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STRESOIL

IN SITU STIMULATION AND REMEDIATION OF CONTAMINATED FRACTURED SOILS

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Deliverable: D6
Selected remediation technologies for two of the stimulated cells at the Kluczewo Airfield, Poland

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1. Scientific Summary

This report summarise the work done on the selection of remediation technologies that will be used in two of the stimulated cells at the field site in Kluczewo, Poland. This report was written as part of the STRESOIL EU project - Work Package 3.

Fractured low permeable sediments/soils cover a major part of the surface especially in Northern and Central Europe. These rock types possess a special problem in relation to the spreading of contaminants into groundwater aquifers, since the fractures form hydraulic avenues through the otherwise low permeable clayey sediments/soils. Traditional remediation technologies used in high permeable soils (extraction, ventilation, etc.) are primarily based on vertical wells that are installed on the subsurface. Regarding the fractured low permeable sediments, the problem is that the transport takes place predominantly in the vertical fractures and normal vertical wells seems to bypass most of these fractures. Therefore any remediation method based on such wells is expected to be very inefficient.

In order to perform effective *in situ* remediation of fractured sediments a large number of fractures have to be connected to a well or to a highly permeable sediment layer. The bulk hydraulic conductivity in the fractured sediments may be stimulated either by increasing the fracture aperture and/or the connectivity between fractures and/or the density of the fractures. During hydraulic fracturing, new fractures are introduced into the system and aperture of the existing fractures is increased due to the uplift of the soil above the fracture.

Various processes that are expected to have very different efficiency on hydrocarbon removal from the vadose zone are presented:

- Free-product recovery
- Enhanced free-product recovery
- Thermal delivery via hot air or steam injection
- In situ oxidation using advecting or diffusing oxidants
- Soil vapour extraction (SVE)
- Bioremediation

Based on the present "state of the art" on the in situ remediation of fractured low permeable sediment, two remediation technologies have been selected combined with hydraulic fracturing. In cell 1 ***Bioventing*** will be used and in cell 4 ***steam injection and soil vapour extraction*** will be used. These two remedial set ups have been chosen after site-specific evaluation of the re-fueling station at Kluczewo airfield, Poland on: (1) the geological settings (natural fractures in glacial till deposits); (2) NAPL composition (C8-C10) and macro-scale distribution of NAPLs in the area, and (3) the intrinsic biodegradation capacities of the micro flora to degrade the pollutant (jet fuel).

2. Introduction

This report was written as part of the STRESOIL project - Work Package 3. The report summarise the work done on the selection of remediation technologies that will be used in two of the stimulated cells at the field site in Kluczewo, Poland. The criteria chosen for selection of the most suitable technologies will be covered in this report.

This report covers the documentation of the following deliverable:

- D6: Selected remediation technologies for three stimulated cells

The report was prepared according to the following milestone:

- M8: Criteria for the selection of the most suitable technology for the in situ remediation

2.1 The Stresoil project

The “fractured soil” stipulated in the STRESOIL project title (In Situ STimulation and REmediation of contaminated fractured SOILs) is glacial till – one of the most common geological sediments in the European countries. The low permeable, fractured till – while contaminated – represents a great challenge for environmental cleanup procedures. Particularly, if the contamination is present in the unsaturated zone removal of the pollutants becomes very difficult.

A combination of field experiments involving various approaches, laboratory, and investigation of soil and water samples as well as computer simulations will be employed to solve the problem. A combined effort of a team from Greece, France, Poland, Denmark and USA should within a three years period result in selection of a suitable method for cleanup of the Kluczewo site in NW Poland – the site selected by STRESOIL for field experiments. It is expected that findings of the project will have significant practical applicability in several Community countries and else where with same geological setting.

2.2 Goals and scope

The scope of work package 3 is to design and install viable remediation / monitoring technologies in fractured soils.

The following tasks are specified in WP3:

2.2.1 Task 3-1 Selection of remediation technologies

- Presentation of "state-of-the-art" on the in situ remediation of fractured low permeable sediments
- Criteria for selection of most suitable technologies for the in situ remediation
- Selection of remediation technologies for two of the stimulated cells

The reporting of this task is identical with this report (D6).

2.2.2 Task 3-2 Design and implementation of in situ remediation technologies on stimulated site

- Design of remediation strategies for two of the three stimulated cells
- Installation of remediation equipment on the stimulated cells

The reporting of the design strategies is identical with this report (D6)
The reporting of the design of remediation strategies are reported in the joint report (D9, D16 and D17)
The reporting of the equipment installation is given in the deliverable report D16 (installation of equipment).

2.2.3 Task 3-3 Testing of the experimental set-ups

- Initial numerical simulations for design and dimensioning purposes
- Testing of remediation equipment on the two remediation cells
- Adjustment of operational parameters by optimising numerical simulations

The reporting of this task contribute to parts of the deliverables D11 (preliminary simulations); D17 (testing of equipment and adjustment of operational parameters)

2.2.4 Task 3-4 Monitoring of the chemical status of soil and groundwater

- Background groundwater sampling for regional chemical baseline
- Periodically sampling of the two remediation cells
- Development of field database describing the transient evolution of the NAPL compounds in the unsaturated and saturated zones at and around the field site

The reporting of this task is given in the deliverables D20 (testing of well-monitoring system) and in D25 (field database on transient NAPL evolution)

3. Stresoil build on outcomes from previous EU projects

3.1 Pore to Core

In the course of the 4^{th} FP –Environment and Climate, the EC-funded "Pore-to-Core" (Pore-to core scale-up studies of the transport properties of organic pollutants with natural attenuation) project (contract no: ENV4-CT97-0457, Duration: 1/11/1997-31/10/2000) was carried out (Pore-to-Core 2001). The overall objective of the project was threefold: (a) to develop quantitative understanding of the natural attenuation mechanisms and their interactions, by performing a series of carefully-controlled and well-characterised laboratory experiments at two different scales, namely pore-scale and core-scale; (b) to develop a self-consistent and reliable theoretical model of natural attenuation that incorporates the above mechanisms in appropriate form, through rigorous scaling up from pore-scale to core-scale to macro-scale; (c) to develop a practical methodology for the determination (calculation or measurement) of all the relevant macroscopic mass-transfer and rate coefficients.

To this end an abandoned tar-factory site (fractured clay-till) in Ringe, Denmark was used as a generic site for the project, in order to ensure the practical relevance and applicability of the results. The experimental investigation of Natural Attenuation at the pore scale allowed the identification of the main mechanisms of the process and their interactions. A theoretical pore scale model and a pore network simulator of natural attenuation, which were developed for the case, were used to analyse the experimental results, to calculate the rates of mass transfer and biochemical reactions and to predict the growth of biomass in soil. Additionally, a rigorous method was developed for the measurement and calculation of the values of the most important parameters affecting Natural Attenuation. The experimental investigation of Natural Attenuation at the core scale revealed that constrictions have to be set during the application of the method at the field scale. Using the knowledge produced from the pore-scale studies and the core- and large-scale experiments a macroscopic phenomenological model was developed incorporating the most important mechanisms identified and consequently it is true-to-mechanisms, self-consistent and consequently reliable and substantially more accurate from other existing models.

<u>The main conclusions are summarized below.</u>

1. Indigenous bacteria can biodegrade organic substances only if the contaminants are dissolved in the aqueous phase and their concentration is relatively low and it is not toxic for the bacteria. The specific upper concentration limits depend on the system (organics and bacteria) and on the temperature.
2. Biodegradation efficiency depends on both the flow velocity and the organic load. Increase of either of them results in a drop of biodegradation efficiency.
3. Biofilm thickness depends on both flow velocity and organic load. Biofilm growth is higher at higher values of either of them and the biofilm plugs smaller pores. At lower values of either flow velocity or organic load, biofilm thickness decreases and hystere-

sis effects may become important for the process.

4. Electron acceptors, which are diluted in the aqueous phase, are consumed during biodegradation and their concentration may become nil and consequently biodegradation may stop. It is very important for a site where natural attenuation is planned to be used for remediation to know if mixing of the aqueous phase with fresh water that contains extra electron acceptors happens and to what degree. Consequently, a detailed hydrological study of the site is needed.
5. The hydrogeological characteristics of the soil in which natural attenuation takes place are very important and affect the fate of the plume significantly. In this case, the microporous matrix has a significant amount of pores (over than 60%) which have a diameter smaller than 1 μm, roughly the size of a bacterium. Consequently, in these pores biodegradation does not take place and contaminant may be transported from these pores only by diffusion (a slow process, which extends the time needed for soil clean up). The fractures are used by the contaminants as highways and consequently the residence time is relatively small and inadequate for biodegradation. **Biodegradation takes place in microfractures which have dimensions of order of 100 μm and connect macro-fractures with micro-porosity**.
6. Near the source, the concentration of NAPL is relatively high and toxic for indigenous bacteria, while far away from the source, the NAPL concentration becomes favourable and the electron acceptors concentration is adequate for biodegradation.

In general, the whole study in the frame of this project has shown that Natural Attenuation is a very practical, useful and inexpensive method for soil remediation from organic contaminants but it has mainly two disadvantages, namely, the long time required for the degradation of many organic contaminants and the relatively low limits of the concentrations of the organic contaminants under which the indigenous micro-organisms (bacteria) are active. The second disadvantage of Natural Attenuation can be amended by various methods, for example, using Permeable Reactive Barriers (PRB) near the source area where the concentration is relatively high. Permeable Reactive Barriers can adsorb or transform a significant amount of the contaminants, which are dissolved in the groundwater, and consequently reduce their concentration to values lower than the critical limit for the activation of bacteria. The first disadvantage that is the long time required for the intrinsic biodegradation of organic contaminants can be amended by using methods, which would increase the rate of biodegradation by the bacteria (e.g. bio-ventilation).

3.2 TRACE-Fracture

In the course of the 5th FP –EESD, the EC-funded "TRACE-Fracture" (Toward an improved risk assessment of the contaminant spreading in fractured underground reservoirs) project (Contract No: EVK1-CT1999-00013, Duration: 1/2/2000-31/1/2003) was carried out (TRACE-Fracture 2003). The overall objective of the project was (1) to develop a novel method of characterization of fractured media at the scales of single fractures and fracture networks, (2) to develop new and true-to-the physics phenomenological models which express the single-phase flow, two-phase flow and solute dispersion effective coefficients of fractured porous media as functions of fracture morphology and fluid rheology, (3) to integrate the new phenomenological models into a novel and reliable numerical simulator of the macroscopic contaminant transport in fractured underground reservoirs, (4) to use the new numerical tool in the development of a generalized methodology of risk assessment and rational design of remedial strategies for contaminated fractured aquifers, (5) to implement the results in two different generic contaminated fractured sites situated in Europe.

The most important scientific achievements of the TRACE-Fracture project are described briefly below.

- Two fractured sites contaminated by organic pollutants (NAPLs) were selected: one (site 1) situated in Northwestern Spain, overlying highly fractured granite rock and contaminated by the waste oils of a facility; another one (site 2) situated in Ringe Site, Denmark, consisting of fractured clay till, and contaminated by leaking storage tanks of an abandoned tar and creosote factory.
- An integrated methodology was developed to characterize fractured formations at the scale of single fractures, fracture networks and whole site and was implemented to the two generic fractured sites.
- Experimental techniques and numerical methods were developed to determine the single-phase flow, two-phase flow and dispersion coefficients of fractured media
- A single porosity numerical simulator (SIMUSCOPP) was updated to dual porosity media for quantifying the NAPL spreading in fractured clay till sediments (unsaturated zone) and underlying homogeneous aquifers (saturated zone).
- The SIMUSCOPP was combined with a multi-scale geological characterization software (FRACA) in order to predict the NAPL migration pathways in fractured granite rocks and underlying aquifers.
- The numerical results of the updated version of SIMUSCOPP were used as input data for the risk assessment of the two NAPL-contaminated sites.
- Feasibility studies were done to investigate the efficiency of various remediation technologies as alternatives for the cleanup of the unsaturated and saturated zones of Ringe site (clay till sediment).

<u>The most important conclusions of the project are summarized below.</u>

1. By taking into account the spatial variation of the glacio-tectonic and desiccation fractures identified in the unsaturated zone of Ringe Site, as well as the statistics of the aperture of single fractures determined with SEM analysis, the calculated absolute permeability at the various depths from the ground is found comparable to experimental values measured with hydraulic tests.
2. The migration pathways of LNAPL toward the underlying aquifer are closely related with the spatial distribution of fractures in the unsaturated zone.
3. In order to predict the chemical status of the groundwater, accurate pollution scenarios must be combined with all relevant processes occurring in the unsaturated (e.g. natural attenuation) and saturated (e.g. dispersion, dissolution) zones.
4. The water-saturated clay layers act as capillary barriers that prevent the downward flow of NAPLs. The transport of NAPLs in clays takes place through dissolution/diffusion which normally is a very slow process.

5. The spatial-temporal dispersion regimes of water-soluble compounds in groundwater are closely associated with the solubility, dispersivity, moisture of the unsaturated zone, and the NAPL flux on the top of the aquifer (water table). The rate of LNAPL accumulation on the top of aquifer depends on the NAPL leakage rate (pollution scenario), the level of water saturation in the clay till, and fracture permeability.
6. The effective multiphase transport coefficients of single fractures are complex functions of the aperture morphology, flow rates, and fluid mobility (rheology). Such information is valuable in the process of calculating the transport properties of the fractured formation (up-scaling).
7. The up-scaled effective transport coefficients of the fractured medium are affected strongly by the fracture geostatistics so that the multi-scale characterization of fractures is the most critical factor for any methodology of risk analysis.
8. Although the downward flow of NAPLs toward an aquifer follows the high permeability avenues of fractures, most of the bulk NAPL phase, remaining for a long period in the unsaturated zone, is accumulated in regions that are permeable at a short length-scale (e.g. sand layers) but impermeable at larger length-scales dominated by clay layers.
9. Preliminary studies indicated that thermal treatment (electrical heating, steam injection, etc) combined with an extraction system is the most suitable method for the unsaturated zone, whereas abstraction of groundwater in conjunction with an appropriate treatment process (pump-and-treat) is likely the best option to decontaminate the aquifer of Ringe site.

Depending on the spatial distribution and interconnectivity of fractures the NAPL may accumulate within various isolated zones of the matrix porosity, and become a permanent source for the pollution of groundwater for a long period. Therefore, in-long term basis, the development of efficient remediation technologies for the in situ cleanup of the unsaturated zone is a much more important task compared to the decontamination of the groundwater from free and dissolved NAPL. The most significant problem encountered in the decontamination of clay till sediments and similar soil types is the low permeability at long distances (large length-scales) in the horizontal direction compared to the high vertical permeability because of the presence of desiccation and glaciotectonic fractures. For this reason, most of the candidate remediation methods seem ineffective. Soil stimulation with the installation of hydraulic fractures may increase significantly the horizontal permeability of such soils and sediments and enable the successful implementation of cleanup technologies. In principle, stimulation technologies were developed by the petroleum upstream companies in order to increase the production rates of oil-wells. During the last 20 years, hydraulic fracturing coupled with various decontamination technologies (e.g. soil vapor extraction, bio-remediation, steam injection, etc) has been applied successfully by an environmental company (Frx) to as series of site cleanup projects in United States. The concept of STRESOIL project was to use the knowledge and expertise gained and methodologies developed, in the context of PORE-TO-CORE and TRACE-FRACTURE projects, in order to investigate the applicability of viable in situ remediation technologies on NAPL-contaminated sites properly stimulated with hydraulic fractures.

4. Remediation practices of LNAPLs in fractured low permeable sediments

4.1 Stimulation of fractured low-permeable contaminated soils

Fractured low permeable sediments/soils cover a major part of the surface especially in Northern and Central Europe. These rock types possess a special problem in relation to the spreading of contaminants into groundwater aquifers, since the fractures form hydraulic avenues through the otherwise low permeable clayey sediments/soils. Traditional remediation technologies used in high permeable soils (extraction, ventilation, etc.) are primarily based on vertical wells that are installed on the subsurface. Regarding the fractured low permeable sediments, the problem is that the transport takes place predominantly in the vertical fractures and normal vertical wells NAPL seems to bypass most of these fractures. Therefore any remediation method based on such wells is expected to be very inefficient.

In order to perform effective *in situ* remediation of fractured sediments a large number of fractures have to be connected to a well or to a highly permeable sediment layer. The bulk hydraulic conductivity in the fractured sediments may be stimulated either by increasing the fracture aperture and/or the connectivity between fractures and/or the density of the fractures. During hydraulic fracturing, new fractures are introduced into the system and aperture of the existing fractures is increased due to the uplift of the soil above the fracture.

4.1.1 Fracturing (stimulation technology)

Fracturing is a method whereby a gas (pneumatic fracturing) or water / slurry (hydraulic fracturing) is injected into the subsurface at pressures exceeding the in-situ pressure at flow rates exceeding the flow rates corresponding to the natural in-situ permeability.
The induced fracture itself is commonly a sheet like feature with maximum dimensions of roughly 20 meters and a thickness of 1 to 20 mm depending on the type of injected fluid. Hydraulic fractures are commonly filled with granular material, which keep the fracture open. Pneumatic fractures are not filled with granular material and are kept open due to irregularities along the fracture walls.

Investigations over the past 15 years in North America have shown that fractures can be created in contaminated, fine-grained sediments, where they increase flow rates to and from wells by one or two orders of magnitude (USEPA, 1993b). The technique appears to offer the possibility of significantly reducing the costs of remediation of contaminated sites underlain by clay till by increasing the rate at which remediating agents can be introduced into the subsurface and the rate at which contaminated fluids can be extracted. Induced fractures can be established either from vertical wells (most common in groundwater) or from angled / horizontal wells.

Hydraulic fracturing is widely used in the petroleum industry where the fractures are created at great depth in rock to improve the productivity of oil wells. It has been shown that hydraulic fractures may be created at shallow depths in sediments to increase their hydraulic conductivity and improve the remediation of contaminated sites (Murdoch et al., 1994). Most of the environmental applications have been developed by researchers in Cincinnati, Ohio, with the applications conducted in silty and clayey glacial drift similar to the deposits found throughout Scandinavia, Balticum and large parts of Germany, Netherlands, UK, Poland and other areas that were transgressed by glaciers during former ice ages. The technique is applicable to the remediation of a wide range of contaminant types, including petroleum hydrocarbons, chlorinated solvents, pesticides and other compounds (USEPA, 1994). The properties of hydraulic fractures vary considerably, but many demonstrations have shown that the rate of remediation can be increased by one to two orders of magnitude (Murdoch et al, 1994). The technique appears to offer the possibility of significantly reducing the remediation costs of contaminated sites underlain by especially silty clay till.

4.1.2 Methods of hydraulic fracturing

The basic method of creating a hydraulic fracture begins by sealing a casing in the ground and creating an opening at the depth where a fracture will be nucleated. This can be accomplished by driving a steel casing with a special point that can be removed to gain access to the subsurface, but more sophisticated methods are also available. A water jet is used to cut a notch in the sediments enveloping the casing, and this notch serves as a nucleation point for the subsequent fracture. Above ground, a specialised mixer is used to create a slurry of guar gum gel and sand, or perhaps some other granular material. Guar gum is a food additive used to thicken yoghurt and toothpaste. It creates a very viscous stiff gel, much like jelly, that is capable of suspending large proportions of granular material as a pumpable slurry. Traces of an enzyme are added in the gel to destabilise and break it down into a thin liquid that can be recovered after injection.

Injecting the slurry into the exposed interval of the borehole creates a hydraulic fracture. The pressure of the injected fluid increases to 250 to 350 kPa at the onset of propagation when fractures are several meters deep. However, as the propagation of the fracture takes place, the pressure commonly decreases to less than 100 kPa. At depths of more than a few meters, injection pressures will increase by 15-20 kPa/m. Nevertheless, the process requires remarkably modest pressures that can be generated with readily available equipment and can be managed with standard site safety measures.

The hydraulic fracture itself commonly is a flat lying to gently dipping disk-shaped or bowl-like feature (Fig.1a, b). In general, the volume of the injected material controls the size of the fracture. Injecting 0.3 m^3 at a depth of 3 m, for example, typically produces a fracture roughly 8 m in maximum dimensions that is filled to a maximum thickness of 1 to 2 cm. Many applications require multiple fractures stacked one on the top of the other. This can easily be achieved by repeating the process at various depths.

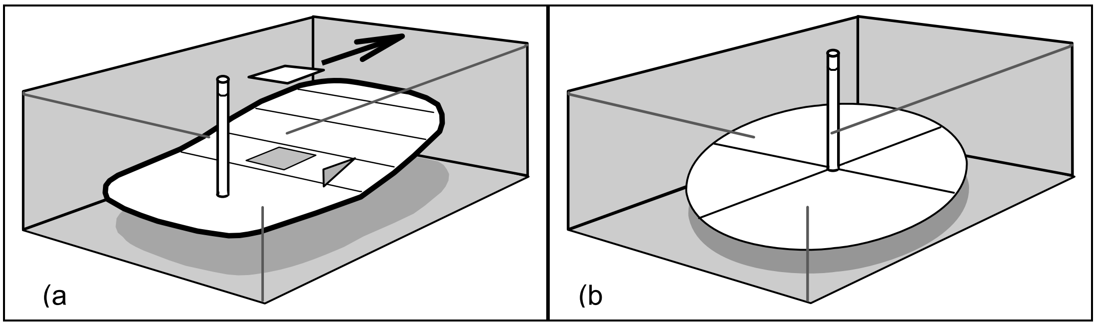


Figure 1. (a) Typical hydraulic fracture inferred from field measurements. The arrow indicates the preferred propagation direction. The white square overlies the thickest area at the centre of the fracture. Triangle shows dip angle. (b) Idealised form used to represent hydraulic fracture in the analyses.

4.1.3 Application of remedial procedures

Well-sorted sand is injected into the fracture to create a permeable layer that will increase the rates of fluid flow in the subsurface. Most applications that use this approach cause the discharge of wells to increase by one to two orders of magnitude. This type of improvement has been confirmed at sites utilising vapour extraction, free-product recovery, dissolved phase recovery, injection of nutrients, air sparging steam injection, and related methodologies (Murdoch et al, 1994; 1997).

Increasing the advective transport by one to two orders of magnitude can provide meaningful improvements to the remediation of many sites, but it is by no means the only environmental application. In recent studies, a wide range of specialised materials were injected into fractures to evoke an equally wide range of processes. Porous ceramics have been inoculated with specialised consortia of bacteria and then injected into hydraulic fractures to form in situ bioreactors capable of degrading contaminants. Solid peroxides treated to release oxygen over several months have been injected alone or with porous ceramics to establish aerobic conditions. Zero-valent iron has been used to create layers that will reductively de-chlorinate TCE and related solvents. Potassium permanganate, an aggressive oxidant, has been injected as solid granules to form layers that will destroy nearly any organic molecule, including fuels and solvents (e.g. Murdoch et al., 1997). Another application makes use of a pair of hydraulic fractures filled with electrically conductive graphite. An electrical potential difference is maintained between the fractures and water and contaminants migrate due to electro osmosis (Murdoch and Chen, 1997). Although there is a great diversity of materials that have been used to fill hydraulic fractures, the basic methods for creating the fractures and their mechanical behaviour during propagation remain consistent.

4.2 Site characteristics relevant for fracturing

4.2.1 Geological, geotechnical and hydrological characteristics

Geological factors influence the form of induced fractures as strongly as variations in the methods of creation. State of stress and toughness of the formation exert principal control. Several other geological or geotechnical characteristics also correlate with fracture form, but these relationships result, at least in part, through effects on the predominant factors.

The state of stress in a formation affects orientation of an induced fracture once it has propagated away from the borehole. Fractures are usually flat lying where horizontal formation stresses are greater than vertical stresses, whereas they tend to be steeply dipping where vertical stresses are greatest. The state of stress of soils and un-lithified sediments depends on several factors, including consolidation history, and wetting and drying history. Soils that were consolidated under a load greater than the present load are over-consolidated, and many such soils contain horizontal stresses that exceed vertical stresses. For example, glacial loads can result in over-consolidation, so soils deposited sub-glacially are good candidates for high lateral stress. Soils containing clay minerals that undergo large volume changes in response to changes in moisture content can become over-consolidated with repeated cycles of wetting and drying. For instance, vertisols (soils rich in swelling clays) are particularly susceptible to large lateral stresses. Soils of poorly sorted particles can be dense, and stress-inducing mechanisms, such as specific volume increases due to oxidation, can readily effect high lateral stress. Thus soils derived from weathered bedrock can sustain horizontal fractures. In some cases lateral stresses are greater in surficial soils, which have been heavily weathered, than in similar underlying units.

The toughness of the soil at the fracture tip, coupled with the elasticity of soil surrounding the fracture, determines whether a horizontal fracture is thick and confined close to the injection well or thin and of large extent. Tougher soil limits propagation of a fracture and favors thicker aperture. Anisotropic toughness can occur along contacts between different strata. Induced fractures may follow contacts in interbedded sediments. The effect of bedding can be capricious, with fractures following beds in some cases and crosscutting beds in others.

Permeability has little direct effect on fracture form but deserves careful attention because of its impact on the application of fractures and also on the creation process. Permeability critically effects the relative performance of wells installed to recover fluid. In order for wells with fractures to discharge at rates substantially greater than conventional wells, the fracture sand should have permeability more than 1000 greater than the surrounding media. If the target soils have sufficient permeability, fractures can not aid the greedy operator who desires faster recovery of contaminants. In cases where fractures are being created rationally in permeable media, such as for the construction of a permeable treatment barrier, the permeability of the media provides a mechanism for separation of fluid and granules in the fracturing slurry. Fracturing techniques are available for such circumstances.

The role that the natural fractures play in determining the form of induced fractures has not been extensively explored. Few sites have undergone thorough evaluation of natural fractures, and fractures have been created at yet fewer (Murdoch, 1995; Murdoch and Slack, 2002). Flat lying fractures have been created in the upper 5 meters of glacial till near Sarnia, Ontario, Canada, for the purpose of characterizing in situ flow around fractures. Below 5m, vertical fractures were favoured. In separate projects, naturally occurring fractures have been described in similar soil nearby. Several natural steeply dipping fractures were traced from the surface to depths of 5m and appeared to have resulting from weathering processes. By inference, a predominance of near vertical natural fractures at a site does not preclude creation of useful horizontal or sub-horizontal fractures.

Water content of a formation appears to have negligible effect on creating fractures by injecting fluid.

4.2.2 Contaminant distribution

The distribution of contaminant within the polluted soils generally effects only the locations selected for fractures and has essentially no impact on the resultant form of the fracture.

Ideally, the fractures will be placed to optimally remediate the site. Exact placement depends, of course, upon the radius of influence of a fracture. Fractures should be concentrated around hot spots or source zones. For remedial designs involving fluid recovery, at least one fracture should be placed at the down gradient limit of contamination.

Fractures can have an optimal orientation for intercepting or recovering contaminants. In homogeneous media, selecting the fracture orientation follows from evaluation of streamlines in the system. In multiple porosity media, such as naturally fractured clay, contaminants may be preferentially distributed in flow channels. Fractures should be oriented to intercept these natural flow paths so that the remedial processes can address the greater portion of contaminant.

4.2.3 Structures, utilities and surface restrictions

A common concern is that fracturing may dislodge or otherwise move and disrupt structures or utilities at a site. The concern arises from the very real fact that creation of a hydraulic fracture displaces surrounding soil by a few millimetres. The magnitude of displacement depends upon the form and size of the fracture as well as the distance between the fracture and the point of interest. In the case of shallow horizontal fractures, the overlying soil and ground surface will be displaced upwards a distance that correlates closely to the aperture of the fracture. Displacement will taper to zero within a short distance outside of the extent of the fracture. At greater depths, the amplitude of displacement is diminished but a larger area is affected. (A pea under a mattress is a simple analogy for this effect.) Elastic soils attenuate the displacements caused by fractures.

Displacement is greatest at the conclusion of fracturing. Afterwards, the fracture closes and the dome of overlying soil subsides. The injected sand prevents the fracture walls from closing completely. The amount of contraction depends on the concentration of sand in the slurry. Here the ratio of maximum aperture when the fracture is pressurized to thickness of resultant sand pack after the liquid separates is similar to the ratio of total slurry volume to bulk volume of sand in the slurry.

Across a site, the displacements experienced by structures and utilities are gradual because the upward displacement follows the aperture of the fracture, both during and after fracture creation. Small fractures created at depths of two to five meters in glacial till may have a radius three to four meters and maximum uplift of 1 cm. This 1:300 gradient can be tolerated by many structures as well as utility lines, which are often constructed to accommodate strain induced by temperature changes or subsidence. Rarely will steep gradients be created at the surface, although slabs of concrete paving, which are stiff and non-bending, may shift to reveal throw of several cm at their edges. Nonetheless, counsel of structural experts should be sought if structures are considered delicate and valuable.

Surface structures can impact the propagation of fractures. The trenches and excavations used to install subsurface utilities represent a path of weak soil. If the tip of a propagating fracture intersects such a feature, it will either quickly penetrate to the ground surface, or (less frequently) propagate along the bottom of it. Fortunately, most utilities are installed close to the surface, above the target depth of many fractures. Note, shallow, sub-horizontal fractures may easily climb to the depth of utilities.

The foundations of buildings and other heavy structures can have a dual impact upon the propagation of fractures. Like subsurface utilities, the bottom of a foundation may intercept a fracture and channel slurry to the ground surface. In such case, the fracture clearly does not propagate beyond the line of the foundation. Deeper fractures that do not intersect the foundation can be influenced by the weight of the overlying structure. Multi-story masonry structures or large tanks filled with liquids impose sufficient load to alter the in situ state of stress that governs fracture form. At the least, these structures deflect propagating fractures. In the extreme, the structures may induce conditions that favour formation of vertical fractures. The phenomena are not sufficiently reliable to be used to advantage during the selection of fracturing locations. A building that appears stout may have little influence on fractures while a light frame building may seem to repel fractures.

The presence of structures and utilities at a site usually complicates the activities of creating fractures. Positioning of a drill rig to create fracture wells requires consideration of overhead electric and communication lines, the course of crushable sewers etc., and the existence of buildings, alcoves, porches, etc. Walls and fences, even with doors or gates, represent obstructions to hoses that connect the fracturing equipment to the fracture well. Likewise, active roadways or railroads disrupt site activities. These factors do not prevent application of fracturing, but must be taken into account during planning for the work.

4.2.4 Interaction with existing wells and abandoned borings

The creation and use of a fracture among existing monitoring wells and borings frequently arises at heavily characterized or confined site. Many effects can occur, and a definitive answer may not be readily forthcoming nor common among sites.

An attempt to create a fracture near an existing well may be frustrated by the tendency of the well casing to suppress opening of the fracture aperture. In a simple sense, the well can act as a reinforcing pin that holds the earth together. This effect is especially pronounced if the well is within a meter of the fracture nucleation point and if the fracture intercepts solid casing as opposed to a screen and gravel pack. Exceptions have been observed with satisfactory creation of horizontal fractures within 40 cm of an existing well.

A more distantly offset existing well may or may not interact with a propagating fracture. In some cases fractures have propagated to and around the well casing, as indicated by sand-filled aperture exposed during subsequent excavation. In other cases the aperture pinches to zero some distance before the fracture encounters the well, only to open at some distance beyond the well, i.e. the well is centred on an island of unfractured soil within the plane of the fracture. The reasons for either phenomenon have not been delineated. The consequences limit the options for planning to connect fractures into existing wells.

If a propagating fracture encounters a borehole or screen section of an existing well, the zone can be pressurized. Unsecured borings, such as those back-filled with cuttings or poorly constructed wells with insufficient annular seal, can provide a pathway for fracture slurry to reach the ground surface and frustrate fracturing operations. Likewise fracturing pressure has popped off the caps of monitoring wells. In an extreme case, well screen has collapsed when fracture intercepted an existing well. The screen is very effective at excluding the sand in fracturing slurry while passing the liquid. The resultant filter pack provides the area over which the fracturing pressure achieves sufficient force to collapse the screen. In addition to these mechanical effects, the pressurized borehole or well provides a pathway for fracture fluid to propagate in unplanned directions, especially if a secondary fracture can nucleate elsewhere along the length of the bore. We have no direct evidence of this phenomenon, but the opportunity exists.

The intersection of fractures with long sections of well screen complicates the flow patterns of almost all remediation schemes. Flow to a fracture can be characterized as linear and generally perpendicular to the fracture face. Flow to a well screen is characterized as radial. Even in a homogeneous infinite case, the flow resulting from merger of the two patterns can not be characterized by simple calculations, and thus becomes more difficult to utilize. In reality, the well often serves as a short circuit that floods the fracture with fluid from an undesired source.

As mentioned, practically no site considered for fracturing is devoid of wells and borings. Thus creative thinking and strategic use of existing wells has become the standard practice. Rarely have wells been abandoned and plugged. Often existing wells have been used as monitoring points during creation of fractures and continue in useful function during remedial activities.

4.3 Transport properties of fractured media and macroscopic NAPL fate simulation

The design and installation of the most suitable remediation scheme on a contaminated fractured site requires information about the distribution of pollutants throughout the subsurface (Murdoch and others, 2000). Macroscopic simulators of the NAPL transport in the subsurface offer a cost-effective method of collecting data concerning the spatial and temporal distribution of pollutants in fractured sites (Wu et al., 2002; Zhang and Woodbury, 2002). The quantitative description of the spatial distribution of the fracture networks over a contaminated site and the determination of microscopic properties (e.g. aperture, surface roughness, etc) of fractures are pre-required to up-scale efficiently the transport properties of such heterogeneous media (Wen and Hernandez, 1996; Miller et al., 1998; Bodvarsson et al., 2003).

The classification of fractures and development of a conceptual fracture model for a given area presumes the determination of a variety of parameters (e.g. fracture order, shape, surface texture, orientation, position, size, aperture, etc) (Keller et al., 1986; D'Astous et al., 1989; Fredericia, 1990; McKay et al., 1993a; McKay and Fredericia, 1995; Baer and Anderson, 1997; Klint and Gravesen, 1999; Klint and Tsakiroglou, 2000). From such data, the different fracture systems may be mapped and the fracture intensity/spacing of the individual systems may be calculated.

4.4 Characterisation of contaminated sites

One of the critical factors in the evaluation of the spreading of contaminants in fractured low permeable soil is the quality of the site characterisation. A proper site characterisation involves a geological model that describes the spatial distribution of primarily high and low permeable sediment. All of Scandinavia, Great Britain, major parts of Germany, Holland, Poland, The Baltic states, Russia and large areas around the mountainous areas in Europe are today characterised as soil of a glaciogene origin. Sediment that has been deposited directly from a glacier is called "till" while poorly sorted material of unknown origin often is referred to as diamict. These sediments are normally mixed with melt-water sediments and they are often influenced by glaciotectonic deformation. Till is accordingly widely distributed, but also very heterogeneous distributed and the construction of geological models offer great challenges to the geologist.

Clay till was formerly regarded to form a good protection for groundwater reservoirs. But approximately 15 years ago scientist realised those contaminants could penetrate till very rapidly through fractures. Fractures in clay till, has accordingly become the subject of intense research since then, because they forms hydraulic pathways for liquids, and allows pollutants to migrate from the ground surface through these otherwise low-permeable beds towards the groundwater aquifers (D'Astous et al, 1989; Fredericia, 1990; Hinsby et al, 1996; Jakobsen and Klint, 1999; Jørgensen and Fredericia, 1992; McKay et al, 1993b; McKay et al, 1999; McKay and Fredericia, 1995; Sidle et al, 1998; Nilsson et al, 2001).

Fractures are widely distributed in till, but the spatial distribution of these fractures is generally poorly known because their density, size and depth varies greatly within different physiographic regions (Brockman and Szabo, 2000). A proper site characterisation of a contaminated site involves accordingly, apart from the mapping of the distribution of contamination, a geological characterisation (Krûger and Kjaer, 1999; Benn and Evans, 1996; Klint and Gravesen, 1999), a hydrogeological characterisation (McKay et al., 1998; Jørgensen and Fredericia, 1992; Murdoch et al., 2000; Boldt-Leppin and Hendry, 2003) and investigation of the geotechnical properties of the till.

5. Description of dedicated processes

The presented dedicated processes are a non-ranked list of various processes that is expected to have very different efficiency on hydrocarbon removal from the vadose zone. The remediation efforts will be focusing on the Diamict / Flow till (Unit 3), which is the most heavily contaminated unit of the low permeable deposits at the site (see Figure 2).

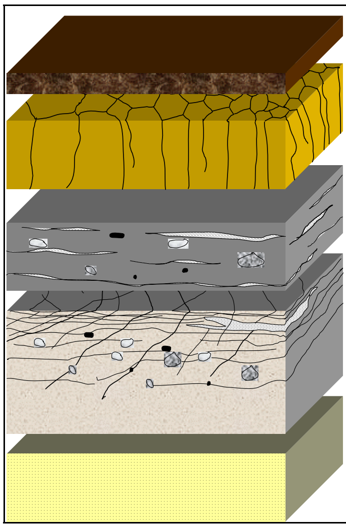


Figure 2. Conceptual geological model presented in deliverable D2 & D3 (Klint et al, 2005).

5.1 Free-product recovery

The first phase of remediation should recover liquids (water and NAPL) by means of fractures at the base of Unit 3. Ideally the fractures will propagate precisely along the contact between the diamict (Unit 3) and the basal till (Unit 4). Various factors affect the trajectory of fracture propagation. The stiffness of the till will most likely preclude much downward propagation, but there is a small chance that the 30 – 40 degree glacial tectonic shear fractures might act as preferential paths. Of greater concern is that fractures created in Unit 3 will dip towards the ground surface – even a dip as little as 10 degrees will propagate the tip of the fracture half-way upwards through the targeted unit.

Recovery through the fractures should be as aggressive as possible. That is, the wells should be placed on vacuum and be constructed to recover liquid as well as vapour. There are various ways to do this. (1) Since the fractures will be on the order of 5 m bgs, it is theoretically possible to lift liquid hydrocarbon and water from the bottom of the fracture well by means of vacuum alone (Figure 3). However, vacuum units rarely have the efficiency to suck more than a couple of meters. (2) Induce a large vapour velocity so that liquids are aspirated, effecting recovery by two-phase fluid flow up the well (Figure 2.3). This requires a careful balance between the well diameter and the specific capacity of the fracture / matrix system. On one hand, if the matrix doesn't yield enough vapour, then flow up the well may be insufficient to induce liquid movement. On the other hand, if the well is too narrow, then drawdown at the fracture face will be diminished, to the detriment of process efficiency. (3) A remedy to inadequate yield is to use a small diameter dip tub and / or provide an air-flow by admitting air into the well (Fig. 5). We do not favour such an approach because it diminishes drawdown around the fracture. In the worst case, the drawdown at the fracture is not measured and not assessed, so that quantitative measure of the fracture becomes impossible. (4) Provide a pump at the face of fracture that can operate in the vacuum imposed by the extraction system (Fig. 6). The pump moves liquids while vapours flow efficiently up the open well. Typically, the discharge of the pump has to be under vacuum. This option offers the advantages of providing maximum drawdown at the fracture and allowing measurement of the drawdown with simple well head measurement. The pump need not be expensive like purge pumps, such as the DC40 offered by Ben Meadows (http://www.benmeadows.com/store/product.asp?dept_id=2009&pf_id=2435), and bladder pumps that run off of compressed air using simple pneumatic oscillating controllers.

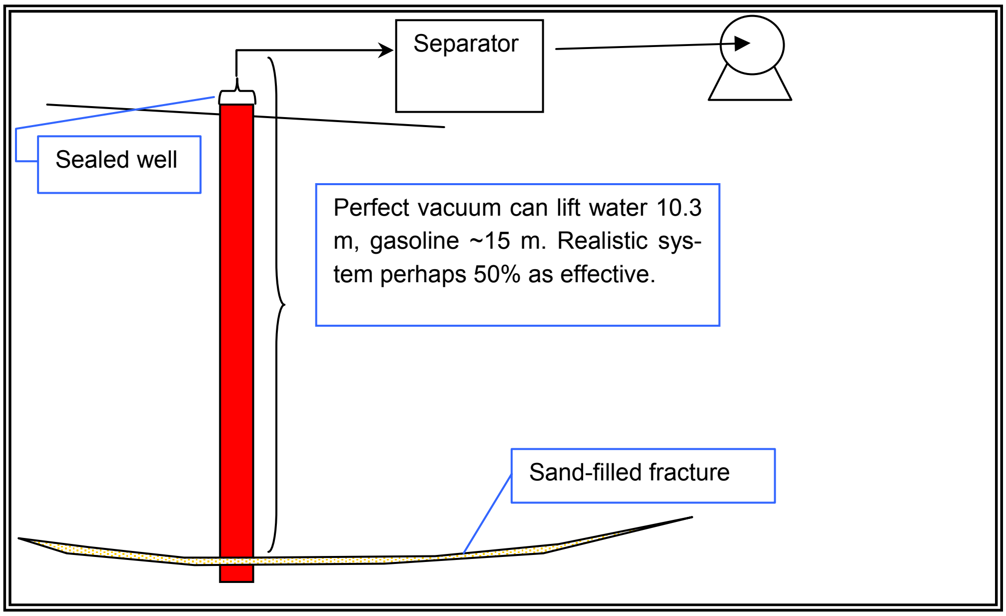


Figure 3. Free product recovery with perfect vacuum effect (theoretical situation) from a single vertical well.

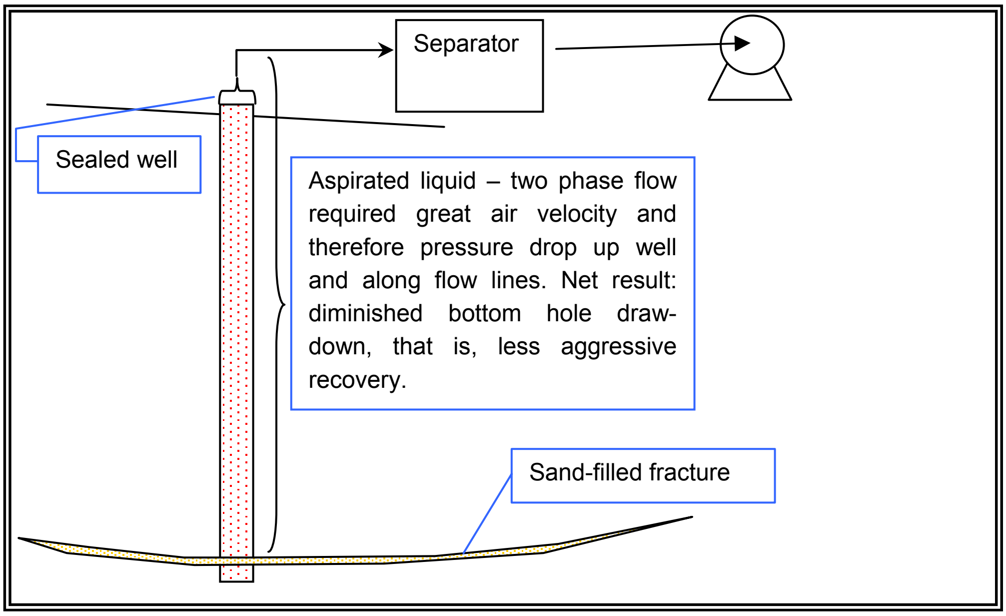


Figure 4. Free product recovery affected by two-phase flow (aspirated liquid and air).

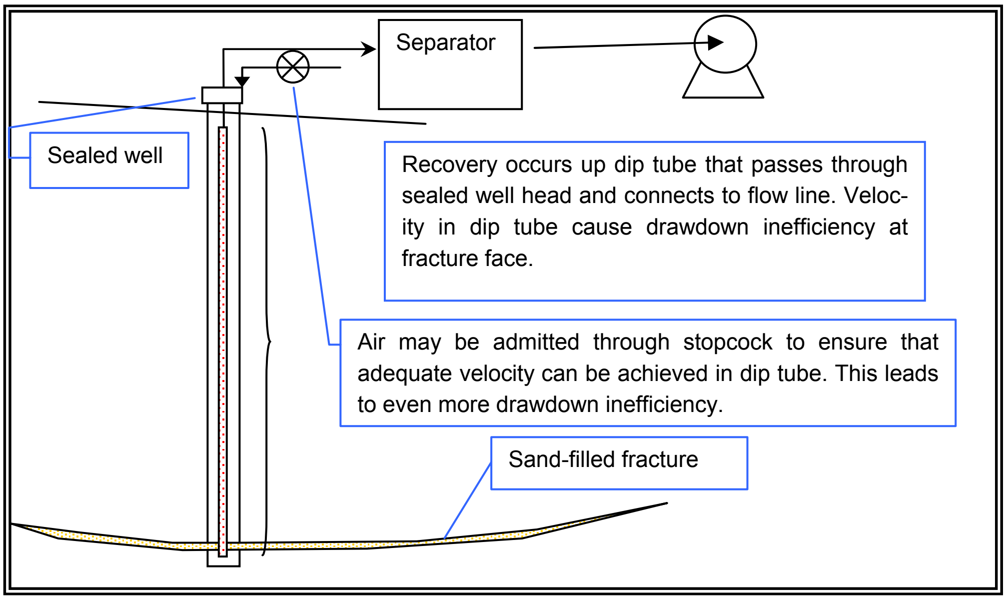


Figure 5. Free product recovery by adding a small diameter dip tube that passes through sealed well head and connects to flow line.

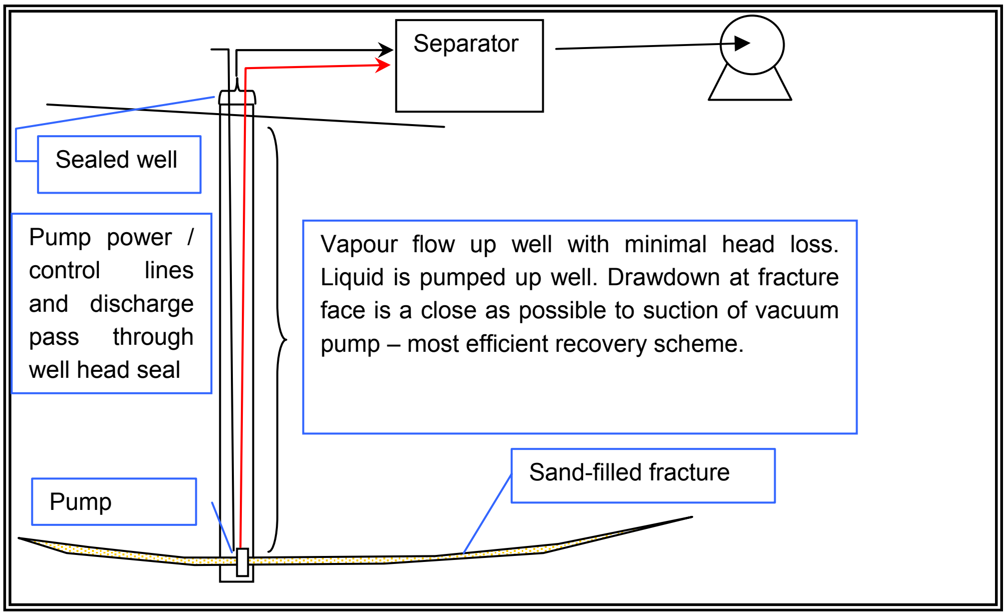


Figure 6. Free product recovery with vacuum pump at depth of the sand filled fracture.

Two phenomena are going to limit the amount of liquid that can be recovered through the fracture. First, the natural fractures in the diamict are going to drain readily. The geologic model presented in deliverable D2 & D3 (Klint et al, 2005) shows that substantial contamination has penetrated the pores and matrix surrounding the fractures. These will drain to the natural fractures, but slowly. Meanwhile the natural fractures will be conducting a great flux of air that is derived from the ground surface. The magnitude of this flux and its distribution across the ground surface will depend upon the degree to which Unit 1 and Unit 2 act as diffusers or restrictions to flow.

Secondly, the soil beneath the fractures will have a very limited contaminant removal (not drain) as readily as soil above – gravity does assist the downward movement of liquid and limit effects of the diffusion mechanism. If the fractures dip upward significantly, large volumes of soil may remain saturated with contamination – both natural fracture and matrix (Figure 7).

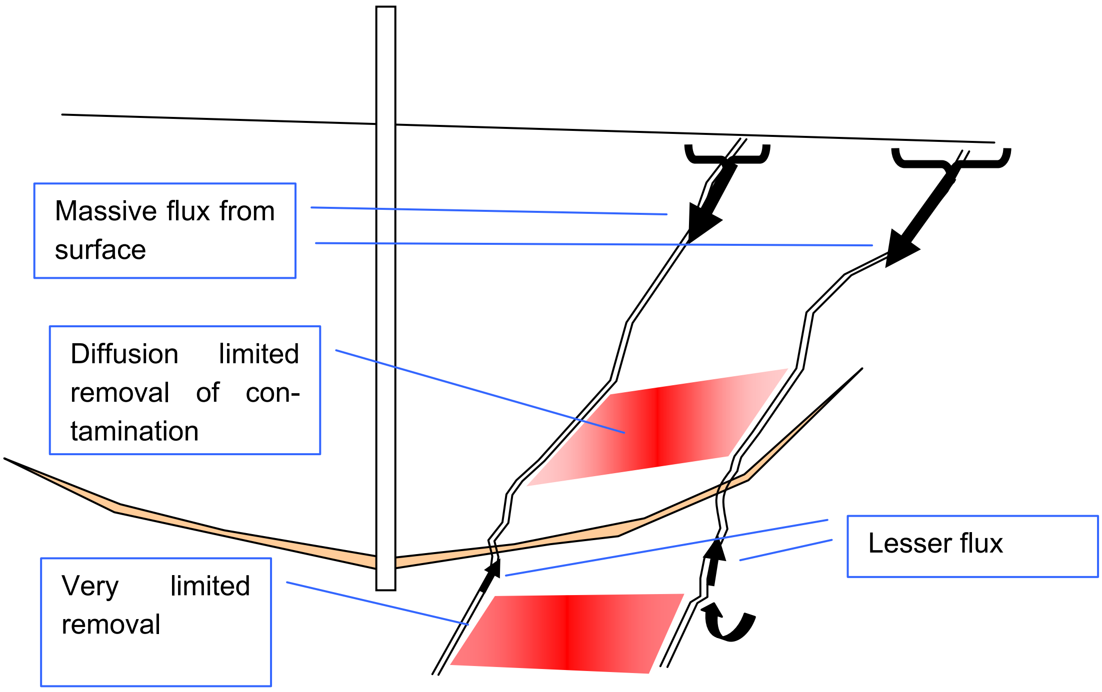


Figure 7. Conceptualisation of contaminant removal below and above a hydraulic fracture.

In terms of operational characteristics initial recovery can be expected to be mostly liquid – probably petroleum hydrocarbons with some water - followed, rather suddenly, by large vapour flow with minimal liquid. At first vapour will be saturated with contamination. Later, contamination concentrations will diminish. However, this system will be very susceptible to rebound. If the recovery operations are paused, a flush of contamination will be recovered upon re-start.

The height of Unit 3 may require the use of fractures at more than one elevation. If the permeability is such that only mediocre flow can be achieved with a single, deep fracture, then fractures at higher elevations provides the opportunity to attack the problem in multiple parts. In such case, fractures should be utilized sequentially downward until the entire target is addressed.

In summary, free product recovery is most likely an ineffective, or incomplete, remediation process. However, more thorough processes that can recover or destroy the last molecule of contamination – will benefit from having a smaller target of contamination. Economic considerations alone support this conclusion in as much as more robust processes require greater expenditure of resources per unit of contamination, so a smaller target will be less expensive. In Work Package 6 process efficiency (including free product recovery) will be discussed and economical indices determined of chosen stimulation / remediation technologies.

5.2 Enhanced free-product recovery

What remediation processes are more powerful than recovery techniques?. The most incremental variation would be to alter the boundary conditions for flow by adding a parallel fracture to provide for push-pull operations (Figure 8). The success of this venture will depend upon whether a second, isolated fracture can be created. Most likely horizontal fractures can be created in Unit 3, especially in those portions that are 2 m thick. It is unsure whether the middle fracture will cut upwards into the lacustrine Unit 2. More critically, push-pull operations may not provide significant advantage over entry of air from the ground surface. Natural fractures will still be the predominant pathways, and contamination will be retained in matrix blocks. The difference between the processes will depend upon the transmissivity and role of Unit 1 and Unit 2.

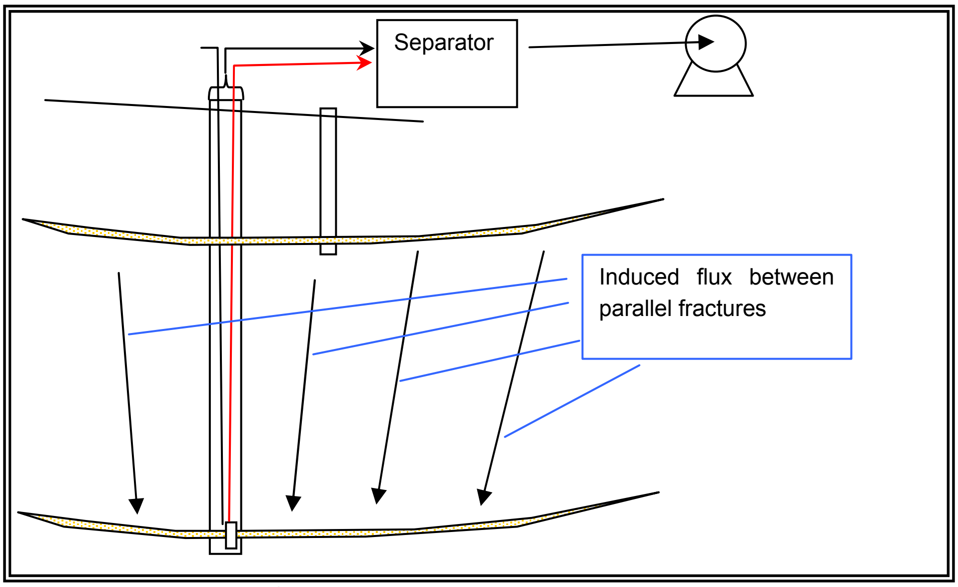


Figure 8. Enhanced free product recovery. Push-pull operation between two parallel fractures

5.3 Thermal delivery via hot air injection

The problem of matrix diffusion can be more directly addressed by the addition of energy to the system. Increasing the temperature of the contamination will trigger a litany of beneficial process – volatilization, desorption etc. Energy can be delivered by steam, hot air, and /or other methods such as resistive heating. Hydraulic fractures will be valuable for the injection of steam or hot air, while all thermal processes can utilize hydraulic fractures to recover volatilized contaminants (Sigriest et al, 1995).

Hot air injection is a straightforward modification of conventional SVE, where hot air will follow the same pathways as air during the enhanced recovery option (section 5.2). Air will move principally along the natural fractures, and heat will penetrate the surrounding matrix blocks by thermal conduction processes. Depending upon the flux through the natural fractures and the thermal conductivity of the matrix, air arriving at the recovery fracture could be hot. The exit temperature can be minimized at the expense of decreasing the injection rate and prolonging the project. Heating with air may be fraught with operational difficulties.

Quantitative interpretation of hot air injection will advance a bit beyond interpretation of free product recovery processes. In addition to non-isothermal flow in the natural fractures, modelling needs to consider the heat conduction aspects through the matrix, the thermodynamics of volatilization and desorption, and the impact of temperature and moisture changes on the pore structure and geotechnical characteristics.

5.4 Thermal delivery via steam injection

Steam injection is the most commonly used thermal remediation technology. It involves the injection of steam into the subsurface combined with extraction of water, gas and NAPL phases. Steam delivers the greatest density of energy, i.e. joules per kilogram or joules per litre of injected material. It enjoys the additional advantage of transporting energy as latent heat. As a result, a much sharper thermal front forms around the injection fracture, and temperature at the recovery well remains depressed relative to hot air injection – in addition to being a more efficient use of energy, the operational advantage of handling cooler fluids should be significant.

Remediation of matrix blocks can be accelerated if steam is injected episodically, with intervening episodes of suction that induces flash volatilization of heated contaminants and water in advance of the steam front. The volume change upon evaporation contributes to the expulsion of material, which is collected by the suction. Repeated cycles will remediate faster than the steady injection of steam and the heating of matrix by conduction (Davis, 1998; Gudbjerg et al., 2004).

Very little research has been performed on remediation of fractured systems by steam injection and only a few field-scale plot-tests have been performed (Siegrist et al, 1998; Dablow et al., 2000). Specification of optimal clean-up will require the ability to assess non-isothermal, multiphase, multi-component transport in the heterogeneous media described by the geologic model. As part of Work Package 5 quantitative analysis will be reported in the deliverable reports D11 (IFP et al, 2006) and D17 (Kasela et al, 2006).

5.5 In situ oxidation – advecting oxidant

Contamination can be destroyed in situ by introducing a suitable oxidant. Much in situ chemical oxidation (ISCO) of petroleum hydrocarbons is done with hydrogen peroxide (H_2O_2), often deployed as Fenton's Reagent or similar formulations. Permanganates, which are another favourite ISCO reagent, react slowly with aromatics that constitute the risk factors in petroleum contamination. Ozone (O_3) is a gaseous oxidant that has been used in lieu of the peroxides. The use of ozone may be attractive in conjunction with the processes described in section 5.1 – 5.3, because it continues along the theme of vapour flow (ITRC, 2005).

Any oxidant applied by advection will suffer the same limitations as injection of hot air and free-product recovery. Principal flow will be through the natural fractures, and penetration of the matrix will be a slow diffusing process. Rebound will be even more noticeable because oxidation essentially will be complete near the flow paths, quickly rendering non-detects at choice sampling locations – the comparison between non-detect and a subsequent rebound value is more startling than the difference between a small value and rebound.

Application of oxidants at extreme concentrations may have the effect of sterilizing the soil and thereby hindering or precluding subsequent bioremediation.

5.6 In situ oxidation – diffusing oxidant

Fractures can be created with granules of solid oxidant instead of sand. FRx has developed equipment and techniques for creating fractures with potassium permanganate. The methods should be readily extendable to other solids. For instance, sodium persulfate was used as oxidizer in tests at the US EPA in 1991 (USEPA, 1991). Alternatively, commercial compounds such as ORC, which is manufactured by Regenesis.

These solid oxidizers within the hydraulic fractures slowly dissolve and diffuse into the surrounding soil (Vesper et al, 1994; Siegrist et al, 1999). The oxidation front around the fracture certainly will be extended along the intersecting natural fractures due to contrasts in dispersivity. Still, conformance should be much more favourable than in the case of advection.

Diffusion from the fractures may require a long time to reach extremes of the matrix – perhaps years. Some of these solid oxidizers act more as a source of oxygen for biological activity. So, interpretation needs to include biological as well as chemical reaction terms.

5.7 Soil vapour extraction

Soil vapour extraction (SVE) is the extraction of soil vapour from the semi-saturated subsurface or vadose zone. SVE induces subsurface air flow by a vacuum applied to a sealed well established in a hydraulic fracture. The method is employed to facilitate mass removal of residual and vapour phase VOCs located in the vadose zone (Bradner and Murdoch, 2005). Volatilisation, with subsequent air advection, is the primarily removal mechanism of these subsurface constituents. Hydraulic fractures have been used with SVE wells at dozens of contaminated sites and the results suggest that they can increase contaminant removal by several times to an order of magnitude or more, largely by increasing the volumetric rate of air flow through the subsurface (Leach et al. 1994; Frank and Barkley, 1994).

5.8 Bioremediation

The microbiological treatment of the soil and the groundwater is a long known option that is very often recommended for the rehabilitation of contaminated sites. For pollutants like petroleum hydrocarbons that may serve as energy and carbon source for an adapted micro flora the limiting factor is most often the availability of an adapted electron acceptor (Blanchet et al, 2004). This may in particular be the major problem for subsoil's characterised by a very low permeability and subsequently a limited hydraulic flow. The hydraulic fracturing of such a low permeable site can significantly enhance the air flow, which may be used to enhance the input of electron acceptors (mainly oxygen in the vadose zone) in the areas where they are lacking.

Bioremediation has proven to be an efficient and cost-effective method to clean up residual contamination. Hydraulic fractures can be used to enhance the biological processes by broadly distributing injected nutrients, oxygen (or air), or augmenting bacteria. Enhancements can be applied episodically or continuously as needed.

In addition to the biodegradation, the pollution will undergo a significant volatilisation enhanced by the bioventing that will be applied through an under pressure. The molecular composition of the jet fuel (refer to D12-D21) is characterised by a significant proportion of compounds susceptible to be volatilised and this volatilisation is influenced by the pressure and in particular highly enhanced by under pressure.

The air flux that will be implemented in the porous media with the air extraction and the air injection in the depressurised system will also serve to supply oxygen, evacuate volatilised hydrocarbons and carbon dioxide.

5.9 Screening of potential remediation technologies for the Kluczewo case site

The following technologies were examined as alternatives for the remediation of the unsaturated zone of contaminated soil at the refueling station on Kluczewo airfield in Poland:

(1) free-product recovery, (2) enhanced free-product recovery, (3) thermal delivery via hot air injection, (4) thermal delivery via steam injection, (5) chemical oxidation (6) soil vapour extraction, (7) bioremediation.

The abovementioned methods of remediation were the output of the screening process included in the RAGS (Risk Assessment Guidance for Superfund) methodology (US-EPA, 1989). Once different remediation alternatives were screened, they should be evaluated in detail with respect to the site-specific characteristics of the Polish case study. The RAGS methodology uses well-established criteria to evaluate and compare different remediation alternatives (Table 1).

Each criterion is assumed to have equal importance (weighting). Depending on the specific context of the site, the criteria may be unequally weighted. Based on the overall protection and total number of positive and negative factors for each method, it seems that the free product recovery, chemical oxidation and soil vapour extraction are not suitable technologies for this site.

Table 1. Evaluation of remediation technologies in combination with hydraulic fractures

Criteria	Soil				
	Free Product Recovery	Thermal Treatment	Chemical oxidation	Soil Vapour Extraction	Bioremediation
Overall protection	-	+	-	0	+
Long-term effectiveness	-	+	+	0	+
Reduction of Toxicity	-	-	-	0	+
Short-term effectiveness	-	+	0	-	-
Implementation	0	+	-	+	+
Cost	+	-	0	+	0
Score	-3	2	-2	1	3

The hydraulic fractures could be used to recover as much free product as possible. It is needed to be realised that it will not complete the job and should not be overly concerned with rebound. Presence of free product will only increase the cost of subsequent operations. Use of push-pull operations between parallel fractures is open to question and should be pursued if appropriate. Steam will be the most efficient way to introduce heat and recover great mass of contamination in combination with a vapour extraction system. Residual to properly applied steam should provide a suitable target to bacteria for an additional biological treatment (e.g. bio slurping or venting). Bioremediation (bio-venting technique) of contaminated soil is possible to implement due to the stimulated nature (hydraulic fractures) and structure of the soil. At non-stimulated conditions the implementation would most likely be more difficult. However, a long term period is expected to be needed to show effective treatment.

On the basis of the foregoing analysis, the suggested strategy for remediation of the Kluczewo case site is a combination of different systems and technologies, including:

- Bioremediation (bio-venting technology)
- Thermal heating of the soil using steam combined with an extraction system
- Gas and water treatment plant to treat the extracted hot air / steam and liquids
- Collection of free-product recovery in storage tanks

6. Selection of remediation technologies for two stimulated cells

Once the different remediation alternatives are screened, they shall be evaluated in detail with respect to the site-specific characteristics of the Polish case site.

6.1 Requirements for selection of the Stresoil field site

Following site-specific characteristics are needed:

- *Geological and geotechnical conditions.* The fracturing technique have been developed to increase the permeability of fine-grained soils, such as silts and clays in Kluczewo, because in situ remediation technologies are not usually applicable when gas-phase permeabilities are less than 0.1 Darcy. Characterisation of the gas phase permeability, gas pressure distribution anisotropy and radius of influence have been investigated during Work Package (WP 2) and are thoroughly described in Nilsson et al (2005).

  The depositional environment is closely related to the formation of natural fractures and may add important information about nature of the natural fracture network in Kluczewo. Till classification and development of a conceptual fracture model is thoroughly described in Klint et al (2005).

  The state of stress in the geological formation in Kluczewo will affect the orientation of a hydraulic fracture once it has propagated from the borehole. Fracturing is particular suited to sites underlain by over-consolidated soils in which the lateral component of stress exceeds the vertical stress applied by the weight of the overburden. The state of stress has been examined on intact soil samples by IFP in Work Package WP4.

- *Depths of creating hydraulic fractures*. Horizontal positioned hydraulic fractures will most likely be created in fine-grained formations at depths of 2-10 m to improve the performance of environmental remediation projects. The state of consolidation or state of stress (mentioned above) favours the horizontal or slightly bowl shaped fracture in formations in which over-consolidated condition appears. Shallow fractures (less than 2 m depth) is typically gently dipping and fractures established deeper than 10m depth very often creates steep / vertical dipping fractures that sometimes intersect the ground surface. The effectiveness of a hydraulic fracture during remediation will depend primarily on its form; that is its shape, thickness, orientation, length, width and location with respect to the borehole.

- *Microbiological characteristics.* Biodegradability and bio-availability of the contaminants have been characterised to determine the intrinsic biodegradation capacities of the micro flora to degrade the jet fuel contamination in the bioremediation area (test cell 1) at the field site. In addition redox conditions and the terminal electron acceptors used for determine intrinsic biodegradation capacity will be used to dimensioning the bioremediation technology used in cell 1. Results of the microbiological characterisation are thoroughly described in deliverable report D13.

6.2 Selection of remediation technologies

Based on the present "state of the art" on the in situ remediation of fractured low permeable sediment, two remediation technologies have been selected. In cell 1 bioventing will be used and in cell 4 steam injection and soil vapour extraction will be used. The selection of these two remedial set ups have been chosen after taking into account the geological settings and NAPL characteristics (WP1) as well as the evaluation using the screening process in section 5.9, that includes the RAGS (Risk Assessment Guidance for Superfund) methodology (US-EPA, 1989).

6.2.1 Bioventing and soil vapour extraction (Cell 1a, 1b and 1c)

For the biological treatment by bioventing, three different approaches will be implemented:

- Cell 1a involving horizontal fracturing in order to interconnect the vertical fractures,
- Cell 1b involving a vertical well screened at the level of the Unit 3 layer,
- Cell 1c also involving a vertical well, but screened in the Unit 4 layer.

The evaluation of the suitability of the Cell 1a pilot to rehabilitate the contaminated soil in Kluszevo is the real goal of the project: the improvement of the treatment with hydraulic fractures. Cell 1b and 1c constitute reference cells as far as they will represent the result achievable in this particular site using a classical vertical well bioventing treatment. The geological structures of Unit 3 and Unit 4 are very different. This difference will significantly affect the transport mechanisms in both units. For this reason it has been decided to realise a classical bioventing by injecting air in both units in two separate cells.

6.2.2 Bioventing involving horizontal hydraulic fractures (Cell 1a)

The efficiency of bioventing by using horizontal hydraulic fractures will be evaluated in the cell 1a. Therefore three hydraulic fractures will be installed (Task 2-3). A conceptual model of this cell is presented in Figure 9 including the major air paths expected. The Figure 10 presents in addition to the air convections flows through the fractures presented in the previous figure, the expected oxygen diffusions in the matrix.

The first hydraulic fracture will be located at the bottom of the Unit 2, the second one at the top of the Unit 4, and the third one will be installed as deep as possible at the bottom of the Unit 4. This last fracture should never be under the free oil phase level floating on the groundwater.

The possibility to lower the ground water level under the cell 1a during high water periods has been discussed and should be feasible by pumping in vertical wells screened in the

Unit 5 (glaciofluvial sand aquifer). These wells should be installed with the appropriate pumps and water disposals.

Due to the presence of numerous vertical desiccation fractures in the Unit 2, the first hydraulic fracture will only by used to apply a vacuum in order to create a convective flux coming from the second fracture located in the upper part of Unit 4. This second fracture will be used for air injection.

The injected air shall migrate from there to the first and the third ones on which vacuum will be applied (see Figure 10). Depending on the monitoring results of the respiration parameters in the gaseous phase (O_2 and CO_2), it could eventually be decided during the treatment to inverse the air fluxes between the fractures two and three. Due to the presence of tectonic fractures in the Unit 4 it is very likely that the convective air transport will go along the existing natural fractures and then induce oxygen diffusion through the matrix (see Figure 10). The paths that will be used for the main convective air transport from the second fracture to the first are presently not clear. Nevertheless it is very likely that there will be a horizontal convective transport along the sand lenses in the Unit 3. The surface of these sand lenses will serve for the oxygen diffusion processes.

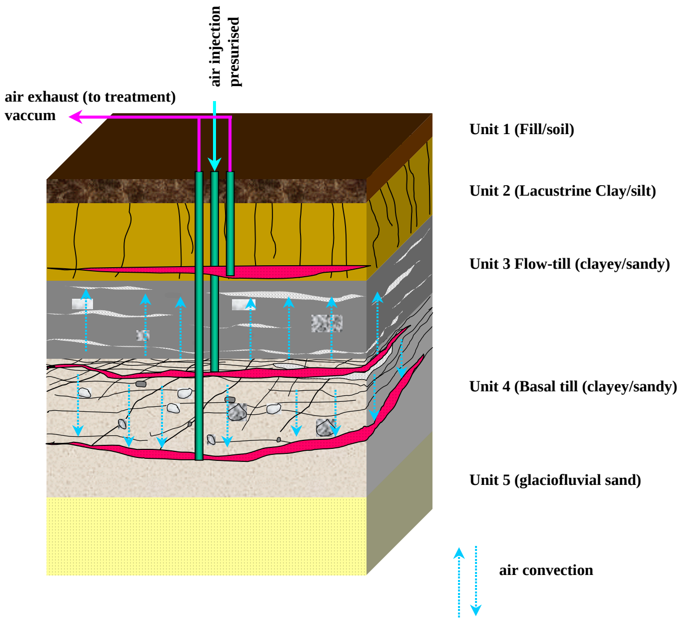


Figure 9. Conceptual fracture model for cell 1a (hydraulic fractured), general airflows.

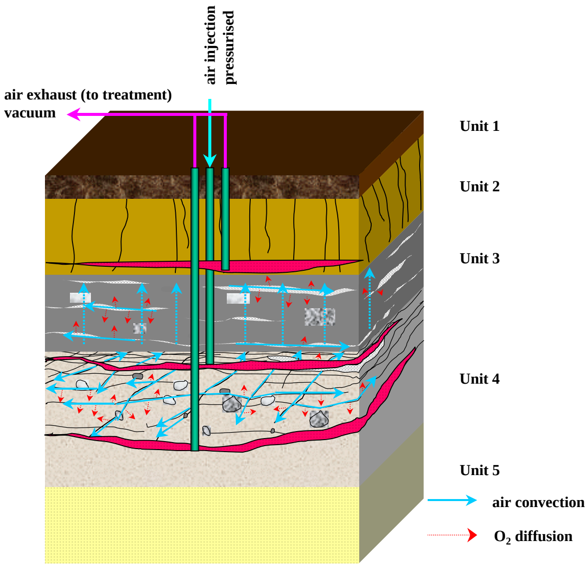


Figure 10. Conceptual fracture model for cell 1a (hydraulic fractured), air convection and oxygen diffusion pathways.

6.2.3 Bioventing involving vertical injection wells (Cell 1b and 1c)

The efficiency of bioventing in the Unit 3 by using a classical vertical well will be evaluated in the cell 1b. The conceptual model of this cell is presented in Figure 11.

In the cell 1b, the air will be injected in the Unit 3 through screens located with the top of the screen 20 to 30 cm under the top of the unit and bottom of the screen 20 to 30 cm above the bottom of Unit 3. This will ensure an air injection limited to this unit with primarily no escape way through the fractures of Unit 2 and 4.

The horizontal convective transport will follow the sand lenses of the Unit 3. It is expected that the surface of these sand lenses will serve for the oxygen diffusion processes. The extension of the effect of the air injection in Unit 3 will largely depend on how the sand lenses are interconnected.

The efficiency of bioventing in the Unit 4 by using a classical vertical well will be evaluated in the cell 1c. The conceptual model of this cell is presented in Figure 11.

In the cell 1c, the air will be injected in the Unit 4 through screens located 30 cm under the top of the unit and 30 cm over its bottom. This will ensure an air injection limited to this unit with primarily no escape way through the Unit 3.

The horizontal convective transport will follow the tectonic fractures of the Unit 4 and it is very likely that the convective air transport will go along the existing natural fractures and then induce oxygen diffusion in the matrix. The extension of the effect of the air injection in Unit 4 will largely depend on how the tectonic fractures are interconnected.

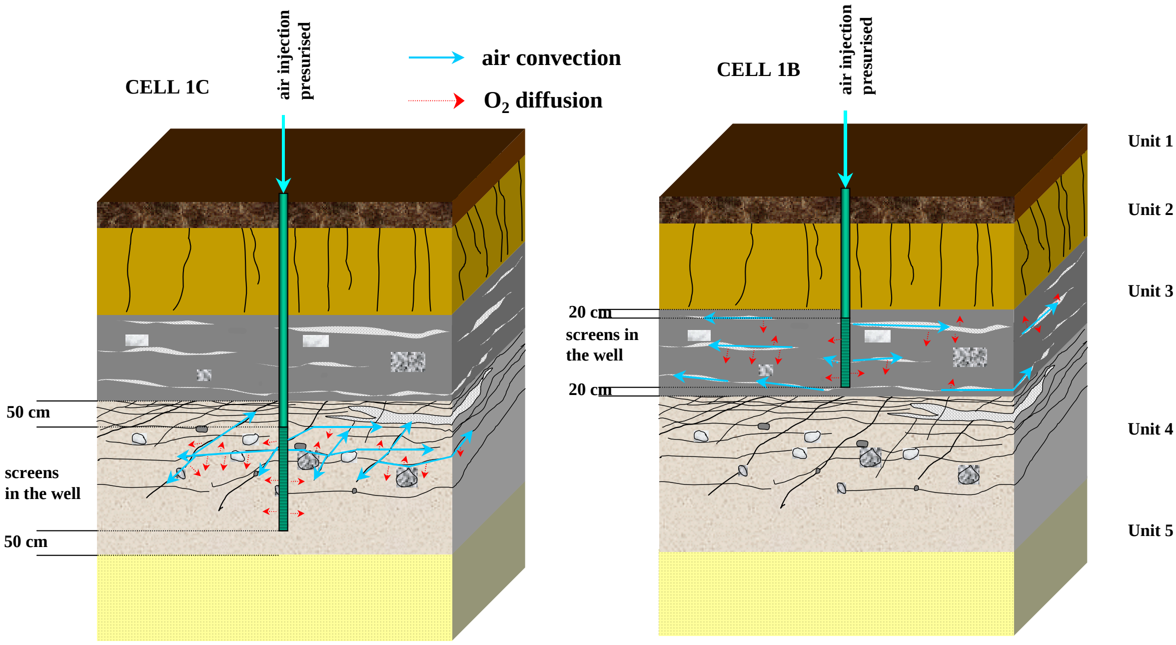


Figure 11. Conceptual model for cell 1b and 1c (classical bioventing through vertical wells in Unit 3 and Unit 4).

6.2.4 Steam injection and vacuum extraction (Cell 4)

For the thermal enhanced treatment by steam injection different approaches have been considered. Various combinations of steam injection, air injection and dual phase extraction from the upper (2.m), middle (3.0m) and lower (3.6m) hydraulic fractures have initially been simulated. Aim of the modelling is to support the decision on design, dimensioning and implementation of the experimental set-up in Task 3-3. Numerical modelling using the code T2VOC at radial symmetrical conditions have been applied to evaluate the fracture geometry and dimensioning of flow rates and pressures / vacuum used in the remediation set up. Based on this modelling a sequential design strategy has been outlined for the steam injection experiment in cell 4 starting with (A) and ending with (F) (Figure 12(A) to 12(F)):

A) Steam injection start in lower fracture at 3.6 m depth (Green fracture).
Steam will be injected in the periphery of the hydraulic fracture at 3.6 m depth. Steam will be extracted from the well placed in the middle of the 3.6 m fracture. At the same time hot air / liquid is extracted from the middle of the hydraulic fracture at 3.0 m depth (red fracture). The injected steam at 3.6 m depth will heat the soil / matrix between the 3.6 and 3.0 m fractures and remobilize the hydrocarbons as volatile compounds. The steam condensate at the matrix/fracture interface at 3.0 m depth and will most likely be extracted from the 3.0 m well as mostly hot air / liquid containing hydrocarbons.

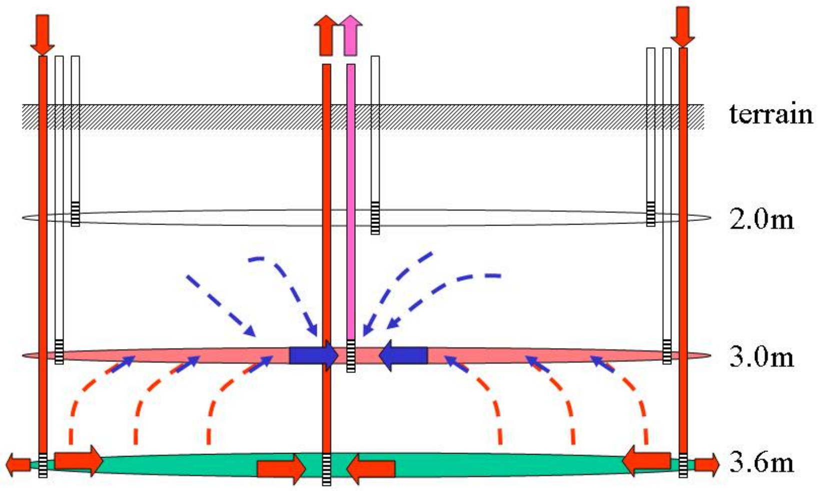
B) Steam injection start in middle fracture at 3.0 m depth (Red fracture).
When the steam injected at 3.6 m depth break through in the extraction well connected to the 3.0 m fracture the steam injection will be reduced in 3.6 m and steam injection will start in the periphery of the hydraulic fracture at 3.0 m depth. The steam front will in such way be maintained in a position close to the bottom of the 3.0 m fracture. Hot air / liquid will now be extracted in the 2.0 m fracture like in (A).

C) and D) Alternating steam and air injection in the lower fracture.
During a certain time alternating periods of steam and air injection will be done in the lower fracture at 3.6 m depth. Steam injection continues in the middle fracture at 3.0 m depth. In general air removes more contaminants from high permeable zones than steam and steam removes more contaminants from the lower permeable zones.

E) Steam injection start in upper fracture at 2.0 m depth (White fracture).
In analogy to (A) and (B) steam will be injected in the periphery of the upper fracture at 2.0m depth when steam from the middle fracture breakthrough in the extraction well at 2.0m. Hot air and liquid is most likely extracted from the middle well at 2.0 m. The steam injection in the middle fracture is reduced.

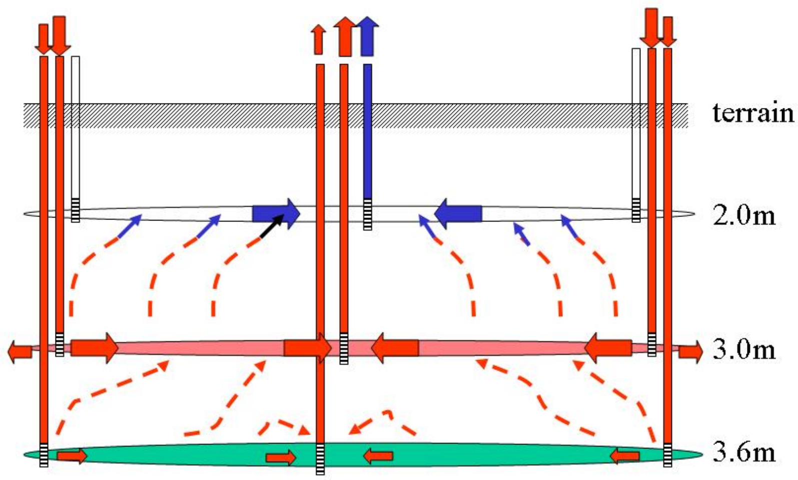
F) Potential steam exhaust on terrain
During a certain time alternating periods of steam and air injection will be done in the middle fracture at 3.0 m depth. Same strategy as followed in (C) and (D). Steam injection continues in the upper fracture. It is uncertain whether steam will exhaust as vola-

tile compounds through natural flow paths in (re)opened natural fractures across the ground surface to the atmosphere.



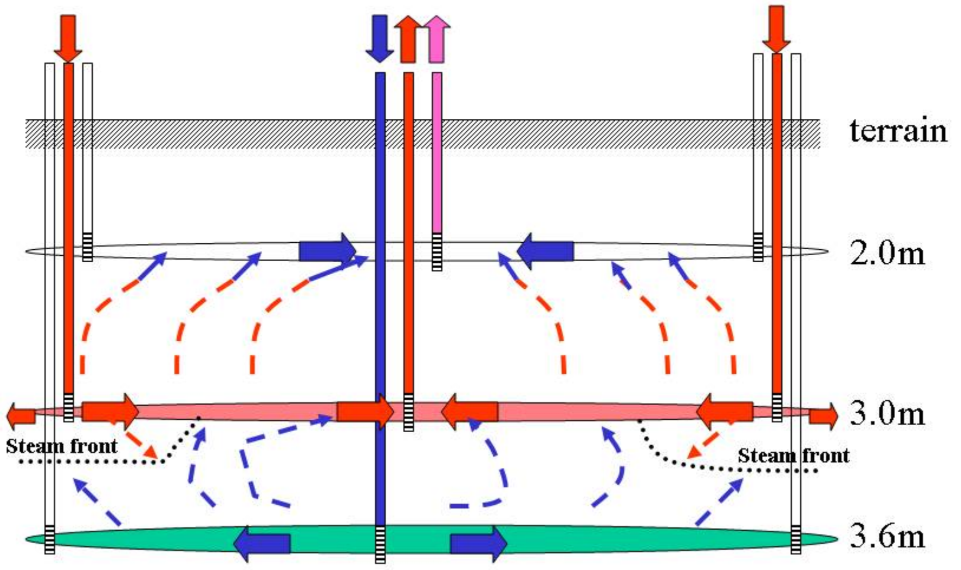
(**A**) Steam injection in 3.6m (green fracture). Hot air / liquid extraction in 3.0 m (red fracture)

Figure 12 (A).



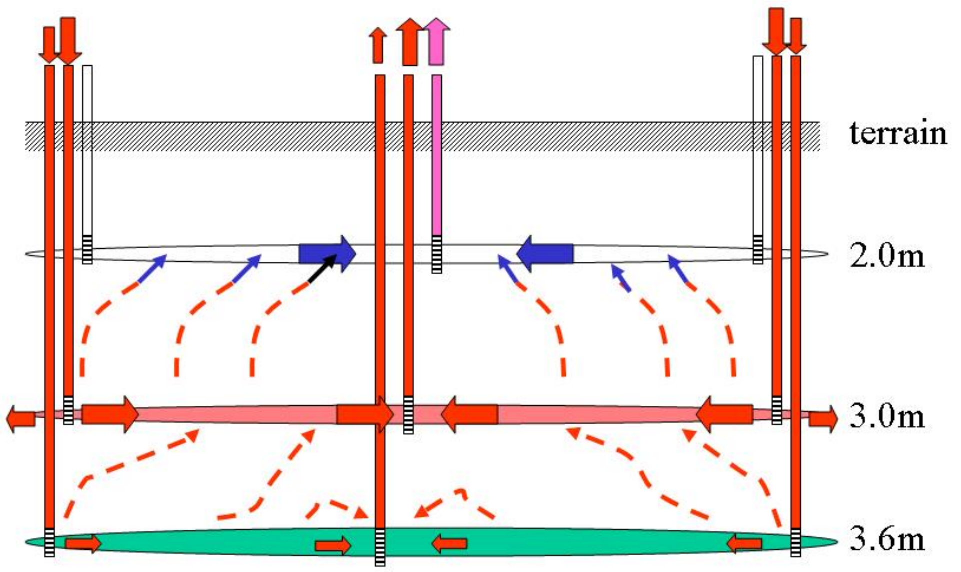
(**B**) Steam injection: high rate in 3.0m (red fracture) & low rate in 3.6 m (green fracture). Hot air/liquid extraction in 2.0 m (white fracture)

Figure 12 (B).



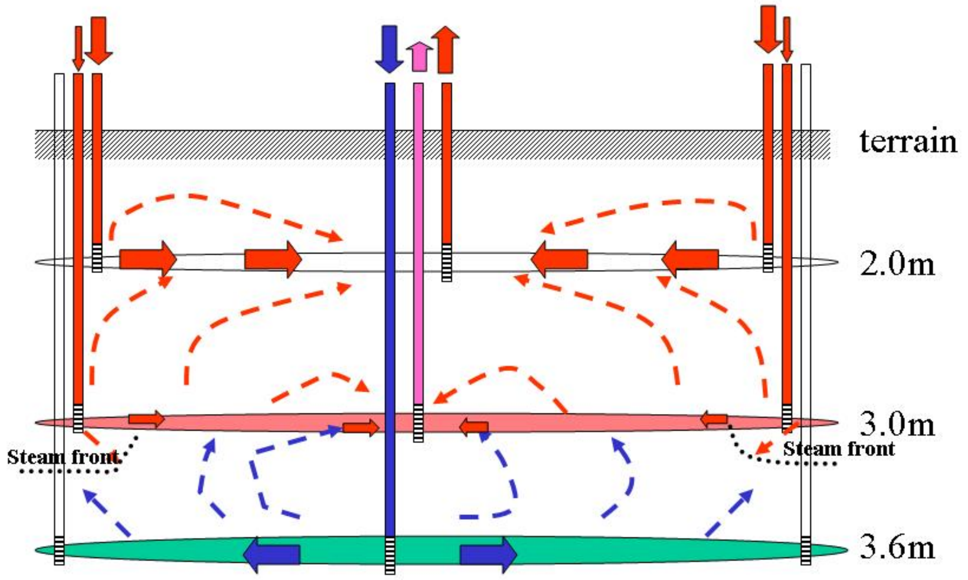
(C) Steam injection: 3.0m (red fracture). Air injection in 3.6 m and hot air / liquid extraction in 2.0 m

Figure 12 (C).



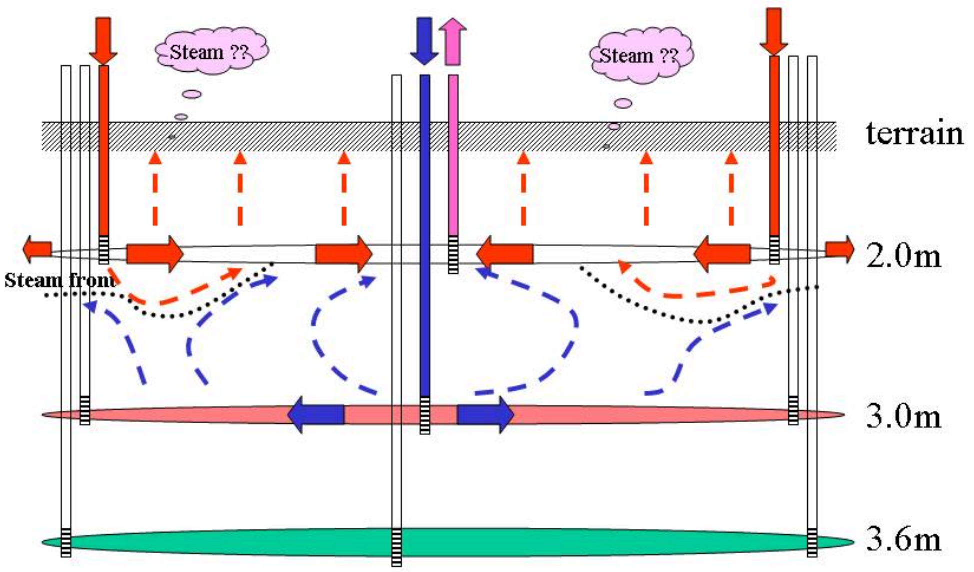
(D) Steam injection: high rate in 3.0m (red fracture) & ***repeat low rate in 3.6 m (green fracture)***. Hot air/liquid extraction in 2.0 m (white fracture)

Figure 12 (D).



(**E**) Steam injection: low rate in 3.0m (red fracture) and high rate in 2.0 m. Air injection in 3.6 m and hot air / liquid extraction in 3.0 m

Figure 12 (E).



(**F**) Steam injection: high rate in 2.0 m. Air injection in 3.0 m and hot air / liquid extraction in 2.0 m

Figure 12 (F).

7. Conclusion

Based on a “state of the art” on the in situ remediation of fractured low permeable sediment, two remediation technologies have been selected combined with hydraulic fracturing. In cell 1 ***Bioventing*** will be used and in cell 4 ***steam injection and soil vapour extraction*** will be used.

The selection of these two remedial set ups have been chosen after site-specific evaluation of the re-fueling station at Kluczewo airfield, Poland on:

(1) Examination of the geological settings (natural fractures in glacial till deposits) by excavating two pits to 5 m depth.

(2) Determination of NAPL composition in the laboratory and mapping the macro-scale distribution of NAPLs in the area.

(3) Determination of the intrinsic biodegradation capacities of the micro flora to degrade the pollutant (jet fuel) in the laboratory.

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