Project no. **SSPI-CT-2003-004017**

STRESOIL

IN SITU STIMULATION AND REMEDIATION OF CONTAMINATED FRACTURED SOILS

Instrument: **STREP**

Thematic Priority: **Global Change of Ecosystems**

Executive summary

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Executive summary

STRESOIL
In situ STimulation and REmediation of Contaminated Fractured SOILs

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Introduction

Over 300 000 potentially contaminated sites have been identified in Western Europe, and the estimated total number in Europe adds up to 1 500 000. In Eastern Europe, soil contamination by fuels (e.g. gasoline, diesel, kerosene, crude oil, etc) around abandoned military bases, airports and oil transportation pipes poses the most serious risk. The majority of the countries in the region have started to assess the problems involved. However, many CEE and NIS countries have still to develop the regulatory and financial framework needed for dealing with such contaminated sites. The development of scientifically supported cost-effective remediation strategies is therefore prerequisite for the initiation of clean up programs on the aforementioned numerous contaminated sites that are widespread all over Europe.

Clay of different origin covers today a major part of the surface of Europe. Glaciers deposited one of the most common sediment/soil types in Central and Northern Europe primarily during one of the last three major "Ice-ages" when glaciers covered more than 1/3 of Europe. All of Scandinavia, Great Britain and major parts of Germany, Holland, Polen, The Baltic States, Russia and large areas around the mountainous areas in Europe are today characterised by soil of glacigene origin.

Sediment that has been deposited directly from a glacier is called "till" and may have a dominant sandy (< 10% clay) or clayey (>10% clay) nature. Clay and clay till was formerly regarded to form a good protection for underlying groundwater reservoirs. However, during the last two decades scientists have realised that especially the till is often fractured and contaminants may migrate very rapidly through such tills as long as the source is active. Clay and clay till is furthermore highly porous (25-40%) and have accordingly excellent storage capacity. Once saturated with especially organic compounds this type of „hot spots"may release contamination via fractures into underground reservoirs for a very long period of time after the initial spill ceased.

Traditional remediation technologies used in high-permeable soils (extraction, ventilation, etc.) are primarily based on vertical wells that are installed in the subsurface. In fractured, low-permeable sediments the transport takes place predominantly in vertical fractures and normal vertical wells seem to bypass most of these fractures. Therefore any remediation method based on such wells is quite inefficient, and remediation of contaminated soil today is based mainly on the so-called “dig and dump” principles, where contaminated soil is excavated and treated (ventilated) on a special facility. Some contaminated areas are however too deep to excavate or situated in areas which are inadequate for excavation. Development of *in situ* (on the site) remedial technologies has therefore been given high priority. A variety of new remedial technologies have been developed over the past decade where horizontal wells have been combined with various remediation technologies. Bio-remediation, ventilation, steam injection and pump-and-treat techniques can be mentioned as examples of remediation methods.

In order to perform an 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 the density of the fractures. This may be achieved by introducing additional horizontal fractures at different depths by injecting fluid under high pressure into the sediment. This process is called hydraulic fracturing and it is widely used by the upstream oil industry in order to increase rock permeability and 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.

During hydraulic fracturing, new fractures are introduced into the system (Fig. 1) and aperture of the existing fractures is increased due to the uplift of the soil above the fracture and most important, existing fractures are connected via high-permeable sandfilled sub-horizontal hydraulic fractures. This may increase the efficiency of any remedial procedure by several orders of magnitude.

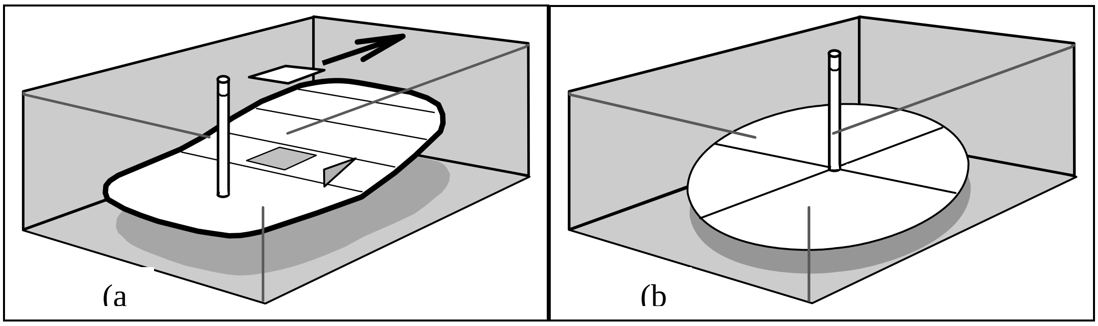

Figure 1. (a) Typical hydraulic fracture inferred from field measurements. The arrow indicates the preferred propagation direction. The white square overlies the thickest area at the centre of the fracture. Triangle shows dip angle. (b) Idealised form used to represent hydraulic fracture in the analyses.

Goals and Scope

At the present, there is a lack of a strong scientific documentation that can support or reject the application of combined stimulation / remediation technologies for the reconstitution of heavily NAPL-contaminated areas.

The EC funded Specific Targeted Research Project STRESOIL focuses on the development of scientifically supported criteria’s for the selection of the most efficient stimulation set-up and remediation strategy to cleanup the NAPL-contaminated unsaturated zone of fractured and low permeable soils.

This summary focuses especially on the applicability of hydraulic fracturing, as a viable method for increasing the radius of influence and improves the performance of traditional "in situ" remediation technologies.

The STRESOIL consortium

The STRESOIL consortium consists of five partners: (1) Geological Survey of Denmark and Greenland (GEUS) are coordinating the project as well as being lead partner for two work packages: WP1 on the geological characterisation and WP 6 on cost benefit analysis. (2) The Danish drilling company Broeker that has developed the stimulation technology in cooperation with the USA Company FrX is lead partner on WP2. (3) The Polish company Hydrogeotechnika are site owners and lead partner on WP3 concerning the remediation and monitoring technology. (4) FORTH/ICE-HT from Greece is lead partner on WP4 regarding laboratory scale experiments and determination of transport properties in soil and fractures. (5) Institut Français du Pétrole (IFP) is lead partner on WP 5 regarding development of numerical tools for simulating the NAPL fate during the experiment.

Project objectives

In order to achieve the aforementioned goal, six (6) work packages associated with specific technical objectives were formulated (Fig. 2): (WP1) A detailed geological characterization of a fractured site was carried out. (WP2) Stimulation scenarios using hydraulic fracturing were installed and tested on five highly contaminated areas (cells). (WP3) bio-ventilation and steam injection were selected and installed on stimulated cells 1 and 4, respectively; advanced techniques of chemical characterization were used to develop databases with spatila and temporal distribution of the total concentration of NAPL along with the concentration of specific families of compounds over the soil and water during each remediation scenario. (WP4) New experimental methods and computational procedures were developed to determine the single- and multi-phase transport properties of porous matrix, natural fractures and hydraulic fractures. (WP5) Simulators were used as tools to design remediation scenario and select operating variables; an existing numerical simulator of the contaminant transport in fractured media (PolluSIM) was updated to simulate bio-ventilation in stimulated fractured media and asses the NAPL fate in long-term basis. (WP6) The databases of NAPL concentration after the completion of remediation processes were employed to evaluate the NAPL removal efficiency for each cell; a cost benefit analysis was carried out to assess the feasibility of the methodology.

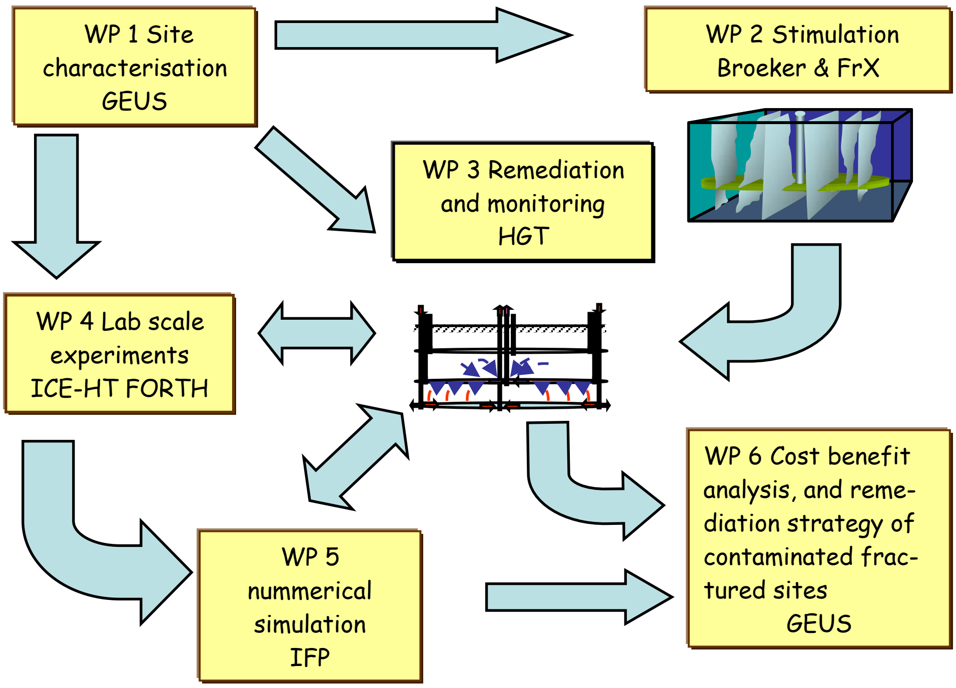

Figure 2. Project components and interconnection between the different work packages.

1.1.1 Site history

The selected experimental site is situated on the former Kluczewo airport in Poland. The Kluczewo airport is situated approximately 4-5 km west of the lake Miedwie and south of the city Stargard Szczecinski in the North-Western part of Poland. Germany (1927-1945) and Soviet Union (1946-1992) used the airport for military purposes (Fig. 3).

Figure 3. Russian Su 27 strategic fighter bomber at the Kluczewo airport Poland 1992.

During that period, extensive contamination of the subsurface took place. The primary source of contamination is jet fuel that has leaking from poorly maintained pipelines and storage tanks placed all over the airport.
The site is characterised by different types of generally low-permeable glacial deposits overlying a regional sandy aquifer, which was heavily contaminated by jet fuel. The extent of contamination covers an area of approximately 0.6 km^2 and range thus the Kluczewo Airport as the second largest contaminated area in Poland.

WP 1 Site characterisation

Geological characterisation

Field-scale studies were performed on the site. Integrated multi-scale geological characterisation of site was conducted and a regional and local hydrogeological / geological model was established.

A total of 5 geological units were identified. The glacial deposits consist of three different units of till, among which an upper water-lain clay till and a lower basal till are fractured. The units are separated by a flow-till with multiple thin sand stringers. The till sequence is approximately 5-7 meters thick and overly a regional sandy aquifer (Fig. 4.)

The fracture networks were carefully mapped and analysed. The fractures were classified and the spacing of the dominant fracture systems was calculated. Intact samples of representative fractures were collected and impregnated with resin in the laboratory. The samples were analysed in a Scanning Electron Microscope (SEM), and the mechanical aperture of the different fracture systems were analysed and measured. Such data were used to estimate the hydraulic transport properties of natural fractures and use them as input in the numerical simulations.. Finally a conceptual 3D-fracture network model was constructed and the statistical properties of the fracture/matrix framework were calculated (Fig.5).

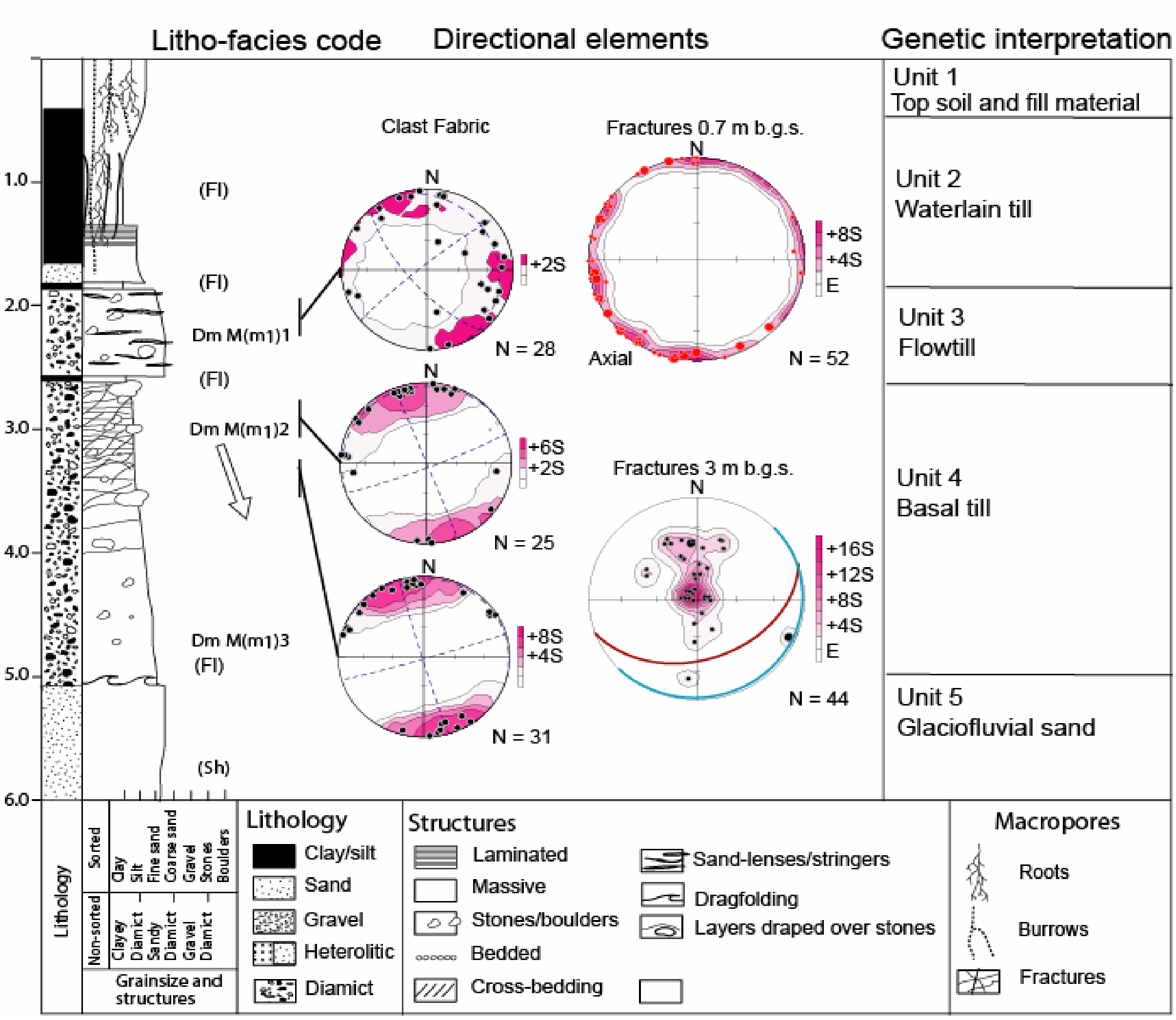

Figure 4. Geological characterisation includes analysis of textural and structural properties of the sediment, clast fabric, fracture orientation, internal glaciotectonic deformations and sedimentary structures.

Chemical/microbiological characterisation

Chemical analyses of soil and groundwater were carried out in order to characterise and quantify the level of contamination. The microbiological activity was investigated in order to evaluate the soil/water capacity for NAPL biodegradation and use of bio-stimulation as a site treatment method.

A detailed analysis of the contaminant fate prior to the remediation experiments in the steam injection cell, and bio-ventilation cell were completed in September 2005 (t_0-sampling) and the results showed that the major pollutant entrapped in the soil of the Kluczewo airport was a kerosene cut with its concentration in soil to increase downwards.

Microbiological characterisation of the site was completed in the spring 2006 and it appeared clearly that despite the good intrinsic capacity of the micro flora to mineralise the jet fuel under optimal conditions (accessibility and nitrogen), its capacity to degrade the hydrocarbons associated to the specific soil matrix from the site is very limited.

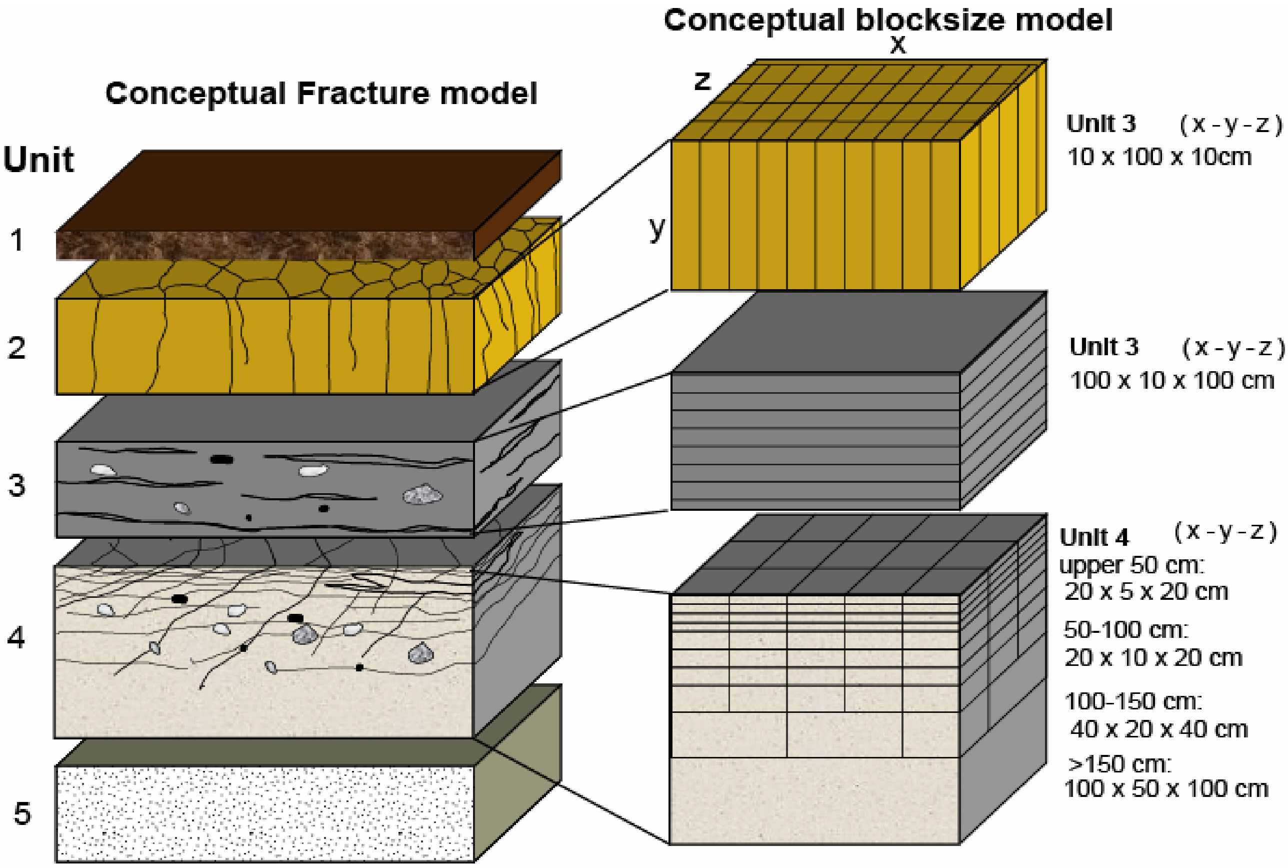

Figure 5. Conceptual fracture model and the corresponding block size model that was used in the numerical model.

Calculation of permeability of natural fractures.
From SEM images of resin-impregnated desiccation fractures (unit 2) and glacio-tectonic fractures (unit 4) the geometrical properties of their aperture were determined in terms of the moments of their statistical distributions. With the aid of approximate phenomenological models and methods of the statistical physics of disordered media (effective medium approximation) reliable estimates of the hydraulic conductivity (permeability) was estimated.

WP 2 Stimulation experiments and set up

A total of 21 hydraulic fractures were installed on five experimental cells (Fig. 6). Cell 2 was used to measure the effect of hydraulic fracturing on the bulk hydraulic properties of the tills and two cells were selected for remediation experiments. Cell 4 was prepared for steam injection experiments, and Cell 1 for bio-remediation enhanced by air ventilation. Two non-fractured cells 1B and 1C were prepared for bio ventilation experiments using traditional wells for comparative analysis of the performance of the stimulation

technique. Cell 5 was used to test the performance of the fracturing equipment and finally Cell 3 was abandoned due to blow out caused by old wells in the subsurface.
prior to the primary experiments.

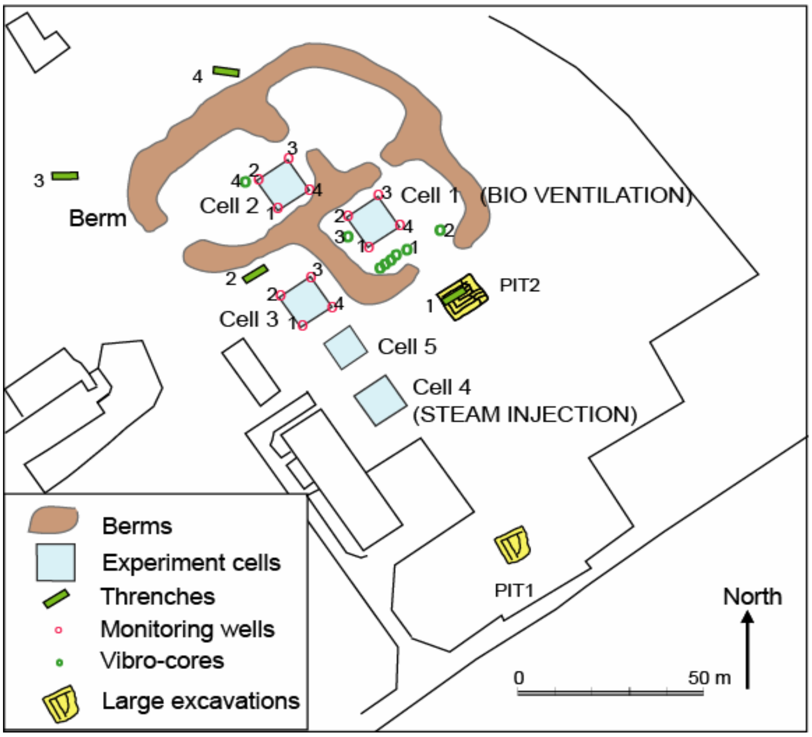

Figure 6. Map over the research area with position of wells, trenches 1-4 and PIT 1 and 2 as well as the five experimental cells.

Hydraulic tests were carried out in Cell 2. Cell 3 was abandoned due to buried junk and cell 5 was used to carry out various stimulation experiments prior to the primary experiments
Guidelines for establishment of hydraulic fractures at the Kluczewo site, including investigations of soil mechanics and rheological properties of the fluids/gel used in hydraulic fracturing have been carried out. During the T_0 -sampling (pre-treatment) of the two cells the hydraulic fractures were mapped, and combined with the uplift data from the injection of the hydraulic fractures, a detailed 3D-model of the hydraulic fracture distribution were constructed for each cell. The 3D-models and field-scale tests formed the basis for lab-scale experiments necessary for determine the transport properties and remediation performance. After the completion of the remediation experiments in cell 4 and 1 the cells were excavated and the hydraulic fractures were carefully mapped and used to verify and calibrate the initial 3D-model.

Hydraulic tests on cell 2
We were unable to quantify the increase in the radius of influence after the establishment of hydraulic fractures at 2.5, 3.5 and 4.5 m depth in Cell 2, but a substantial change in the air pressure distribution in the total soil volume in Cell 2 has certainly been observed. There was a strong indication that the sand-filled fractures had been bypassing the observation points, properly in an upward dipping angle, and that the in-

jected air travelled through the sand-filled fractures to areas of lower permeability zones. This indication was later confirmed during the excavation of the hydraulic fractures cell 2.

WP 3 Remediation setup

The technical solution for the two remediation experiments were designed, constructed and installed in the period September - December 2005.

Steam injection experiment

The steam injection field experiment was performed during a 3½ months period from 30th April to 15th August 2006 (Fig. 7). Numerical modelling using the code T2VOC was applied to evaluate the fracture geometry and dimensioning of flow rates and pressures/vacuum used in the remediation set up.

Figure 7: Testing of the steam remediation set-up.

Based on this modelling a sequential performance strategy was outlined and followed during the experimental performance. The injection of steam started along the periphery of the lowest hydraulic fracture and moved gradually upwards from the middle to the top. Vacuum extraction was simultaneously carried from the centre of the hydraulic fractures. In September 2006 the T_2 sampling (post-treatment) was carried out, the whole cell was excavated and fractures were mapped carefully.

The results show a complex picture of the contaminant distribution in the excavation of cell 1, where zones of NAPL mobilization and other zones of NAPL removal can be seen visually. An analysis of detailed fracture mapping data combined with position of injection / extraction points and chemical analysis before and after remediation has been carried out in order to evaluate the efficiency and removal / displacement processes of the two remedy efforts.

Bio venting experiment

A number of hydraulic tests were performed in the bioventing cell in order to quantify the performance of the hydraulic fractures. A strategy for the performance of the experiment in the bioventing cell was discussed and outlined before the bio venting experiment was initiated (fig. 8).

Figure8a: Air pressure permeability test

Figure 8b: Field set-up of bioventing experiment

The experiments were carefully monitored and gas samples were collected according to a carefully outlined protocol. The bio venting experiment was performed for a period of nine (9) months, the experimental cell was excavated and the distribution of hydraulic fractures was mapped carefully for the evaluation of the stimulation set-up and calibration of the numerical model. In April 2007 the bio ventilation experiment was interrupted and the final T_2 samples were collected. During the end of April 2007 both Cell 1 and Cell 2 were excavated and the geology and hydraulic fractures were mapped carefully in order to collect important information about the fracture distribution and determine the aperture of the individual hydraulic fractures. Also the nature of the fractures in relation to the geological setting was carefully described.

WP 4 Laboratory experiments:

A new method was developed for the characterization of the pore structure of soil matrix by combining BSEM images, datasets from Hg porosimetry tests, and inverse modelling algorithms. The method was applied successfully for the determination of the geometrical/topological properties of 5 soil samples collected from all units of Kluczewo site. The very broad range of grain sizes (sand/silt/clay) of such soils is reflected in a broad range of pore sizes, spanning 5-6 orders of magnitude. The multi-scale soil porosity is responsible of the creation of preferential flow paths (channelling) and limited accessibility to micro-pores where most of the pollution has commonly been accumulated.
The multiphase transport coefficients (relative permeability curves, capillary pressure curve and longitudinal dispersion coefficient) of soils originating from Unit 3 and interface of Units 2/3 were measured by performing immiscible and miscible displacement experiments on disturbed and undisturbed soil columns (Fig. 4). This was done by monitoring the electrical resistance across successive segments and over selected cross-sections of the soil and using inverse modelling algorithms to match the numerical pre-

dictions to experimental datasets. The same approach was used to estimate the relative permeability curves of the sand filling in the hydraulic fractures by neglecting the capillary forces. Novel pore-space models, that account for multi-scale soil heterogeneities, were incorporated into inverse modelling so that parameters quantifying soil heterogeneity, such as the permeability distribution, were estimated along with the rest parameters.

Figure 4: Photographs showing details of the connection of electrodes inserted in undisturbed soil samples with external conductivity meter.

Quasi-static 2-D or 3-D pore network simulators were developed and used to calculate the capillary pressure and relative permeability curves of natural fractures or micro-porous matrix from microscopic properties concerning the fracture aperture or pore space morphology, respectively. A dynamic large-scale network simulator of oil (gas)/water drainage was developed and used to estimate the up-scaled reletaive permeability curves of heterogeneous soils accounting for capillary, viscous and gravity terms. Beyond the heterogeneity associated with the presence of the various structures comprising the void space of the soil(matrix, fractures, etc), the microscopic studies coupled with soil column experiments revealed that the micro-porous matrix, left between sand/silt/clay particles, is strongly heterogeneous by itself at multiple scales. The soil micro-heterogeneity is associated with a broad range of pore length scales (spanning 5-6 orders of magnitude) and is reflected in preferential flow processes. The macro-heterogeneity of a soil sample is length dependent and can be attributed to the non-uniform 3-D arrangement of the elementary pore systems (networks) probed and is reflected in macro-fingering during displacement processes. Micro-heterogeneity coupled with macro-heterogeneity may explain the limited accessibility of the NAPL, contained as bulk phase or dissolved in water in pores, to fluids (steam, condensed water, air) injected, bacteria and nutrients.

WP 5 Numerical modelling

Macroscopic simulators of ventilation and steam-injection were used as tools to optimize the treatment conditions (air flows, pressure), estimate the duration, localise the injection and production wells and designing the treatment plants for air injection (bio-venting cell) and injection scheme for thermal treatment with steam.

Regardless of any biodegradation process (not taken into account in our simulations because not present in the porous medium) a large part of the residual jet fuel (light and medium fractions) can be extracted by air stripping in a reasonnable time (between 6 months and 1 year) depending on the pilot conditions, fracturation density, air flowrate at the injectors etc.

A "Dual Medium" option was implemented in PolluSIM allowing performing numerical simulations of pollution or remediation *scenarios* in fractured medium. After an important validation step with a very good agreement between the results (providing from both, the new dual medium model and the reference case with single porosity), a great number of simulations were performed to simulate the air injection in fractured clays. Thus the single porosity module is providing a finer view in the residual hydrocarbons mapping of the porous medium during the treatment, the Stresoil project allowed to demonstrate the excellent coherence between the results obtained with the dual porosity and the single porosity options. Due to much more rapid simulation times (factor 100) the dual porosity module should be used for optimisation of the treatment conditions before implementing a numerical simulation with the single porosity module allowing a better view of the residual oil in the soil.

In the bioventing operations, a forced extraction close to 0.5 bar at the producer (instead of a well at the atmospheric pressure) should have strongly improved the efficency of the stripping process, by increasing the pressure drop of course but also by the favourable pressure condition around the producer, the vaporization constant increasing when the pressure decreases.

WP 6 cost benefit and efficiency analysis

Evaluation of the efficiency of the stimulation remediation technologies, and cost benefit analysis of various scenarios was carried out in the final part of the project:

Steam injection efficiency
The steam/extraction treatment gives a removal effect on the more volatile total aromatics (TA) ranging from 75 to 82 % removal. These results indicate that much of the lighter HC fraction is removed from the subsurface. The leaching potential from the soil to a water analyses before and after the treatment indicate that the composition of the oil has significantly been affected by the treatment in the Unit 3 in particular concerning the BTEX with 68% reduction (most volatile and most toxic part of the pollution) in the Unit 4 the compositional changes where more limited with about 10% reduction for all the compounds analysed in the leaching experiments. This shows that the steam treatment mainly displaces the bulk oil without modifying its composition.

Approximately 43 % of total hydrocarbons (THC) have been removed from the 1.5-3.9m target zone during the 3.25 months long steam injection / extraction period. In comparison has 72% of THCs been removed from the same profile, but by including additional sampling points between 3.9m and 5.5 m depth. An oil/water table is observed at 4.2 m depth underneath the test cell. The higher removal percentage in the deeper profile can arise from negative effects of a mass loss of remobilized total hydrocarbons to the underlying groundwater aquifer due to the displacement mechanism along the lower steam front.

Based on hydrocarbon analysis of soil a total of 2400kg hydrocarbons have been removed from the target zone of the steam cell between 1.8 and 5.5m depth. The total hydrocarbon mass extracted from the steam cell are distributed on the three phases (air, water and separate phase) with contributions of 425-450 kg in air, 355-360kg in water and 54kg in the separate phase, or in total 825-850kg hydrocarbons. I.e. 95 % of the total mass removal of VOC belongs to the air & water phase. This mass balance indicate clearly that a significant part of the hydrocarbons that have been displaced to the sides or downward to the underlying aquifer by displacement or oil convection.

Bio ventilation/soil vapour extraction efficiency
Before starting the bioventing experiment Blanchet et al (2007) showed that the micro flora present in the soil of the Kluczewo site, even though highly adapted and highly able to biodegrade the polluting hydrocarbons, was unable to degrade the jet fuel when installed in the soil of unit 3 and unit 4. This was due to the lack of bioavailability of the hydrocarbons to the bacteria when the pollution was migrating into the fine textured silty clay sand of the Kluczewo site.

This is very unfortunate since about 20 to 40% of the hydrocarbons constituting the jet fuel are potentional more easily biodegradable than susceptible to be volatilised. This has clearly reduced the potential efficiency of the treatment proposed, and enhanced the residual concentration of hydrocarbons that will remain after treatment.

The biodegradation (O_2 consumption and CO_2 production) observed in the cell C1a is attributed to the biodegradation of the guar gum that was added to the sand during the creation of the hydraulic fractions. These very easily biodegradable compounds have been mineralised aerobically once the air injection has started. This conclusion is reinforced by the fact that no significant O_2 consumption and CO_2 production have been measured in the C1b and C1c cells.

From the quantitative point of view we observed respectively for C1a, C1b and C1c hydrocarbon removal values of 72%, 83% and 76%. This removal is attributed to stripping and oil convection. A limited part (10%) of the removed hydrocarbons has been recovered in the monitored air from the cell C1a. For the cell C1b much more hydrocarbons have been recovered as those removed from the unit 3 (but we did not measure de concentrations in the underlying unit 4 which certainly contributed to the hydrocarbons monitored in the exhaust air). For the cell 1C the order of magnitude of recovered hydrocarbons is the same than those removed. This last fact indicates that the hydrocarbon fluxes in the five spot treatments are better constrained than in the hydraulic fractured systems.

C1a: 3.000 kg hydrocarbons removed from the soil and 260 kg recovered in the monitored air
C1b: 21 kg hydrocarbons removed from the soil and 114 kg recovered in the monitored air
C1c: 78 kg hydrocarbons removed from the soil and 93 kg recovered in the monitored air

Cost benefit analysis
The final task of the Stresoil project was to provide a cost benefit analysis.

A cost benefit analysis is required to be undertaken to evaluate the efficiency of clean up efforts using stimulation remediation technologies in fractured low permeable soils. This cost benefit analysis is based on two main evaluations:

- the quantitative decontamination of the soil,
- the estimation of the costs for each clean-up process.

The estimations of the costs need to be done assuming some prerequisites:

- the results of preliminary characterisation studies of the pollution are available,
- the decision to clean-up has been taken,
- the clean-up technique has been selected,
- all the parties do agree with the clean-up strategy and the costs induced (site owner, authorities, third parties, NGOs...),

The costs estimations have to be divided between:

- Capex: Capital Expenditures (investments in site characterisation, material and various installations...)
- Opex: Operational Expenditures (site survey, monitoring, energy...)

These cost estimations have to be done for each remedy scheme, which has been performed. In the STRESOIL project this include:

- steam injection in hydraulic fractured soil
- bio venting in:
  - hydraulic fractured soil
  - five spot systems (without hydraulic fractures)

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Normally a contaminated point pollution source is larger than the test cells examined in Kluczewo, Poland. For that reason has the experimental setups been up scaled from the test cell size (approximately 7 x 7 x 4,5 m) to a more typical source area to be treated of 900 m^2 with 10 m depth (30m*30m*10m).

The total costs for each treatment in the conceptual 30m x 30m x 10m site is summarised in Table 1. It includes Capex and Opex, the time needed to achieve the mass removal calculated according the data obtained on the pilots operated in Kluczewo during the Stresoil project and also the reduction of the environmental impact estimated as the reduction of the leaching potential of the residual pollution. All the figures are expressed in €uros and are (to our best knowledge) typical commercial Western European prices and costs

Table 1: Treatment costs including Capex and Opex, time constrains and reduction of environmental impact (leaching potential of the residual pollution)

	Total costs [k€]	Time [months]	Efficency	
			Mass remouval from soil [%]	Environmental impact reduction
				Leachate
Steam injection hydraulic fractures	534	3	72%	8% - 68%
Bioventing hydraulic fractures	463	12	72%	93%
Bioventing vertical wells	403	12	82%	51%

It appears very clearly that:

- the steam injection with hydraulic fractures is 14-25% more expensive treatment than both bio venting scenarios, but also the most rapid. It presents a good pollutant mass removal of 72% with various reduction of the environmental impact (8 to 68% reduction of the leaching potential to water from the hydrocarbons polluting the soil),
- the bio venting with hydraulic fractures is less expensive but must be operated four times longer for the same clean up efficiency (72% mass removal). This process presents from far the best reduction of the environmental impact (93% less leaching potential to water from the hydrocarbons polluting the soil) this is probably due to the best interconnection to the natural fracture system allowing the best air flow / stripping effect,
- the bio venting with vertical wells and operated in five spots is a little bit less expensive than the one with hydraulic fractures. It must also be operated for 12 months to achieve the best of clean up efficiency of the three tested approaches (82% mass removal). This process presents a significant reduction of the environmental impact (51% less leaching potential to water from the hydrocarbons).

Table 2: Volume and mass treatment costs. (Mass estimated as 1,6Ton / m^3 soil).

	Total cost	
	[€/m^3]	[€/Ton]
Steam injection hydraulic fractures	59	37
Bio venting hydraulic fractures	51	32
Bio venting vertical wells	45	28

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According to the most important criteria selected by the parties concerned by the rehabilitation of the site (owner, administration, third parties) each of the three tested technology can be chosen:

- the most rapid: steam injection with hydraulic fractures,
- the less expensive: the bio venting with vertical wells.
- the most efficient for mass reduction: the bio venting with vertical wells,
- the most efficient for environmental impact reduction: the bio venting with hydraulic fractures,

So as a conclusion it appears very clearly that the cost benefit analysis is the best tool for selecting the treatment process to be applied at a site. It is an efficient help for decision makers providing a multi criteria data set.

The results of a calculation presenting the treatment costs in relation to the volume and the mass of soil treated gave prices ranging from 45 to 59 €/m3 and 28 to 37 €/ton with lowest costs on the bio venting scenarios and highest on steam injection (table 2). Such calculation is very useful to compare the costs of the remediation strategy proposed to all type of approaches including ex-situ techniques. The prices indicated are low compared to ex-situ washing or thermal techniques that may be closer to 60 - 120 €/ton. Such low costs will make the tested in-situ methods (bio venting and steam injection) very attractive, especially in cases where excavation is impossible due to the presence of buildings or when the pollution is very deep (which may be the case in particular for dense non aqueous phase liquids D-NAPL) fractured soils.

1.1.2 Conclusions

Generally the experiments conducted during the STRESOIL project indicate that alternative and cost effective technologies combining stimulation and remediation is a realistic alternative to traditional technologies, and has a large potential as a viable treatment method compared to traditional “dig and dump technologies”, which is the foremost used technology today.

The environmental impact from emission to the atmosphere during excavation of volatile compounds in *ex-situ* treatment of contaminated sites is not included in the efficiency analysis, but growing awareness of the risk of air pollution during excavation of contaminated soil potentially increase the demand for *“in situ”* technologies.

The modelling results indicate that applying vacuum extraction during SVE from hydraulic fractures, as well as the potential for termal treatment of other compounds such as chlorinated solvents, seems very promising.

The potential of applying hydraulic fractures as a methodology for successfully stimulating hydraulic performance of natural fracture systems in especially clayey soils of glacial origin has been greatly improved during this project. The application is already being introduced into new research areas.

This work was performed under FP6, Global Change of Ecosystems, project no: SSPI-CT-2003-004017 (project acronym: STRESOIL) supported by the European Commission.