

NORTHERN ALBERTA INSTITUTE OF TECHNOLOGY:**FIELD DEMONSTRATION AND SYMPOSIUM ON ENVIRONMENTAL APPLICATIONS
OF HORIZONTAL DIRECTIONAL DRILLING TECHNOLOGY****Paper Presentation on:****ENVIRONMENTAL FRACTURING OF SOILS IN HORIZONTAL AND VERTICAL
BOREHOLES FOR ENHANCED SITE REMEDIATION****EDMONTON, ALBERTA - APRIL 15, 1998****by****Gordon H. Bures, M.Eng., P.Eng.
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This presentation provides an overview of environmental fracturing technology and its applications in both vertical and horizontal boreholes. The field implementation of environmental fracturing at a contaminated site is described. The technical feasibility of fracturing contaminated sites and design criteria used for designing a subsurface fracture network are discussed. Three case histories are presented to illustrate the effectiveness of combining environmental fracturing with various drilling and remedial technologies to expedite the remediation of contaminated sites underlain by low permeability soils.

ENVIRONMENTAL FRACTURING - WHAT IS IT?

Environmental Fracturing is simply the application of conventional hydraulic fracturing (used in the oil & gas industry and water well industry) to increase the effectiveness of remediation in contaminated, low permeability or "tight" soils. Let's briefly examine the concept of hydraulic fracturing:

Hydraulic fracturing is a process whereby a fluid is pumped into a formation (ie. soil or rock) at a rate and pressure high enough to overcome the in situ confining stress and the material strength of a formation resulting in the creation of a fracture or parting.

Hydraulic fracturing has long been used in the petroleum industry (since the late 1940's) to enhance the production of oil from low yielding formations which would otherwise be uneconomical to produce. When a hydraulically fractured well is produced, the induced fractures provide a conduit so that fluids can flow to the well at a greater rate than would otherwise be possible. Today, about 70% of all oil wells drilled worldwide are hydraulically fractured to stimulate and enhance oil production.

In environmental fracturing, we use the above described technology for enhancing the removal of subsurface contamination instead of crude oil. Since virtually all of the contamination in the environmental industry occurs at relatively shallow depths and in soils, it is in these conditions where environmental fracturing is most commonly used.

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IN SITU REMEDIATION OF LOW PERMEABILITY SOILS

Much of Western Canada is covered with fine grained sediments as a result of glaciation and post-glacial processes. These fine grained soils are generally not very permeable to either liquids or gases. Consequently, the effectiveness of conventional in situ remedial technologies at contaminated sites underlain by fine grained soils is extremely limited, and remediation is often long term and costly. Limitations to the in situ clean-up in fine grained soils are generally manifested by low contaminant removal/treatment rates and small zones of influence at recovery wells (Figure 1).

Environmental fracturing, when coupled with the appropriate remedial technology(s), has been shown to enhance the effectiveness of clean-ups in low permeability soils (ie. those with a hydraulic conductivity of 10^{-6} m/s or less). The fracturing process creates a network of subhorizontal to subvertical fracture pathways in a contaminated soil mass. These induced fracture pathways are filled with permeable sand or “proppant” which keep the fractures propped open. The fracture pathways function as permeable conduits to expedite the removal or in-place degradation of contaminants.

Frequently, the network of sand filled fractures intersect natural fractures and permeable lenses in which contamination often resides. This serves to drain the contamination more effectively and generally results in an increased radius of influence and contaminant removal rate for the recovery well (Figure 1). Furthermore, as contaminant migration in fine grained soils is controlled to a large degree by diffusion, the fracture network significantly lessens the time to remediate a site by reducing the length of the diffusion pathways.

It is important to understand that environmental fracturing by itself is not a stand alone remedial technology; rather, it is a technique to enhance the performance of existing remedial technologies which would otherwise be ineffective in low permeability soils. As such, environmental fracturing can be used in three primary modes:

1. To provide pathways to enhance the movement and removal of liquid and vapour contaminants through low permeability soils;
2. To provide improved hydraulic containment and vapour phase containment of contaminants; and,
3. To serve as a mechanism for the delivery of chemical or biological reagents such as oxygen, nutrients, microbes or reactive metals (eg. iron filings) into low permeability soils to enhance the in situ remediation of contaminants.

When combined with the range of uses described above, environmental fracturing becomes a powerful tool for effective, in situ remediation of low permeability soils.

ENVIRONMENTAL FRACTURING PROCESS

The process of environmental fracturing requires three major components (Figure 2):

- equipment for the formulation, mixing and pumping of the fracture slurry;
- a fracturing probe and toolstring for injecting the fracture slurry into contaminated soils under sufficient hydraulic pressure to initiate and propagate fractures; and
- equipment to advance and withdraw the fracturing probe and create a borehole of the required diameter to install a recovery well (usually an auger drill rig for vertical boreholes and directional drilling rig for horizontal boreholes).

In practice, a slurry mixture containing a proppant (sand) and a viscous fluid (guar polymer and water mixture) is formulated in the mixing tank. The sand proppant grain size is designed to meet geotechnical filter requirements for the native soils being fractured and to provide good permeability. In order for the viscous fluid to hold the sand proppant in a uniform suspension during the fracturing process, a crosslinker is added to further viscosify the slurry. An enzyme or chemical “breaker” is then incorporated into the fracture slurry to break down fluid viscosity after the fracturing process. A site specific surfactant is typically incorporated in the slurry to minimize formation damage and expedite the drainage of the fracture network during development of the well.

Once the fracture slurry has been prepared, it is pumped into the contaminated soil zone at a rate such that the fluid pressure becomes high enough to create a fracture or parting in the soil. The process is repeated at increasing depths to create a network of sand-filled fractures in the zone of contamination.

The viscosity of the fracture slurry is designed to break down after a period of time, usually two to eight hours. After this period of time has elapsed, the enzyme or chemical “breaker” activates and breaks down the viscosity of the fracture slurry to that of water. The broken fracture fluid drains from the sand filled fractures into the “fracture hole”. During development of the fractured recovery well the fracture fluid is recovered, leaving high permeability sheets of sand in the contaminated soil mass.

In a vertical borehole, fractures are typically initiated at the top of the contaminant zone and are placed at 0.5 m to 1.0 m vertical intervals until the base of the contaminant zone is reached. After the fractures have all been initiated and propagated, the fracture tool assembly is pulled out of the borehole and a recovery well is installed as per conventional installation procedures.

In a horizontal borehole having an entry and exit point to the ground surface, the fracturing tool assembly is pulled through the borehole through the contaminated zone and individual fractures are initiated at 2.0 m to 3.0 m intervals along the borehole. The well casing and well screen are pulled behind the fracture tool assembly and are left in the borehole once the fracturing has been completed. The well can consist of either a prepack well screen thereby foregoing the need to inject a sand filter pack into the borehole annulus; alternatively, a sand pack can be tremied into the borehole after the well has been placed in the borehole.

MAPPING OF SUBSURFACE FRACTURES

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Individual fractures created during the fracturing process can be accurately mapped using tiltmeters. Tiltmeters are highly sensitive instruments (to nanoradian resolution) used in the hydraulic fracturing industry to measure the minute ground surface deformations created during the fracturing process. The direction and magnitude of ground surface deformation or “tilt” measured by tiltmeters is used to determine the shape, thickness, extent and orientation of fractures in the subsurface. This information is useful in confirming the extent and areal coverage of fractures placed in the subsurface, as few fractures ever propagate in a perfectly radial or horizontal manner.

Typically, an array of 12 to 25 surface-mounted tiltmeters is set up in a grid or concentric array around each fracture hole location. During fracturing, ground surface “tilt” is measured at each tiltmeter station and the information is stored in on-site dataloggers. Selected tiltmeter stations are directly connected to an on-site computer so that a real-time assessment of the nature of fracture propagation and orientation (ie. predominantly horizontal vs. vertical) can be made. Based on this information, the fracture design can be modified in the field, if necessary, to maximize fracture exposure in the zone of contamination.

FEASIBILITY ASSESSMENT AND DESIGN CONSIDERATIONS

Although environmental fracturing can significantly enhance site remediation, its application must be carefully considered based on site-specific criteria. The two main criteria that determine the suitability of a site for fracturing are soil type and depth of fracturing. For example, fracturing would not be expected to substantially increase bulk permeability and thus contaminant removal rates in clean sands and gravels or soils with hydraulic conductivities of greater than 10^{-6} m/s. Logistically, soil fracturing is problematic and often difficult to achieve in non-engineered fills, or in soils containing a significant proportion of cobbles and boulders. Sites at which contamination resides at shallow depth (ie. within 3 metres depth of the ground surface) are generally not candidates for fracturing because conventional methods of remediation (eg. excavation and disposal) are usually more cost-effective. Table 1 summarizes the criteria for assessing the feasibility of fracturing a site and the design parameters required for designing a subsurface fracture network. Appendix I contains a detailed site data checklist for assessing the feasibility of fracturing a contaminated site.

FIELD APPLICATIONS

This section presents three case histories of environmental fracturing used in combination with various remedial technologies applied at sites underlain by different soil types.

The first case history involves the use of environmental fracturing for enhanced recovery of liquid condensate at a former gas plant site in Alberta; the second case history describes the use of environmental fracturing to remove residual gasoline contamination at an operational fuel storage and transfer terminal in Saskatchewan; and, the third case history illustrates the application of environmental fracturing in combination with horizontal drilling as part of an ongoing research project for enhanced in situ bioremediation of amines at a former sour gas plant site in Alberta.

ENVIRONMENTAL FRACTURING CASE HISTORY NO. 1

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SITE:

Former Gas Plant and Compressor Station located in northwestern Alberta, Canada.

PROBLEM:

Soil and groundwater contamination caused by a release of 460,000 litres of liquid condensate from a former flare pit. Free phase liquid condensate is present up to a thickness of 4 m on the groundwater table both on site and beyond the property boundary. Potential receptors are groundwater supply wells, a recreational lake and gas pipeline located within 1.5 km of the site.

OBJECTIVES:

To halt the migration of condensate and recover the bulk of free-phase condensate to reduce the risk of impacting down-gradient receptors.

FIELD PROGRAM:

The contaminated soils consist of clayey silts to silty, fine grained sands. The depth of contamination and fracturing at the well locations ranges from 7 metres to 11 metres below ground surface. The groundwater table is located at 10 metres below ground surface. A total of 14 fractured wells containing 85 fractures were placed within the condensate plume in 1995 and 1996. The wells were used for recovery of liquid hydrocarbons (ie. condensate) using pneumatic pumps and dual phase (ie. liquid/vapour) extraction of hydrocarbons. A surfactant was incorporated into the sand-laden fracture fluid to assist in the mobilization of liquid condensate to the wells by improving its relative permeability to water. Tiltmeters were used to individually map the size, geometry and thickness of fractures created in the subsurface.

TECHNICAL EVALUATION:

The performance of hydraulically fractured wells was extremely impressive as the results indicate:

PARAMETER	UNFRACTURED WELL	FRACTURED WELL
Hydraulic conductivity	3.0×10^{-8} m/s	4.3×10^{-6} m/s
Condensate liquid recovery rate	24 litres/day	360 litres/day
Condensate vapour recovery rate	4 litres/day	100 litres/day
Condensate:Total Fluids ratio	0.18	0.77
Radius of Influence (liquids)	1.5 to 2.0 m	7 to 10 m
Radius of Influence (gas)	4 to 5 m	15 to 25 m

Effective capture of the contaminant plume using fractured wells has occurred. The total cost savings to the client over the anticipated 3 to 5 years of remediation using fractured wells vs. conventional remedial technologies is estimated at \$1.5 million dollars Canadian.

CURRENT STATUS:

Remediation is ongoing using both a pneumatic recovery system and dual phase extraction (ie. "bioslurping") system. Liquid condensate recovered from the site is being reprocessed and sold by the site operator to offset operating and monitoring costs related to the remediation of the site.

ENVIRONMENTAL FRACTURING CASE HISTORY NO. 2

SITE:

A Fuel Storage and Distribution Terminal located in Regina, Saskatchewan, Canada.

PROBLEM:

Subsurface gasoline contamination originating from tanker truck fuel-loading racks. Gasoline contamination is present over an area of two hectares and is migrating off-site towards an adjacent industrial facility. The contamination is present in low permeability, naturally fractured, glaciolacustrine clays and clayey silts.

OBJECTIVES:

To assess the performance of fractured wells for enhancing the recovery of free-phase and residual hydrocarbons.

FIELD PROGRAM:

A total of 43 hydraulic fractures were induced at 7 fracture well locations within the contaminant plume identified at the site. Fractures were initiated within 1.5 metres above and below the saturated zone at four of the well locations, and in a four metre thick interval in the vadose zone at the remaining three well locations. Approximately 500 litres of sand-laden fracture fluids was used to induce each fracture. The performance of fractured wells was subsequently tested by connecting them to a high vacuum, Dual Phase Extraction (DPE) pump to pump both liquids and vapours. The DPE technology is often referred to as “bioslurping” in the literature.

TECHNICAL EVALUATION:

The enhancements in fractured well performance are summarized below:

PARAMETER	UNFRACTURED BASELINE WELLS	FRACTURED WELLS
Hydraulic conductivity	4.3×10^{-8} to 8.0×10^{-8} m/s	4.1×10^{-7} to 2.3×10^{-6} m/s
Air permeability	1.0×10^{-9} to 2.9×10^{-9} cm ²	4.6×10^{-8} to 1.2×10^{-7} cm ²
Radius of influence (liquid)	2 to 3 m	16 m
Radius of influence (gas)	5 to 7 m	>16 m

The results of testing both hydraulically fractured wells and unfractured baseline wells revealed that hydrocarbon removal rates were not sustainable in the unfractured wells because the high vacuum pressure induced closure of natural fractures at the well bore. This resulted in a “choking off” of the air flow which subsequently caused a pump failure. Conversely, hydrocarbon removal rates were sustainable at high operating vacuums in hydraulically fractured wells because the induced fractures were kept open by the frac sand proppant, thereby preventing these fractures from closing.

CURRENT STATUS:

The combination of Dual Phase Extraction, Horizontal Directional Drilling, and Hydraulic Fracturing technologies are presently being considered by the client for application in contaminant plumes at their refinery complex.

ENVIRONMENTAL FRACTURING CASE HISTORY NO. 3

SITE:

A former sour gas processing facility located in Central Alberta.

PROBLEM:

Subsurface amine contamination from sour gas processing operations is present in clay till soils at a depth of approximately four metres.

OBJECTIVES:

To assess the performance of a horizontal, fractured well for enhancing the in situ bioventing of amine contaminants. This project represents the first ever combined use of horizontal drilling and fracturing at a contaminated site in Canada.

FIELD PROGRAM:

A total of 12 individual planar fractures were induced at two metre intervals along a horizontal borehole located in the contaminant plume identified at the site. Fractures were initiated at a depth of 4.0 m below the ground surface from within the horizontal well bore. A surfactant and a phosphate nutrient solution were incorporated into the fractures to enhance the in-place biodegradation of amine contaminants using bioventing technology. All subsurface fractures were mapped using surface mounted tiltmeters which indicated that 80 percent of fractures had an inclination of 31° or less to the horizontal.

TECHNICAL EVALUATION:

Bioventing of amine contaminants is ongoing and the performance of the remediation is being monitored on a long term basis. Preliminary field testing indicated that the amines were biodegradable at concentrations measured in the subsurface. Fracturing is anticipated to accelerate the rate of biodegradation by serving as permeable pathways for oxygen and nutrient to the contaminants. Field data measurements have shown elevated concentrations (13% by volume) of CO₂ which is an indication that vigorous, aerobic biodegradation of the contaminant is taking place. There is some concern, however, that biodegradation rates may not be as great as they could be due to water ingress into the fracture network and subsequent blockage of air delivered to contaminants.

SUMMARY OF BENEFITS

The case histories presented provide a dramatic illustration of the improved performance and associated benefits of fracture-enhanced in situ remediation as compared to conventional remediation technologies applied in low permeability soils. To date, our experience in fracturing sites underlain by low permeability soils has resulted in the following remedial performance enhancements:

- up to three orders of magnitude increase in bulk hydraulic conductivity;
- up to five times the radius of influence in fractured recovery wells;
- up to twenty times the contaminant mass removal rate; and,
- reduction in remediation time to less than one half,

compared to conventional in situ remedial technologies applied in low permeability soils.

The above technical enhancements have translated into significant cost savings (up to 60% of the cost of conventional remedial methods proposed) at sites where commercial environmental fracturing has been conducted to date. For example, the use of environmental fracturing to recover subsurface condensate contamination at the former gas plant site described previously, saved the client approximately \$1.5 million compared to the best alternative remedial options considered by their environmental consultant.

Perhaps one of the most important advantages of environmental fracturing is that it expands the range of feasible remedial options in low permeability soils. Fracturing often enables a remedial technology, that would not otherwise be effective or even be considered at a particular site, to become a feasible alternative.

EMERGING INNOVATIONS

As illustrated by the case histories presented above, some of the more innovative remedial applications currently evolving is the coupling of environmental fracturing with other emerging technologies in the environmental industry such as horizontal directional drilling and in situ bioremediation.

Horizontal Directional Drilling (HDD) has traditionally been used in the oil and gas industry for enhanced oil and gas recovery, and the utilities industries for the placement of underground utility lines, and the placement of pipelines under river and stream crossings. Recently, HDD is being applied to the environmental industry for the in situ remediation of contamination. Motivating factors for the increased use of HDD in the environmental industry are lower remediation cost, greater flexibility of application, and greater treatment area per well. Using HDD technology allows the installation of a single horizontal well that is in direct contact with a comparatively large contaminated area in comparison to vertical wells. Under some circumstances, a single horizontal well may have a contact area equal to that of ten vertical wells (Parmentier and Klemovitch, 1996). In addition, horizontal wells can be installed beneath buildings, roads, and other surface or subsurface obstructions to reach contamination inaccessible by other means.

In situ biological treatment (ie. “*in situ bioremediation*”) is widely regarded as one of the more promising of the emerging methods of site remediation. This is because of its lower cost and greater effectiveness; it is a relatively non-disruptive technique; and, it does not simply transfer the contaminant to a different medium - it converts the contaminant to innocuous end products without harmful secondary emissions (NRC,1996). However, as with any in situ remedial technology, its limitations are associated with poor access to contaminants and low area of impact in soils of low permeability (ie. hydraulic conductivity of less than 10^{-6} m/s). Geology is the primary factor that controls the effectiveness of all in situ remediation technologies (Nyer, 1996).

The specific limitations of *in situ bioremediation* relate to the severely limited delivery of necessary nutrients and oxygen in low permeability soils (Davis-Hoover et al., 1991). Current technology requires ideal site conditions to provide the remediating organisms with the nutrients and oxygen required for their metabolism, but the shortage of oxygen in many subsurface sites is the factor that most frequently limits biological activity. Attempts to overcome this limitation have included injection of gaseous or dissolved oxygen, and injection or percolation of hydrogen peroxide into the subsurface. This method of delivery requires the subsurface to be fairly permeable and is therefore not practical at many sites underlain by silts, clays, or even silty\clayey sands. Moreover, preferred flowpaths, such as natural fractures, sand lenses, and macropores, can channel fluids and leave large blocks of contaminated soil mass unexposed to injected oxygen.

Environmental Fracturing not only creates an increase in soil permeability and improved access to contaminants, it also becomes an injection vehicle for oxygen, nutrients, microbes, catalysts, etc. for the in-place biodegradation of contaminants. Once in place, the fracture network essentially acts as a reservoir of the injected compounds which continue to enhance the bioremediation of subsurface contaminants. Almost any kind of chemical or biological reagents can be put into the fracture network; these may include granules of slow dissolving nutrients, or oxygen-releasing chemicals, for example.

Any sound remediation plan should consist of an integrated approach that uses appropriate remedial technologies to bring a contaminated site to closure. It is apparent that the coupling of conventional and innovative environmental technologies with environmental fracturing offers a very powerful, cost-effective, and non-disruptive method of site remediation in low permeability soils.

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TABLE 1**ASSESSMENT AND DESIGN CRITERIA FOR ENVIRONMENTAL FRACTURING**

Feasibility Assessment Criteria	Fracture Network Design Criteria
<p>Subsurface Conditions:</p> <ul style="list-style-type: none"> • Soil Types and Stratigraphy; • Grain Size Distribution; • Soil Density; • Relative Permeability : (air/water/LNAPL/DNAPL) • Natural Fracture System; • Depth to Groundwater 	<p>Remediation Objectives:</p> <ul style="list-style-type: none"> • Primary Bulk Recovery of Contaminant; • In Situ Treatment of Contaminant Residuals; • Hydraulic or Vapour Containment of Contaminant
<p>Contaminant Characteristics:</p> <ul style="list-style-type: none"> • LNAPL/DNAPL/Other; • Phase Distribution: dissolved, vapour, immiscible, residual; • Areal extent of Contaminant; • Vertical Distribution of Contaminant 	<p>Fracture Slurry Design:</p> <ul style="list-style-type: none"> • Proppant properties: purity, grain size, and sphericity; • Base gel type; • Viscosifiers, Crosslinkers, and Breakers (enzyme vs. chemical); • Incorporation of Surfactants, Nutrients, other Chemical Reagents or Biological Amendments.
<p>Other Considerations:</p> <ul style="list-style-type: none"> • Regulatory Approval; • Site location, access and trafficability; • Clean water supply; • Geotechnical Constraints (eg. unacceptable ground heave) 	<p>Fracture Network Design:</p> <ul style="list-style-type: none"> • Number of fractures and wells required; • Fracture placement (Saturated or Unsaturated Zone); • Fracture Configuration: Predominantly near-horizontal or near-vertical; • Fracture depths and spacing; • Fracture slurry volume and fracture radius; • Selection of appropriate downhole fracturing equipment; • Design of tiltmeter array for mapping fractures

APPENDIX I
SITE DATA CHECKLIST FOR FRACTURING FEASIBILITY