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9 HYDRAULIC AND PNEUMATIC FRACTURING

9.1 INTRODUCTION

Low-permeability, fine-grained soils such as clay, and silt and rock represent a significant challenge to *in situ* remediation due to the meager rates of fluid flow extractable under these conditions. Despite the low permeability of clays, silts, and competent rock, these formations can still become impacted. The density of these formations often renders conventional cleanup techniques, such as soil vapor extraction and bioremediation, ineffective.

In the recent past, hydraulic and pneumatic fracturing methods have been developed for creating fractures in dense soils and making existing fractures larger to enhance the mass transfer of contaminants. The fractures created increase the effective permeability and change paths of fluid flow, thus making *in situ* remediation more effective and economical. Fracturing also reduces the number of extraction wells required, trimming labor and material costs.

Pneumatic fracturing injects highly pressurized air or other gas into consolidated, contaminated sediments to extend existing fractures and to create a secondary network of fissures and channels. This process accelerates the removal of contaminants by soil vapor extraction, bioventing, enhanced *in situ* biodegradation, and *in situ* electrokinetics. Typically, pneumatic fracturing is used in formations where the fractures will remain open for a long time without support.

Hydraulic fracturing involves injecting a fluid, usually water, at modest rates and high pressures into the soil matrix to be fractured. High pressure water is used to cut a disc-shaped notch at the bottom of a borehole: the notch becomes the starting point for the fracture. A slurry mixture of sand and biodegradable gel is then pumped at high pressure to create a distinct fracture. As the gel degrades, it leaves a highly permeable sand-lined fracture with the sand acting as a propping agent preventing the fracture from collapsing. The fractures, thus formed, can be utilized to augment various other *in situ* technologies discussed previously.

The utility of hydraulic fractures is by no means limited to well stimulation. Relatively large volumes of solid compounds can be delivered to the subsurface as granular materials, filling the fractures. The capability to deliver solid compounds, which previously required excavation techniques, presents a variety of possible new applications. These new *in situ* applications include injection of solid compounds that slowly release oxygen and nutrients to enhance *in situ* aerobic degradation; filling the fractures with electrically conductive material such as graphite to enhance electroosmosis and perhaps electrical heating for *in situ* vitrification; and filling the fractures with metal catalysts, such as elemental iron, to degrade a wide range of chlorinated organic compounds.

9.2 APPLICABILITY

Almost any rock or soil formation can be fractured, given enough time, energy, and effort. The key aspects that have to be considered for remediation purposes are: will the

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benefit derived from fracturing offset the cost of the process, and what are the risks and benefits of the process? Armed with the answers to these questions, the decision to proceed with testing and, ultimately, full-scale application of the technique can be made on an informed basis.

Fracturing is most appropriately applied to soils where the natural permeability is insufficient to allow adequate movement of fluids to achieve the remediation objectives in the desired time frame. The following soil types and rocks are generally suitable for applying fracture techniques:[1]

- silty clay/clayey silt
- sandy silt/silty sand
- clayey sand
- sandstone
- siltstone
- limestone
- shale

Fracturing a sand or gravel formation, while possible, is probably not justified because the benefits derived from the increase in soil permeability will not match the cost of the process.

Fracturing, by itself, is not a remediation technique. Fracturing has to be combined with other technologies to facilitate the reduction of contaminant mass and concentration. Fracturing techniques are equally applicable to both vadose zone (unsaturated) soils and saturated zone soils to improve the flow of air and water, respectively. Fracturing should be considered primarily to overcome the poor accessibility to the contaminants for extraction and also to overcome the difficulty in uniform delivery of treatment reagents.

By fracturing, not only are higher permeability zones created for enhancement of advective flow through the contaminated zone, but the pathways for diffusion-controlled migration of the contaminants are also created. The creation of advective flow channels and shortened diffusive pathways result in enhanced mass removal rates during soil vapor extraction. Diffusion-limited extraction will still influence the rate of contaminant recovery even after fracturing, and the properties of the contaminant and the media will still influence the residual concentrations.

As noted earlier, fracturing can also expand the applicability of other *in situ* remediation technologies beyond enhanced vapor and liquid extraction in low permeability soils. These technologies include

- *in situ* biodegradation (by enhancing the delivery of oxygen and nutrients into inaccessible locations)
- *in situ* electrokinetics (enhancing the fluid flow in the fractured zones)
- *in situ* vitrification (creating heating zones by injecting graphite into the fractures)
- *in situ* air sparging (by creating fractured pathways to collect the injected air laden with contaminants)

9.2.1 Geologic Conditions

As with all subsurface remediation techniques, fracturing is applicable only for a range of site conditions. In addition to the consideration of soil/rock types, described in the previous section, the mode of deposition of the sediments, and the changes that took place after deposition affect the effectiveness of fracturing. Most notably, the state of *in situ* stresses has long been characterized as the primary variable in the orientation of fracture formation.[2]

Fractures can be generated in geologic formations if the pressurized fluid is injected at a pressure which exceeds the natural strength, as well as the *in situ* stresses present in the

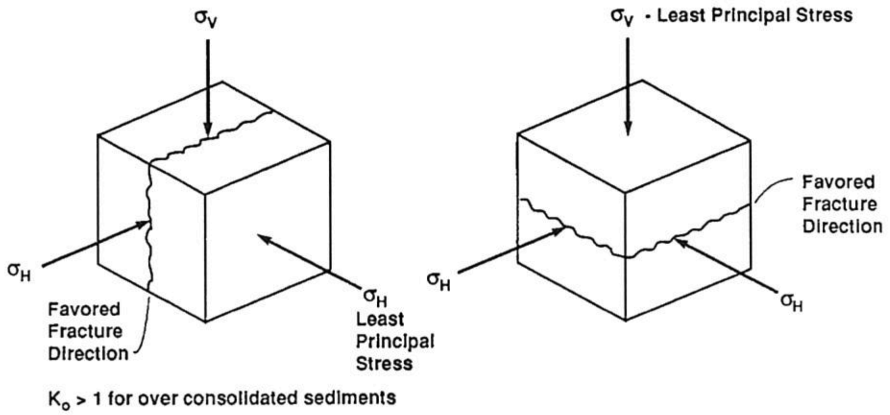

Figure 9.1 Directions of fracture formation as influenced by the least principal stress.

formation. It must also be injected at a flow rate that exceeds the natural permeability of the formation so that sufficient "back" pressure can be developed. Fractures will tend to propagate in the direction normal to the least principal stress in the formation, with propagation following the path of least resistance.

In situ stress fields are subdivided into horizontal and vertical components (σ_x, σ_y, and σ_z). When initially deposited, the three principal stresses are in equilibrium and are equal to the overburden pressure. External forces (tectonics, burial/excavation, glaciation, and cycles of desiccation/wetting) after deposition modify these stress fields.

Overconsolidation is defined as compaction of sedimentary materials exceeding that which was achieved by the original overburden. The formation and later melting of glaciers is one condition that results in overconsolidation. The weight of the ice on the soil initially compacts the sedimentary grains. When the ice melts, the vertical stress is relaxed but the horizontal stress still maintains a residual component of the loaded conditions. Erosion or overburden removal by excavation also present conditions which relax the vertical stress field. Additionally, the cyclic swelling and desiccation of clay rich formations can also create conditions of over consolidation.

In overconsolidated formations where the least principal stress is vertical, fractures will tend to propagate horizontally (Figure 9.1). Conversely, in normally consolidated or under consolidated formations, fractures will tend to propagate vertically (Figure 9.1). Since most contaminated sites have overconsolidated formations, it is expected that pneumatic and hydraulic fracture propagation will be predominantly horizontal. In stratified formations, which have natural weakness along the bedding planes, the tendency toward horizontal fracture patterns is even more accentuated. For implementing soil vapor extraction technology, horizontal fractures will be favored, since vertical fractures will create a significant amount of short circuiting of the extracted air.

Geotechnical engineers express the ratio of the horizontal to vertical stress, K_o. In general, values of K_o greater than 1.0 will favor flat-lying fractures, and the larger the value of K_o the more the flat-lying orientation will be favored.

9.3 DESCRIPTION OF THE PROCESS

Currently there are two types of fracturing methodologies employed for environmental applications. Hydraulic (water-based) and pneumatic (air-based) fracturing are the two variants of this technology. The selection between these two types of fracturing are based on the following considerations:

- soil structure and stress fields
- the need to deliver solid compounds into the fractures
- target depth
- desired areal influence
- contractor availability
- acceptability of fluid injection by regulatory agencies

9.3.1 Hydraulic Fracturing

Hydraulic fracturing has been used for more than 50 years to enhance the yield of wells recovering oils at great depth, and it has recently been shown that hydraulic fracturing will also enhance the yield of wells recovering liquids and vapors from contaminated zones in the subsurface.[3] The process is reportedly responsible for making 25 to 30% of the U.S. oil reserves economically viable. The parallels between economic recovery of petroleum hydrocarbons and viability of *in situ* treatment alternatives are very evident.

Hydraulic fracturing may be defined as the process of creating a fracture or fracture system in a porous medium by injecting a fluid under pressure through a well bore in order to overcome native stresses. To fracture a formation, energy must be generated by injecting a fluid down a well and into the formation. Effectiveness of hydraulically created fractures is measured both by the orientation and areal extent of the fracture system and by the postfracture enhancement of vapor or liquid recovery.

Hydraulic fracturing begins by injecting a fluid into a borehole at a constant rate until the pressure exceeds a critical value and a fracture is nucleated. The properties that a fracturing fluid should possess are low leak-off (fluid loss) rate, the ability to carry a propping agent, and low pumping friction loss. The fluid also should break down easily after the fracture formation.

Low leak-off (fluid loss) rate is the property that permits the fluid to physically open the fracture and one that controls its areal extent. The rate of leak-off to the formation is dependent upon the viscosity and the wall-building properties of the fluid. Postfracture breakdown is necessary such that the injected fluids do not "clog" the formation.

Cross-linked guar gum is an example of a common fracture fluid used for environmental application. The most widely used form is the continuous mix grade of gum, referred to as such because it hydrates rapidly and reaches a usable level of viscosity fast enough that it can be used continuously. Since guar gum is a food-grade compound, it minimizes the potential for regulatory objections for the process.

Because of the characteristic high viscosity, guar gum is capable of transporting coarse-grained silica sand or other granular material, as a slurry, into the fracture. The coarse-grained silica sand is called a propping agent to keep the fracture open upon relaxation of the injection pressure, when the guar gum gel is decomposed by an enzyme added during injection. Pumps specifically designed for high-viscosity, high-solids fluid handling should be selected to inject the slurry at the required pressures.

Hydraulic fractures are generally created beneath a casing into which a lance is advanced and withdrawn to the required depth with a hammer. Lateral pressure of the soil seals the casing during the controlled injection of the fracturing fluid and the proppants. The casing can be driven deeper to create another fracture (Figure 9.2). Stacks of gently dipping hydraulic fractures can be created with vertical spacing of 0.5 to 1 ft using the driven casing method; vertical spacings of less than 0.5 ft tend to result in fractures that merge at short distances from the borehole.[3] A high-pressure water nozzle is used to cut a disc-shaped notch with the preferred horizontal orientation at the bottom of the casing, and the notch becomes the starting point for the fracture.

The injection pressure required to create hydraulic fractures is remarkably modest (less than 100 psi). For example, at the beginning of injection during a test at 5 ft depth, the pressure increased abruptly to 64 psi, but then decreased sharply when the fracture began to

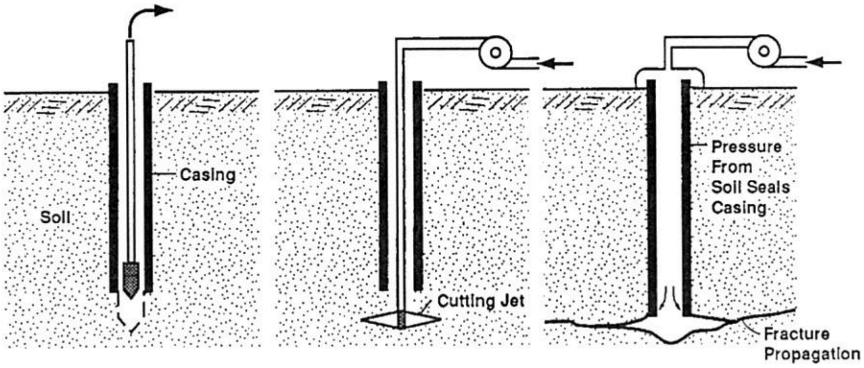

Figure 9.2 Method for creating hydraulic fractures in soil.

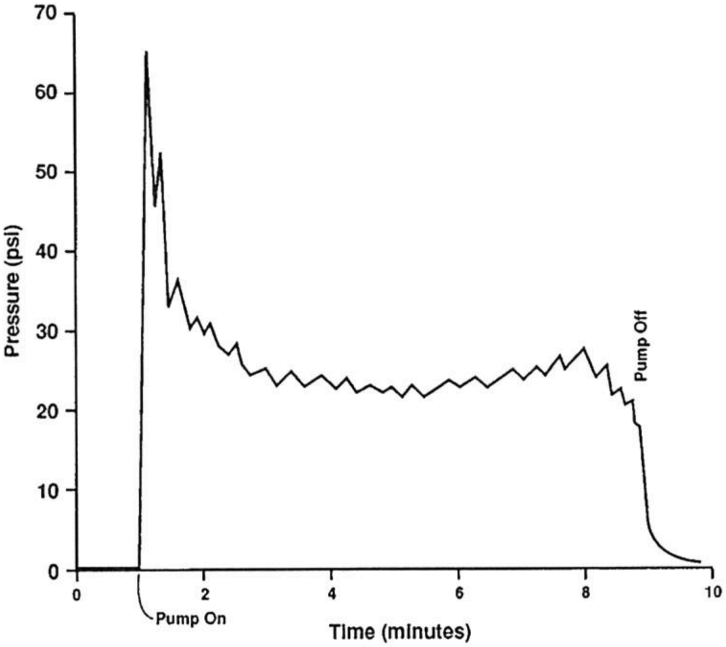

Figure 9.3 Injection pressure as a function of time during hydraulic fracturing.

propagate (Figure 9.3).[3] Injection pressure was between 15 and 20 psi during propagation.[3] Slightly greater pressures are required to create fractures at greater depth.

In some cases, the fracture is nearly flat-lying in the vicinity of the borehole and the dip increases to approximately 20° at some distance away, whereas in other cases the fractures appear to maintain a roughly uniform dip from the borehole to the point of termination (Figure 9.4). In nearly every case, the fracture has a preferred direction of propagation so that the borehole is off the center of the fracture. The preferred direction of propagation is commonly related to distribution of vertical load at the ground surface, with the fractures propagating toward regions of diminished vertical load. Beneath sloping ground, therefore, it is possible to anticipate the preferred direction; it is typically downslope.

It has been reported that radial dimensions of 20 to 35 ft have been achieved during hydraulic fracturing at depths of up to 30 ft.[3] The average thickness of the fracture ranged from 0.2 to 0.4 in. The largest fracture that has been characterized was 55 ft in the radial direction and the thickest was 1 in.[3] The maximum dimension of a hydraulic fracture depends on the volume of fluid injected into it. But this dimension is not without bounds, because

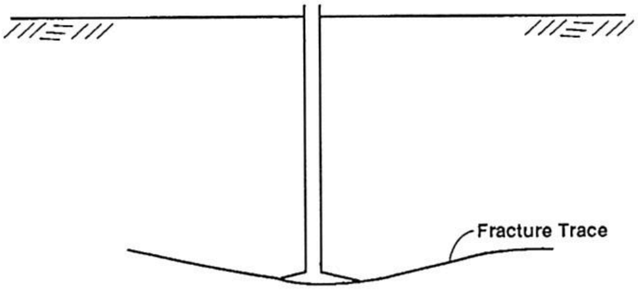

Figure 9.4 Trace of idealized hydraulic fracture.

the fracture climbs and will vent at the ground surface with continued injection. The volume of injected slurry then becomes critical, and currently, empirical methods that make use of observations and field measurements serve to develop an initial design. The empirical design is developed by creating a fracture in an uncontaminated area and then adjusting the design based on collected data.

9.3.2 Pneumatic Fracturing

Pneumatic fractures can be generated in geologic formations if air or any other gas is injected at a pressure that exceeds the natural strength as well as the *in situ* stresses present in the formation. As noted earlier, pneumatic fracture propagation will be predominantly horizontal at overconsolidated formations. However, in shallow recent fills, some upward inclination of the fractures has been observed, the reason for which is attributed to the lack of stratification and consolidation in these formations.[4]

The amount of pressure required to initiate pneumatic fractures is dependent on the cohesive or tensile strength of the formation, as well as the overburden pressure (dependent upon the depth and density of the formation). An expression for predicting pneumatic fracture initiation pressure has been developed by assuming the geological material to be brittle, elastic, and overconsolidated.[5] Assuming the formation has an effective unit weight, δ', and an apparent tensile strength, t_a, the fracture initiation pressure, P_i, may be estimated by

$$P_i = C\delta' Z + t_a + P_o \tag{9.1}$$

where C = coefficient (ranging from 2.0 to 2.5)
Z = overburden depth
P_o = hydrostatic pressure.

Substituting typical values for clay soil and shale bedrock at a depth of 20 ft, the above expression yields initiation pressures of 100 psi and 200 psi, respectively. Fracture initiation pressures are, therefore, relatively modest at shallow depths (where most of the contamination occurs).

The most important system parameter for efficient pneumatic fracturing is injection flow rate, as it largely determines the dimensions of a pneumatic fracture. Once a fracture has been initiated, it is the high volume airflow which propagates the fracture and supports the formation. The design goal of a pneumatic fracturing system therefore becomes one of providing the highest possible flow rate. Field observations indicate that pneumatic fractures reach their maximum dimension in less than 20 seconds, after which continued injection simply maintains the fracture network in a dilated state (in essence, the formation is "floating" on a cushion of injected air).[4] Pneumatically induced fractures continue to propagate until

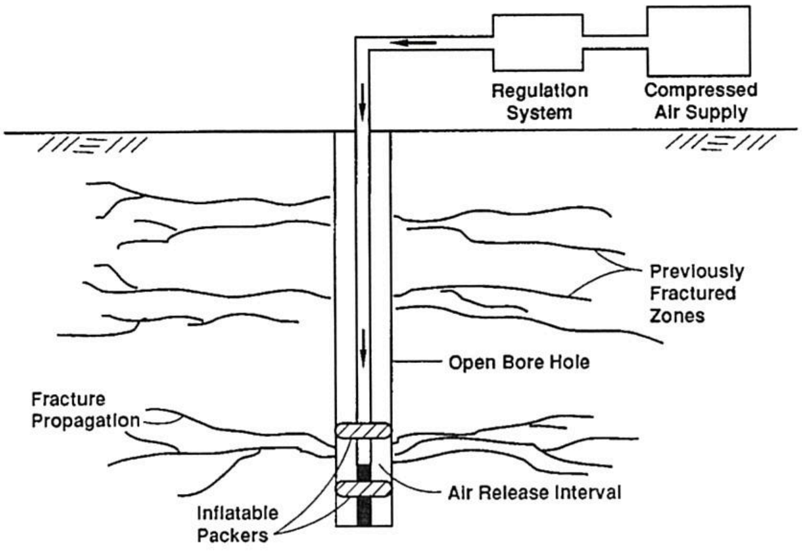

Figure 9.5 Schematic of pneumatic fracturing process.

they intersect a sufficient number of pores and existing discontinuities, so that leak-off (fluid loss) rate into the formation exactly equals the injection flow rate.

In general, injection rates of up to 1000 scfm are sufficient to create satisfactory fracture networks in low permeability formations. To date, the radii of pneumatic fractures have ranged from 10 to 25 ft from the injection point.[6]

Figure 9.5 shows the major components including a compressed air supply, a flow-pressure system, a flow-pressure regulation system, and an injector. The compressed air supply may consist of either a bank of compressed gas cylinders, or an air compressor and receiver tank. The regulation system allows control of the two parameters critical to successful fracturing—injection pressure and injection flow rate—which are adjusted according to the geology of the site and the depth of fracture. Air is injected into the formation through an injector which is placed in the borehole.

An individual pneumatic fracture is accomplished by (1) advancing a borehole to the desired depth of exploration and withdrawing the auger, (2) positioning the injector at the desired fracture elevation, (3) sealing off a discrete 1 or 2 ft interval by inflating the flexible packers on the injector with nitrogen gas, (4) applying pressurized air for approximately 30 s, and (5) repositioning the injector to the next elevation and repeating the procedure. A typical fracture cycle takes approximately 15 min, and a production rate of 15 to 20 fractures per day is attainable with one rig.

The pneumatic fracturing procedure typically does not include the intentional deposition of foreign propping agents to maintain fracture stability. The created fractures are thought to be "self propping," which is attributed to both the asperities present along the fracture plane as well as the block shifting which takes place during injection. The aperture or thickness of a typical pneumatically induced fracture is approximately 0.5 to 1 mm.[4] Testing to date has confirmed fracture viability in excess of 2 years, although the longevity is expected to be highly site-specific.[1]

Without the carrier fluids used in hydraulic fracturing, there are no concerns with fluid breakdown characteristics for pneumatic fracturing. There is also the potential for higher permeabilities within the fractures formed pneumatically, in comparison to hydraulic fractures, as these are essentially air space and are devoid of propping agents. The open, self-propped fractures resulting from pneumatic fracturing are capable of transmitting significant amounts of fluid flow. The high flow potential for even small fractures may be explained by

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the "cubic law," which states that flow rate in planar fractures is proportional to the cube of the aperture.

9.4 FEASIBILITY EVALUATION

Fracturing success is dependent on the application of both sound engineering and sound judgment. The knowledge base and literature information on successful cleanup of contaminated sites where fracturing has been applied for testing and more so for full-scale remediation is very limited. With continued testing and reporting of both successes and failures, understanding of the technology will develop to the point where geologic conditions favoring the technology will become better understood.

Screening a site for possible application of fracturing first requires the understanding of the mechanics and applicability of fracturing to enhance permeability, but also the integration with the selected cleanup technology. Based on the site investigations and the extent of contamination, a preliminary estimate of the number of fractures necessary to provide adequate coverage can be determined. As a general rule of thumb, fracture formation in the range of from 20 to 35 ft or more is possible for near-surface soils and, with all other factors remaining the same, increased radius with depth may be possible. The relationship between depth (loading) of fracture location and fracture dimensions needs to be considered for a full-scale application. Specifically, more closely spaced shallow fractures may need to be created to achieve the desired end result. Fracture propagation in rock formations has been found to be greater than in soil formations, primarily due to the competence and cohesion of these units.

9.4.1 Geologic Characterization

A primary step in the evaluation of feasibility of fracturing is an examination of detailed and accurate geologic cross sections illustrating sediment layering and grain sizes in the target zone, and the contaminant characteristics present in the target zone. Because contaminants often reside within low-permeability, fine-grained soils, it is important to understand this relationship.

At least one continuous core boring should be installed to characterize major and minor changes in lithology. Cores collected during continuous and depth-specific sampling should be examined for factors contributing to secondary permeability such as coarse-grained sediment inclusions and naturally occurring fractures. These secondary permeability characteristics of the soil or rock formation may influence the creation of engineered fractures. Pneumatic fractures, in particular, may propagate along existing fracture patterns. Hydraulic fractures have been found to be less influenced by existing fractures.[3] The site and geologic parameters to be evaluated are summarized below.

- Type of soil/rock
- Type of deposition
- Groundwater depth
- Perched water level (if any)
- Type of contamination (e.g., VOCs, hydrocarbons, etc.)
- Depth of contamination

9.4.2 Geotechnical Characterization

In addition to the qualitative evaluations described above, target zone soil samples should be submitted for geotechnical evaluations of grain size analysis, liquid and plastic limits of

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soil, moisture content, and unconfined compressive strength. Details and implications of these tests for a candidate site for fracturing are as follows:

- Grain size analysis: Although fractures can be created in sediments and rock of nearly any grain size, the highest degree of permeability improvement can be expected from the finer grained soils. Grain size analysis can be performed by using the sieve analysis method (ASTM methods D421 and D422) and/or the hydrometer analysis method (ASTM methods D421 and D422).
- Liquid and plastic limits of soil: This parameter is also known as the Atterberg limits and characterizes the plasticity of a soil. In general, fractures created in highly plastic clays will not propagate as well as in more brittle materials. Formations having $W_n < W_l$ are most suitable for artificial fracturing, where W_n is the natural moisture content and W_l is the liquid limit. Soils having $W_n > W_l$ (or liquidity index > 0) may liquefy under a sudden shock imparted during the fracturing process. The estimation of W_n and W_p (plastic limit) would also give an indication of the degree of consolidation of soil. If W_n is closer to W_p than to W_l, the soil may be over consolidated. If W_n is closer to W_l (or larger), the soil may be normally consolidated. Liquid and plastic limits of soil can be measured by ASTM method 4318.
- Soil moisture content: Overall soil permeability improvements are achievable with fracturing; however, vapor flow in particular is also controlled by soil moisture. Improvements in vapor flow through highly saturated soils (at or near field capacity) will not be achieved by the production of fracturing alone. Additional means of moisture removal may be required to obtain the desired effect through fracturing under these circumstances. ASTM method D2216 may be used to estimate the soil moisture content.
- Unconfined compressive strength: The unconfined compressive strength can be used for predicting the orientation and direction of propagation of fractures. As noted earlier, the state of *in situ* stresses plays a key role in the orientation and ultimate effect on permeability enhancement. The artificially induced fractures are assumed to be vertical in normally consolidated soil and horizontal in over consolidated deposits. ASTM method 2166 is used to measure the unconfined compressive strength of soils.
- Permeability: As discussed previously, fracturing is generally applied at sites with characteristically low permeability. A baseline estimate of permeability (vapor and/or liquid) is often available from testing concluded at the site during site investigations. This baseline estimate of permeability provides a basis for evaluating the necessity, benefit, and effectiveness of the fracturing process. In general, greater improvement of vapor or fluid flow and radial influence is observed in formations with lower initial permeability.
- Cohesion: The more cohesive the soil is, more amenable it will be to fracturing. Longevity of the fractures, upon relaxation of fracture stress, is high in cohesive soils. Fracturing in cohesive soils such as silty clays has been particularly successful.

9.5 PILOT TESTING

Upon completion of the preliminary screening and geotechnical testing, pilot testing is typically conducted for further performance evaluation and to provide a design basis for a full-scale system. Pilot testing is by far the most powerful and useful means of screening a site for a full-scale remediation incorporating fracturing, since experience has shown that preliminary screening of a site cannot always accurately predict the performance of either hydraulic or pneumatic fracturing.

The pilot test plan should incorporate the following steps:

- area selection
- baseline permeability/mass recovery estimation
- fracture point installation
- test method and monitoring.

9.5.1 Area Selection

Selection of the area for the pilot test within the contaminated site is the first step in designing the pilot test. The decision must be made whether to test the technology within the impacted area(s) of the site or to conduct testing outside the contaminated zone. It is generally preferred to test within the contaminated zone to reduce the impact of lateral heterogeneities and to collect data on contaminant recovery rates prior to and after fracturing.

For pilot testing of a single fracture well, an area of approximately 4000 ft^2 should be sufficient. This area should encompass the anticipated maximum limits of fracture propagation.

9.5.2 Baseline Permeability/Mass Recovery Estimation

To aid in the evaluation of fracturing benefits vs. the costs and risks of the technology, a baseline estimate of soil permeability and contaminant mass recovery rates is typically conducted prior to implementing the fracture formation. Because fracturing is generally considered for low-permeability formations ($K_{\text{air}} < 1$ Da, $K_H < 10^{-5}$ cm/s, where K_{air} is pneumatic permeability, and K_H is hydraulic conductivity in the horizontal direction), careful evaluation of the location-specific permeabilities will enhance the success of fracture formation.

After a geologic formation has been fractured, the ability to treat and/or remove the contaminants will depend on the flow and transport characteristics of the artificially fractured medium. The two general approaches for analyzing flow in fractured media include the equivalent porous medium and the dual porosity approaches.[7]

As the name implies, the *equivalent porous medium approach* assumes that the fractures are distributed sufficiently throughout the formation so that it can be analyzed with standard porous media methods. The applicability of this approach largely depends on the scale of the domain under study. For example, if the fractures are very closely spaced and/or the area under study is very large, the porous media method will yield satisfactory results.[7]

Many situations require the use of the *dual porosity approach* to analyze flow and transport in the fractured media. In the dual porosity approach, the fractured media is assumed to be a superposition of two flow systems over the same volume, consisting of a porous matrix and the open fracture network. As a special case of the dual porosity method, it is often useful to analyze the discrete fractures only and ignore the flow and storage characteristics of the porous matrix blocks. It can be concluded that the vast majority of the flow in an engineered fracture formation occurs as discrete fracture flow.[7]

9.5.3 Fracture Point Installation

Specifically designed fracture point installation is required for pilot testing of the fracturing technologies. The fracture intervals are selected to coincide with the target zone of contamination. Fracture locations are also targeted for the low-permeability sediments or rock within a layered setting.

The multistage processes of implementing hydraulic and pneumatic fractures have been discussed in previous sections. Upon reaching the desired maximum depth of fracture formation through the processes described earlier, the borehole is often completed using conventional well installation techniques. The placement of a well central to the point of radiating fractures allows for the withdrawal of vapors and liquids through the relatively permeable zones containing secondary permeability.

9.5.4 Test Method and Monitoring

Pilot testing of the fracturing technologies is generally a two-step process. The first step is conducted during the actual formation of the fractures. During this step, the approximate dimensions and the orientation of the fracture pattern are determined. The second step in the testing process is to determine the increase in vapor or fluid movement within and beyond the area of fracture propagation and the corresponding increase in contaminant mass removal rates.

9.5.4.1 Fracture Aperture

Fracture aperture is the perpendicular distance between the adjacent walls of a fracture which is air- or water-filled. Fracture aperture is the major controlling factor for fluid flow through a fractured media. It is very difficult to define apertures in terms of true width, since the asperities that create fracture surface roughness also affect the fracture aperture.

Field measurement of fracture aperture is most commonly performed indirectly, using borehole hydraulic tests. Assuming only one fracture intersects the test interval, a packer test will yield an aperture thickness as a function of the hydraulic conductivity by using the cubic law. The cubic law states that the functional relationship between flow, Q, and fracture aperture thickness, b, can be represented by

$$Q \propto b^3 . \tag{9.2}$$

If more than one fracture intersects the test interval, then this method will overestimate the aperture of either fracture. A borehole camera and ground surface heave measurements also can be used to estimate the fracture aperture. A high-resolution borehole video camera can be lowered into the borehole to obtain insight into the effects of fracturing by comparing the films from before and after conditions.

9.5.4.2 Fracture Spacing

Fracture spacing is the perpendicular distance between adjacent fractures. Fracture spacing is influenced by the soil or rock composition, texture, structural position, and bed thickness. As a general trend, fracture density decreases with depth, as does fracture porosity.

9.5.4.3 Fracture Orientation

The orientations of fractures, though not regular, is not purely random. For soils, the loading history, and thus the degree of consolidation, is assumed to govern the orientation of the artificially engineered fractures. Orientation of a fracture can be expressed by its strike and dip. The change in ground surface elevation during fracturing has been found to provide a reasonable approximation of the fracture locations in the subsurface.

Ground surface displacement (heave) is generally recorded during fracturing by an array of survey points that are monitored in real time. Heave detection can be used to estimate the dimensions of both aperture and length of the fractures. Simplistically, the heave can be measured with an engineering level and graduated rods driven into the ground. A limitation of this method for surface heave measurement is apparent when the observed surface effects

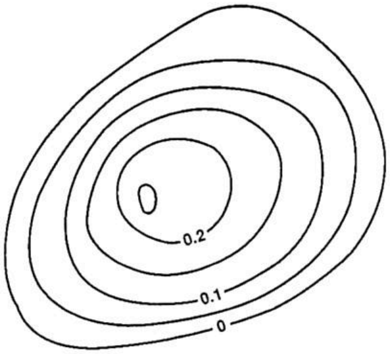

Figure 9.6 Typical tiltmeter ground surface heave contour.

become smaller as the depth of fracture formation becomes deeper. Tiltmeters can be used to collect the dynamic time history data of fracture propagation. Tiltmeters sense the tilting of the surface, and the array of tiltmeters can generate the data to develop the contours of the surface deformation caused by fracturing (Figure 9.6).

Pressure and/or flow measurement devices also can be used at existing or installed monitoring wells for estimating the horizontal extent of the fractures as they establish fluid communication with outlying monitoring wells. During fracture injection, evidence of direct communication is often observed in the form of air rushing out of the monitoring wells. Additional evidence can be collected in the form of negative pressure in the outlying wells during vacuum extraction. Air communication measurements are valuable since they not only provide absolute confirmation of whether fractures have intersected a particular well, but also provide useful data for evaluating the postfracture enhancement of permeability of the formation.

For pneumatic fracturing, the surface heave during pressure application is substantially higher than the residual heave after pressure relaxation. The residual heave is generally 10 to 20% of the maximum displacement (typically less than a few inches). For hydraulic fracturing, the ground displacement is directly related to the volume of the injected slurry, and the thickness of the fractures decreases with distance from the point of injection, following the path of least resistance. Heterogeneity within the soil matrix, naturally occurring fracture patterns and, to a lesser degree, bedding planes appear to influence the orientation of the created fractures.

Surface loading also influences the pathway of the fracture font. High surface loading created by manmade structures or changes in topography can also influence the fracture patterns. If needed, temporary surface loading can be used to “steer” the fractures toward a desired location. Vehicles have been used successfully for this application.

Because of the displacement caused by the fracture formation, care must be exercised when working adjacent to buildings or other structures. While some structures can withstand these moderate displacements, the integrity of others may be compromised. A careful evaluation of the structure’s strength and stability must be performed prior to implementing a fracture test near a building.

9.5.4.4 Enhancement of Vapor or Fluid Movement

During the second step of pilot testing, the permeability enhancement resulting from the fractures formed should be evaluated. The enhanced flow characteristics should be compared with the baseline measurement or estimate of vapor or fluid movement prior to fracturing. The applicability of the process and, ultimately, the number, locations, and depth intervals of a full-scale fracture system will depend heavily on this evaluation.

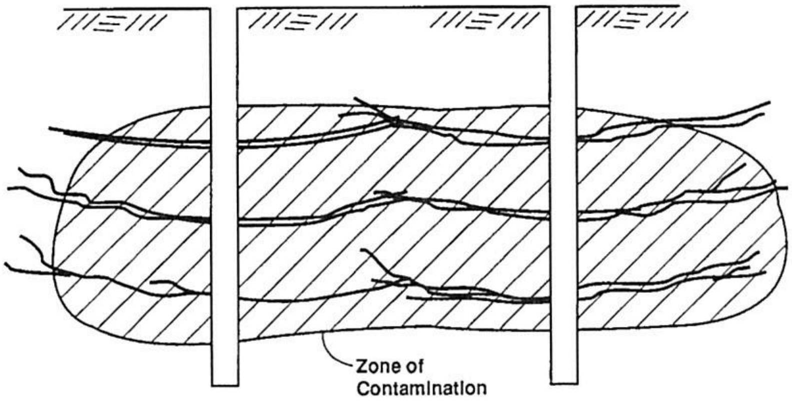

Figure 9.7 Successive fracturing of target zone with overlapping fractures.

The second step of the pilot testing program may entail a soil vapor extraction test or groundwater pumping test to determine the enhancement in permeability. In addition, it is also important to monitor the changes in chemical composition of the soil gas as a result of the access to new pockets of contamination caused by fracturing.

9.6 SYSTEM DESIGN

Upon completion of preliminary screening and pilot testing, design of a full-scale fracturing system can be initiated. The implementation of a full-scale program should be based on economic and feasibility evaluations. In essence, fracturing should be selected as a component of the final remediation system, only if the cost of integrating fracturing is less than alternative methods such as multiple wells with closer well spacings or excavation and above-ground treatment and disposal.

Based on the results of field testing, a fracture wells location plan should be selected to encompass the area of known contaminant impact (Figure 9.7). The fracture wells locations plan must take into consideration the asymmetric orientation of fracture propagation. For instance, the fracture points may be more closely spaced north to south than east to west due to asymmetry. To control the role of diffusion and the possible creation of low flow zones, an engineering safety factor should be applied such that the fracture zones overlap in the plan view.

The depth intervals for the fractures should correspond with the known distribution of contaminants. This requirement again emphasizes the importance of site characterization.

Because of geologic heterogeneity present at almost every site, the full-scale fracturing plan should be designed with some flexibility in mind. In most instances, it would be wise to specify a range of possible fracture point locations with field adjustments made during installation to optimize the overall system performance. Depending on the size of the site and number of fracture points, it may also be advisable to implement the fracturing program in a phased approach. For example, fracture wells could be installed on a 1-week cycle. During the first week, fracture points could be installed, followed by testing of these points for performance (e.g., enhancement of vapor or liquid extraction rates). Adjustments can then be made for the next cycle of fracture installations.

Even with fracturing, contaminant removal rates will be rate-limited by diffusional flow between the areas of high, advection-controlled flow. When compared to contaminant removal rates before fracturing, postfracture rates will be higher, if the process is successful and applied under the right conditions. Eventually, however, diffusion-controlled mass transfer will influence the time required to reach the cleanup standards. The diffusive distances will be shortened significantly due to the fracture network formed.

9.7 INTEGRATION WITH OTHER TECHNOLOGIES

As noted earlier, hydraulic or pneumatic fracturing are not "stand-alone" remediation techniques. Once a fracture network is established in a low-permeability formation, the gaseous, adsorbed, and liquid contaminants are more easily accessed by complimentary remediation technologies.

9.7.1 Soil Vapor Extraction Combined with Fracturing

A major obstacle for the application of soil vapor extraction (SVE) as a remediation technique is permeability of the formation. Low-permeability formations, such as fractured shales, silts, and clays, usually do not allow sufficient subsurface airflow for conventional SVE to be effective. Fracturing of such formations will help in overcoming the difficulties in implementing SVE at these sites.

The increase in extraction airflow rate provided by both pneumatic and hydraulic fracturing means that contaminants can be removed faster by volatilization. The formation permeability increase created by fracturing also allows for a much greater vacuum radius of influence to be induced from an extraction well. Since the spacing between extraction wells is significantly increased, the total number of wells needed to remediate a site is reduced. This leads to a substantial costs savings.

It is noted that often the highest contaminant concentrations occur within and adjacent to existing structural discontinuities in low-permeability formations (e.g., joints, cracks, bedding planes). Since fracturing dilates and interconnects existing discontinuities, direct access is provided to a majority of the contaminant mass. Even the small airflows through the smaller fracture network are capable of volatilizing and removing contaminants, thereby causing an outward diffusive gradient of the contaminant from the matrix block to the larger fractures.

The following two case studies illustrate the efficacy of fracturing in enhancing the mass removal rates during SVE.

1. The impacted zone at this site (in the northeastern U.S.) was characterized as siltstone and shale with naturally occurring fractures. Pneumatic fractures were installed between 9 and 16 ft below grade. Before fracturing, the vapor extraction rates from each of the tested wells was below the sensitivity of the measuring instrument (less than 0.6 scfm) at an applied vacuum of 136 in. of water. A single fracture well was installed central to the monitoring points, as shown in Figure 9.8.[8] The distances between the fracture well and the monitoring points were 7.5 to 20 ft.
   Based on elevation measurements recorded by an electronic tiltmeter during fracturing, surface heave was observed up to 35 ft from the fracturing well. The flow rates from each of the test wells surrounding the fracture well increased substantially after fracturing. Specifically, the flow rate increased by more than 15-fold after fracturing. Vacuum measurements within the monitoring points also increased after fracturing by 4 to 100 times in comparison to prefracture conditions. Pneumatic fracturing improved access to the contamination substantially by increasing the mass removal rate by approximately 25 times (Figure 9.9).[4] It is also interesting to note the change in chemical composition of the soil gas summarized in Table 9.1. Before fracturing, TCE was the predominant component of the soil gas, representing approximately 84%. However, after fracturing, other compounds became more dominant, even though the removal rate of TCE had increased substantially. This shift in soil gas composition indicates that new pockets of contamination were accessed by pneumatic fracturing.[4]
2. Hydraulic fracturing tests were conducted on vadose zone soils at a site in the midwestern U.S. The site was contaminated with TCE, 1,1,1-TCA, 1,1-DCA and PCE.[9] The soils were characterized as a silty/clayey till to a depth of approximately 20 ft below grade. The permeability of the soil was estimated to be 10^{-7} to 10^{-8} cm/s. The pilot-scale demonstration created six fractures in two wells at depths of 6, 10, and 15 ft below grade over a 1 day period. At an applied vacuum of 240 in. of water, the vacuum influence in unfractured soil

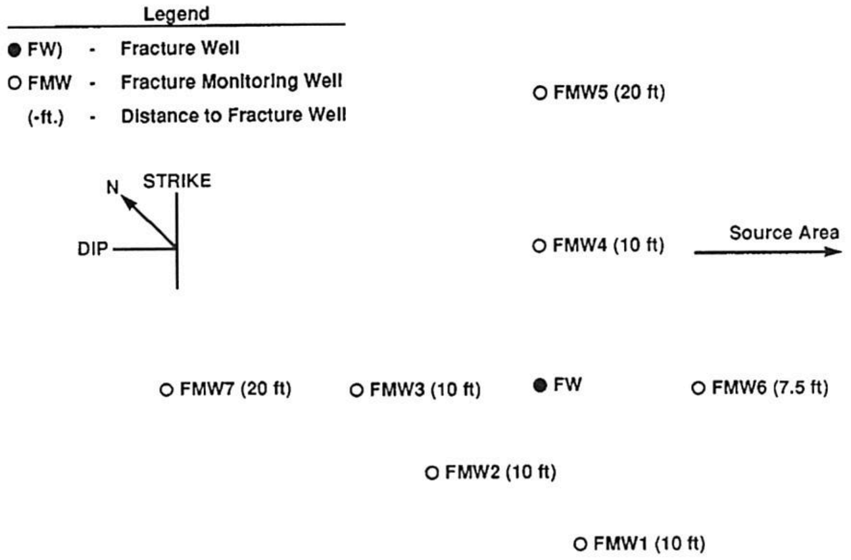

Figure 9.8 Well location plan for pneumatic fracturing.

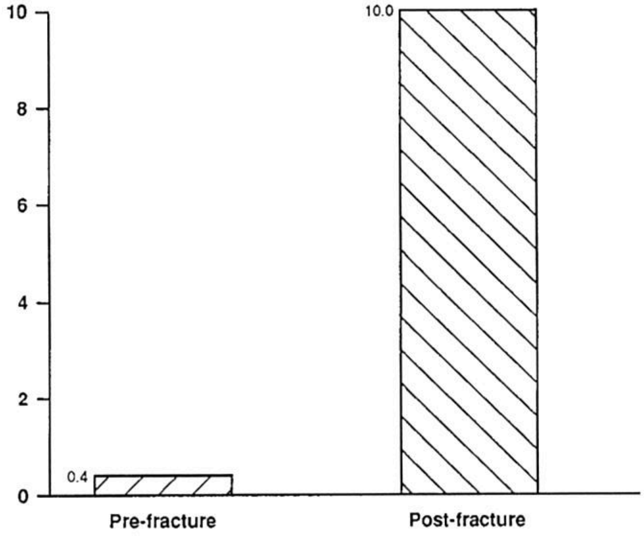

Figure 9.9 Comparison of TCE mass removal under pre- and postpneumatic fracturing by SVE.

Table 9.1 Volatile Organic Compounds Present in Extracted Soil Gas at Pneumatic Fracturing Site

Compound	Prefracture % of total	Postfracture % of total
TCE	84	15
Benzene	6	37
PCE	5	33
Chloroform	4	13
Methylenechloride	1	2
Total mass removal rate of all compounds	0.78×10^{-5} lbm/min	113.6×10^{-5} lbm/min

Note: lbm/min = pound mass per minute.

Adapted from Schuring, J. R., Pneumatic fracturing to remove soil contaminants, *NJIT Res.*, 2, Spring 1994.

was negligible, decreasing to a few tenths of an inch of water column at a distance of 5 ft from the extraction well. This clearly demonstrated the limitations of a conventional SVE system at this site. The flow rates in unfractured soils were also very low, measured to be approximately 1 scfm. In the fractured soils, flow rates from approximately 14 to 23 scfm were achieved under similar vacuum levels. Vacuum level measurements in the fractured soil also increased dramatically up to 25 ft from the fracture wells. Contaminant recovery rates similarly increased in the fractured soil by 7 to 14 times.

9.7.2 *In Situ* Bioremediation

The success of *in situ* bioremediation depends on the availability of electron acceptors, such as O_2, and nutrients such as N and P. The delivery and transport of these nutrients may become the rate-limiting factor in low-permeability formations.

Fracture networks formed during hydraulic and pneumatic fracturing can be utilized as delivery pathways for introducing reagents as sources of O_2, N, and P. These reagents can be introduced both in the saturated and unsaturated zones in the form of gaseous or liquid reagents.

In addition, slowly reactive materials containing O_2 and nutrients can be used as proppants during hydraulic fracturing to enhance *in situ* biodegradation both in the vadose and saturated zones. A "time-release" oxygen source such as sodium percarbonate[10] or magnesium peroxide can be used as proppants and, when injected into the impacted soils, will slowly release oxygen over a long period. The advantage of this process is that aerobic conditions can be locally maintained in the subsurface, which might not have been possible otherwise.

9.7.3 Reductive Dechlorination

Testing is currently underway for the injection of elemental iron filings for the creation of subsurface conditions favoring reductive dechlorination of chlorinated aliphatic compounds. A horizontal "flat-lying" reactive wall can be thus created to promote the accelerated attenuation of chlorinated compounds.

9.7.4 *In Situ* Vitrification or *In Situ* Heating

The *in situ* vitrification technology uses electric power to heat contaminated soil past its melting point and, thus, destroy organic contaminants in the soil. The process destroys organic contaminants by means of pyrolysis and oxidation, thermally decomposing some inorganic contaminants, and immobilizing thermally stable compounds within a glass and crystalline vitrified material. The most important operational parameter for this technology is the electrical input to the melting zone.

In situ vitrification technology uses graphite electrodes to implement the input of electrical energy to heat the soil. A graphite-based proppant can be used during hydraulic fracturing to install the graphite as electrodes to conduct electricity. In addition, flaked graphite and glass frit can be used as a mixture of proppants to act as a starter path since dry soil is usually not electrically conductive.

In the recent past, electrical soil heating has been considered as a means of enhancement to soil vapor extraction. If graphite-based proppants are used during hydraulic fracturing, the graphite can be used as the electrodes to implement electrical soil heating to increase the contaminants' vapor pressure.

9.7.5 *In Situ* Electrokinetics

Recently, the use of electrokinetics as an *in situ* method for soil remediation has received increasing attention due to its unique applicability to low-permeability soils. Electrokinetics

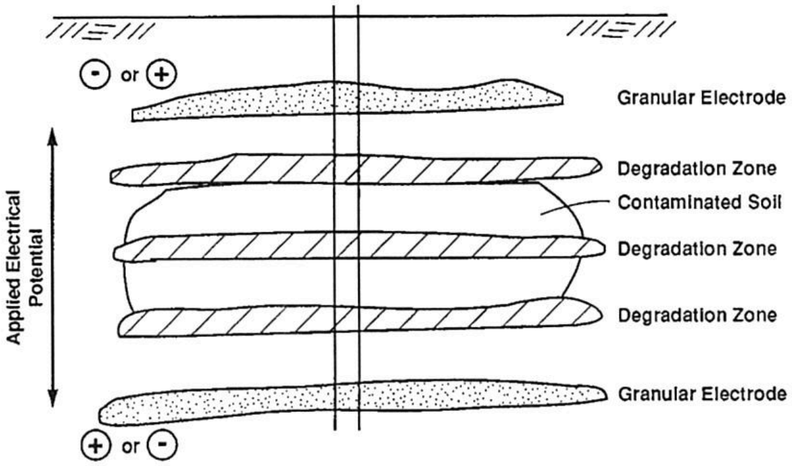

Figure 9.10 Schematic diagram of the "lasagna process."

includes the transport of water (electroosmosis) as well as ions (electromigration) as a result of an applied electric field.[11] Electroosmosis, in particular, has been used since the 1930s for dewatering clays, silts, and fine sands.[11] For remedial applications, water is typically introduced into the soil at the anode to replenish the water flowing toward the cathode due to electroosmosis. The water flow is utilized to flush and/or degrade the contaminants in the subsurface soil. The contaminants flushed from the subsurface soil to the ground surface at the cathode region can be collected for further treatment and disposal, if needed (Figure 9.10).

Advantages with electroosmosis include uniform water flow through heterogeneous soil, high degree of control of the flow direction, and very low power consumption. There are, however, several major drawbacks associated with electroosmosis for remedial applications. These include low liquid velocities induced by electroosmosis, (typically about 1 in./day for clay soils), additional above-ground treatment, steep pH gradient in the soil bed, and precipitation of metals near the cathode.

An integrated approach coupling electrokinetics and hydraulic fracturing with complimentary *in situ* technologies to eliminate or minimize the drawbacks associated with the use of electrokinetics has been developed recently. This process, called the "lasagna process" by its developers, is so named for its layers of electrodes and treatment zones.

The general concept is to use electrokinetics to move contaminants from the soils into "treatment zones," where the contaminants are removed from the groundwater by adsorption, immobilization, or degradation. Hydraulic fracturing can provide an effective and low-cost means for creating such zones horizontally in the subsurface soil within the contaminated zone. A graphite-based proppant can be used to install the horizontal electrodes above and below the contaminated zone (Figure 9.10). Hydraulically fractured zones also will create much more permeable zones than the native soils to enhance the liquid velocities induced by electroosmosis.

The treatment zones can also be vertical, which can be constructed using sheet piling, trenching, slurry walls, or deep soil mixing techniques. The treatment zones can also be continuous instead of being discrete.

Liquid flow can be periodically reversed, if needed, simply by the cyclic application of low-voltage DC current to the electrodes. This mode will enable multiple passes of the contaminants through the treatment zones for complete sorption or degradation. The polarity reversal also serves to minimize complications associated with long-term operation of unidirectional electrokinetic processes. For example, the cathode effluent (high pH) can be recycled directly back to the anode side (low pH), which provides a convenient means for pH neutralization as well as more simple water management.

REFERENCES

1. Schuring, J. R. and Chan, P. C., Pneumatic Fracturing of Low Permeability Formations — Technology Status Paper, unpublished paper, 1993.
2. Hubbert, M. K. and Willis, D. G., Mechanics of hydraulic fracturing, *Petrol. Trans. AIME*, 210, 153, 1957.
3. Murdoch, L., Hydraulic and Impulse Fracturing Techniques to Enhance the Remediation of Low Permeability Soils, unpublished paper, 1993.
4. Schuring, J. R., Pneumatic fracturing to remove soil contaminants, *NJIT Res.*, 2, Spring 1994.
5. King, T. C., Mechanism of Pneumatic Fracturing, M. S. thesis, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, 1993.
6. Nautiyal, D., Fluid Flow Modeling for Pneumatically Fractured Formations, M. S. thesis, Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, 1994.
7. Gale, J. E., Assessing the Permeability Characteristics of Fractured Rock, Geological Society of America, Special Paper 189, 1982.
8. U.S. Environmental Protection Agency, Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase I, Applications Analysis Report, EPA/540/AR-93/509, 1993.
9. U.S. Environmental Protection Agency, Hydraulic Fracturing Technology, Applications Analysis and Technology Evaluation Report, Risk Reduction Environmental Laboratory, EPA/540/AR-93/505, 1993.
10. Vesper, S. J., Murdoch, L. C., Hayes, S., and Davis-Hooper, W. J., Solid oxygen source for bioremediation in subsurface soils, *J. Hazardous Materials*, 1993.
11. Ho, S. V., Sheridan, P. W., Athmev, C. J., Heitkamp, M. A., Brackin, J. M., Weber, D., and Brodsky, P. H., Integrated in situ soil remediation technology: The lasagna process, *Environ. Sci. Technol.*, 29, 2528, 1995.