Cold' SVE at the beginning</td>
</tr>
<tr>
<td>CVOC</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>CVOC</td>
<td>C</td>
<td></td>
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<tr>
<td>BTEX, petr. hydroc.</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>CVOC</td>
<td>E</td>
<td></td>
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</tbody>
</table>

**Legend:**
- Cold' SVE at the beginning
Workshop usage during THERIS remediation

Specific energy consumption per recovered contaminant mass [kWh/kg]

- CVOC
- BTEX, petr. hydroc.

Site A, Site B, Site C, Site D, Site E
Evaluation of the technology

Eurodemo sustainability demands:

- processes understood
- results from applications are well documented
- high contaminant extraction rates
- fast decontamination
- costs & environmental impacts are significantly less
Conclusions

• Thermally enhancements can be efficiently applied for the in-situ remediation of the unsaturated and the saturated zone.

• Thermally enhancements can enable a continued usage of the building during remediation.

• Thermally enhancements consume less energy than ‘cold’ SVE.

• The quality of site evaluation effects the quality of the design.

• The remediation goals can effect the efficiency.
Heat-up and relax
Thermally enhanced In-situ-Remediation

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Guidelines: Application of thermally enhanced in-situ remediation available in April 2011