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GWRTAC E SERIES

Fracturing Technologies to Enhance Remediation

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April 2002

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FOREWORD

About GWRTAC

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) is a national environmental technology transfer center that provides information on the use of innovative technologies to clean up contaminated groundwater.

Established in 1995, GWRTAC is operated by Concurrent Technologies Corporation (*CTC*) in association with the University of Pittsburgh's Environmental Engineering Program through funding provided by the U.S. Environmental Protection Agency's (EPA) Technology Innovation Office (TIO), the U.S. Department of Defense (DoD), and the U.S. Department of Energy (DOE).

About "E" Series Reports

This report is one of the GWRTAC "E" Series of reports, which are developed for GWRTAC to provide a state-of-the-art review of a selected ground-water remediation technology or ground-water topic. These technology evaluation reports contain information gathered primarily from peer-reviewed papers and publications and, in some instances, from personal communication with involved parties. These reports are peer-reviewed prior to being released.

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1.0 SUMMARY

Over the last decade, fracturing techniques have emerged as viable methods for enhanced remediation of contaminated soil and groundwater. The general approach is to create a network of artificial fractures in a geologic formation that serves two principal functions. First, the fractures can facilitate removal of contaminants out of the geologic formation. Second, the fractures may be used to introduce beneficial reactants into the formation. The overall objective of fracturing is to overcome the transport limitations that are inherent at many remediation sites. Subterranean fracturing is an established concept that has been applied in various forms within the petroleum and water well industries for more than 50 years.

Three general categories of fracturing technologies are currently available for site remediation. One is pneumatic fracturing, which creates subsurface fractures with controlled bursts of high-pressure air or other gas. Another is hydraulic fracturing, which creates subsurface fractures by pumping liquid into the formation. Blast fracturing is the other technique, which propagates subsurface fractures by detonation of high explosives. All three techniques propagate fractures by forcing a fluid into the geologic formation at a flow rate that exceeds the natural permeability and at a pressure that exceeds the normal geostatic stress. In blast fracturing, fractures are also generated by stress waves. The velocity of fracture propagation varies considerably among the three techniques, with hydraulic fracturing exhibiting the slowest velocity (0.1± m/sec) and blast fracturing the fastest (300± m/sec). Pneumatic fracturing exhibits an intermediate propagation velocity of 2± m/sec.

Normally, fracturing is coupled with another primary *in situ* or ex situ remediation technology such as vapor extraction, pump and treat, or bioremediation. Over the last decade, several benefits of fracturing have been defined. A principal use of fracturing is to increase the effective hydraulic and pneumatic conductivity of the geologic formation being treated. This is important when treating fine-grained soils such as clay or silt, as well as tight bedrock. In such formations the movement of vapors and liquids is predominantly diffusion-controlled, so transport occurs rather slowly. By establishing a network of artificial fractures in the formation, advection increases and diffusive paths become shortened. The result can be quicker removal and/or treatment of contaminants, as well as access to pockets of contamination that could not be reached previously. The increase in formation permeability is accompanied by an increase in influence radius of treatment wells, so fewer wells are normally required. A related benefit of fracturing is that it can reduce the heterogeneities that are present in essentially all geologic formations. This makes pressure gradients more uniform throughout the formation, and operational control of the remediation process is improved.

Another beneficial use of fracturing is for delivering various types of liquid and granular supplements into the geologic formation to support contaminant treatment. With pneumatic or hydraulic fracturing the supplements can be injected either during the

fracturing event or after the fractures have been created. With blast fracturing the supplements are introduced after creation of the blasted bedrock zone. Examples include: (1) nutrients, buffers, and inocula to support bioremediation; (2) reactive solid media such as iron powder to support chemical reductions; (3) liquid or solid oxygen-generating chemicals; (4) electrically conductive media to support *in situ* electrokinetics and *in situ* vitrification; and (5) solid proppants.

Another potential benefit of fracturing is that it may be retrofitted to sites already under active remediation in order to enhance recovery rates or treatment rates. In some cases it is possible to conduct fracture injections directly inside existing wells. Alternatively, new fracture wells can be installed between an existing array of treatment wells.

Two restrictions in the use of fracturing technologies have become apparent during the past decade of experience. The first is localized mobilization of contaminants in the fracture-enhanced zone that results from increased transport rates. It is therefore important that the coupled treatment process, e.g., soil vapor extraction, product recovery, be installed in a timely manner. Also, it is extremely important to employ consultants and fracturing vendors who have specific experience with hazardous site applications of fracturing techniques. A second restriction is that fracturing has the potential to cause vertical movement or heaving at the ground surface. Therefore, if fracturing is performed in the vicinity of buildings or utilities, the effects of fracturing on these structures must be carefully evaluated. The amount of ground surface movement that may be caused by fracturing is related to a number of factors including the type of fracturing, depth of injection, number of fractures, and the geologic characteristics of the formation under treatment. Fracturing applications involving injection of solid media or proppants will cause the largest permanent vertical heave and potential structure movement. Also, blast fracturing produces transient vibrations that must be evaluated, which may limit its application in areas close proximity to sensitive structures. The number of projects involving fracturing in the vicinity of active structures and utilities is increasing rapidly. Recent experiences suggest that it is feasible in most cases as long as sound geotechnical design practices are followed.

A number of geotechnical factors must be considered in evaluating potential sites for fracturing applications. The most important factor is the type of soil or rock that is to be fractured. Other important considerations include depth, soil plasticity, soil density/consistency, secondary structure, rock fracture frequency, intact rock strength, rock weathering, and water table configuration. Exploratory borings in the proposed treatment zone with continuous sampling or coring are always recommended. The borings are supplemented with both field and laboratory geotechnical tests. A fracturing pilot test is normally recommended to establish actual fracture behavior in the formation.

To date, pneumatic fracturing and hydraulic fracturing projects have most frequently been applied in soil formations containing silt and clay for the purposes of permeability enhancement and improving the performance of wells. Pneumatic and hydraulic fracturing have also been used for delivery of liquid or granular supplements into the subsurface, and in these applications essentially all soil and bedrock types are considered treatable including sands, gravels, and mixtures. Blast fracturing has been applied exclusively in bedrock formations for permeability enhancement, and some applications of pneumatic and hydraulic fracturing have also been performed in bedrock. The application depths for most pneumatic fracturing and hydraulic fracturing projects have ranged from 3 to 15 m (10 to 50 ft), and application depths for blast fracturing have typically ranged from 6 to 20 m (20 to 65 ft). There is no theoretical depth limit for the fracturing technologies as long as sufficient pressure and flow can be delivered to the fracture zone, so future applications are expected to extend to deeper depths. Applications of fracturing at shallow depths < 3± m (<10± ft) can lead to venting of the fractures to the ground surface, otherwise known as "daylighting".

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) has compiled 86 project summaries of pilot- and full-scale fracturing projects in their "S" Series Report TS-00-01, "Technology Status Report Hydraulic, Pneumatic, and Blast-Enhanced Fracturing" (Roote, 2000). This database is companion to the present report. In addition to providing project summaries, the "S" Series report analyzes various trends including integrated technologies, contaminant classes, site geology, and fracturing results. This "S" Series report can be downloaded in PDF format from the GWRTAC website at http://www.gwrtac.org.

The most common method to evaluate fracturing effectiveness is to measure increases in effective permeability/conductivity and contaminant mass removal rate. Alternatively, the change in the specific capacity (discharge/drawdown) of installed wells may be used. Other evaluative methods include increase in the radius of well influence, measurement of fracture radius, and delivery rate of supplemental media. A review of the 86 case studies reported in the companion "S" Series report was undertaken to assess the general capabilities of the three fracturing technologies. The overall similarity of results produced by the three techniques was notable. For example, the reported increases in permeability/conductivity and specific capacity for pneumatic, hydraulic, and blast fracturing ranged from 1.5 to 175 times, 5 to 153 times, and 0.7 to 100 times, respectively. Due to diffusion limitations, reported enhancements of mass transport rate were consistently less than permeability enhancements. When pneumatic fracturing or hydraulic fracturing is used as a delivery system for liquid or solid media, effectiveness is measured by distribution accuracy and delivery rate. The main determining factor for success of any fracturing application is properly matching process design and layout with the geologic conditions of the site.

All three of the fracturing technologies, pneumatic fracturing, hydraulic fracturing, and blast fracturing, are commercially available for site remediation. Fracturing has been most often applied to enhance various physical treatment processes including vapor extraction, product recovery, dual phase extraction, and pump and treat. Pneumatic fracturing and hydraulic fracturing have also been coupled with bioremediation and permeable reactive walls and zones. Pneumatic fracturing has been field pilot tested with *in situ* vitrification, and hydraulic fracturing has been field pilot tested with *in situ* electrokinetics.

There are specific areas in remediation projects where fracturing can reduce cost. First, fracturing can reduce the number of treatment wells that must be drilled, and thus provide savings on initial capital costs and operating costs. Fracturing can also reduce treatment time, which proportionally reduces project operational costs. At some sites, the improvements manifested by fracturing may provide the only feasible way to use *in situ* remediation methods. In these situations the potential savings are more difficult to define, although one approach is to compare fracturing with an ex situ method that is feasible for the site.

The cost of fracturing varies according to the size of the project, depth of fracturing, and how it will be integrated with the primary integrated technology. Recent data suggest unit costs for pneumatic fracturing range from $250 to $400 per fracture, and the unit cost for hydraulic fracturing ranges from $1000 to $1500 per well (assuming 3 to 5 fractures per well). The unit costs for pneumatic and hydraulic fracturing normally do not include drilling, well installation and long distance mobilization. When these fracturing technologies are used to deliver supplemental media into the geologic formation, the costs are higher since materials and special equipment are involved. Blast fracturing is normally applied in a trench configuration so it is estimated on a linear foot basis. The unit cost of blast fracturing normally ranges from $120 to $200 per linear foot of blast trench. The cost includes drilling and blasting but does not include well installation. The preceding costs for all the fracturing technologies do not include those associated with the primary integrated technology, e.g., soil vapor extraction, product recovery. Unit fracturing costs also do not include engineering controls that may be required to mitigate potential effects on nearby structures and utilities.

2.0 TECHNOLOGY DESCRIPTION

2.1 OVERVIEW OF FRACTURING TECHNOLOGIES

When remediating contaminated soil and groundwater *in situ*, the mass transport rate allowed by the geologic formation is critically important. Permeable formations such as sand and gravel allow relatively high transport rates, and cleanup of certain contaminants can proceed relatively quickly. However, geologic formations containing clay, silt, and tight bedrock impede transport rates and can severely limit the efficiency of both *in situ* and ex situ technologies. Remediation of such formations can be difficult, if it can be accomplished at all. Significant transport limitations can be expected if the hydraulic conductivity of the formation is below about $\sim 10^{-4}$ cm/sec (pneumatic conductivity of $\sim 10^{-5}$ cm/sec) (Schuring et al., 1995). The limiting level varies somewhat according to the viscosity of the fluid being transported in the formation, e.g., vapor, water, oil, and the adsorption potential of the soil or rock minerals.

Over the last decade, fracturing techniques have emerged as a viable approach for overcoming transport limitations at some sites. The idea is to create a network of artificial fractures in the geologic formation that can be used for two principal purposes. First, fractures can facilitate removal of contaminants out of the geologic formation. Second, fractures may be used to introduce beneficial reactants into the formation. Subterranean fracturing is an established concept that has been applied in various forms within the petroleum and water well industries for more than 50 years (Howard and Fast, 1970). Currently available fracturing techniques for site remediation can be divided into three general categories:

- Pneumatic fracturing, which uses pressurized gas to propagate fractures;
- Hydraulic fracturing, which uses pressurized liquids to propagate fractures; and
- Blast fracturing, which detonates high explosives to propagate fractures.

Normally, fracturing is used as an enhancing technique that is coupled with another primary remediation technology such as vapor extraction or product recovery. In these applications, fracturing improves the efficiency of the primary technology by increasing the effective permeability of the geologic formation, which is usually manifested by an improvement in well performance to recover or deliver fluids. Fracturing may also permit extension of the primary technology to a geologic condition that would not normally be treatable with the primary technology. The use of fracturing in site remediation is not limited to permeability enhancement. The fracturing technologies can also function as delivery systems to introduce various types of treatment media, either liquid or granular, directly into the geologic formation. For example, nutrients can be injected to enhance bioremediation, and iron powder can be injected to support reductive dechlorination.

2.2 FRACTURING CONCEPT

Successful fracturing of a geologic formation with a fluid requires that two basic operational conditions be met (Hubbert and Willis, 1957; King, 1993). First, the fluid must be injected at a flow rate that exceeds the ability of the formation to receive the fluid, i.e., the flow rate must be greater than the native permeability of the formation. Second, the fluid must be injected at a pressure that equals or exceeds the *in situ* geostatic stresses at the depth of injection. As long as these two operational conditions are met, fractures will propagate from the point of injection and into the geologic formation. With blast fracturing, fractures are also generated by a stress waves in addition to those created by expanding gases from the explosion (DuPont, 1980).

The propagation of fractures in geologic formations has been studied for more than 50 years in a variety of industrial applications. Most applications have focused on the creation of artificial fractures for beneficial purposes, as in the hydraulic fracturing techniques used in the petroleum industry (e.g., Perkins and Kern, 1961; Gidley et al., 1989). Other beneficial uses of fracturing include permeability testing (Bjerrum et al., 1972) and pressure grouting (Wong and Farmer, 1973). Studies have also focused on avoiding fracture propagation, as in the design of landfill liners and caps (Vallejo, 1993). The key distinguishing characteristic of the various fracturing techniques is the kind of the fracturing fluid that is injected. There are also differences in the propagation velocities of the fractures through the geologic medium. Propagation velocity is related to the rate of pressurization, as well as the viscosity of the fracturing fluid. Table 1 summarizes the various fracturing phenomena according to fluid type and propagation velocity. The reader is referred to Puppala (1998) for additional discussion of the various fracture propagation mechanisms.

Table 1. Summary of Fracturing Techniques (adapted from Puppala, 1998)

	Increasing Propagation Velocity →		
	Hydraulic Fracturing	**Pneumatic Fracturing**	**Explosive Fracturing**
Fracturing Fluid	Liquid, usually water or polymer gel	Gas (usually air or nitrogen) at ambient temperature	Gas (combustion products) at high temperature
Propagation Velocity	0.1± m/sec	2± m/sec	300± m/sec
	Decreasing Fluid Viscosity →		

2.3 PROCESS DESCRIPTIONS

2.3.1 Pneumatic Fracturing

Pneumatic fracturing is performed by injecting high-pressure gas down a borehole to create subsurface fractures (Figure 1). Proprietary injection nozzles are normally used with or without inflatable packers. The technology can be applied in an open borehole, through specially designed well screens (no pack), or through a direct push probe. The

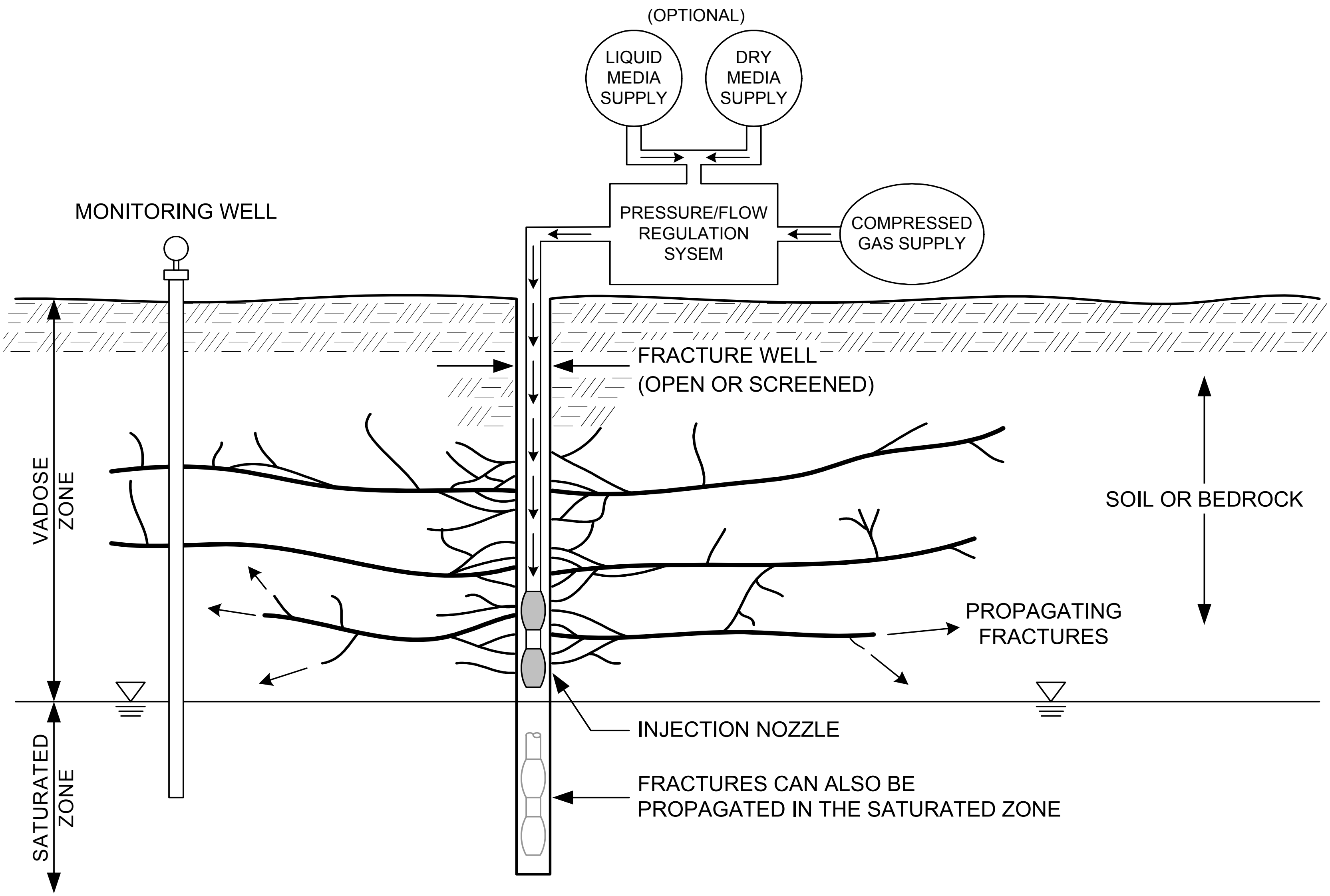

Figure 1. Method of Pneumatic Fracturing

source of compressed gas is typically high-pressure storage cylinders. Formations are fractured sequentially by moving the injection nozzle vertically within the borehole or well, and then moving the injection nozzle to adjacent locations until the entire treatment zone is fractured. The vertical interval between fractures varies from 0.2 to 0.9 m (0.5 to 3.3 ft), although 0.6 m (2 ft) is typical. Fracture propagation is relatively rapid (2± m/sec), and a single injection event typically lasts about 15 to 20 seconds. Pneumatic fracturing equipment is normally trailer-mounted and relatively portable. Accessory equipment is available to inject a wide variety of liquid or granular supplements into the formation along with a pressurized gas to complement various remediation technologies.

Many applications of pneumatic fracturing rely on "self-propping" of the geologic formation. The basis for this approach is the Cubic Law, which demonstrates that fluid flows through open fractures can be substantial, even ones with relatively small dimensions. Brittle geologic materials such as stiff clays and bedrock exhibit good self-propping since irregularities along the fracture surface (known as asperities) and shifting of the geologic medium prevent fracture closure. In plastic clays research has demonstrated that even if a fracture constricts temporarily due to swelling, the process is fully reversible and the fracture will recover due to natural conditions or operational controls. Proppants such as sand or ceramic beads can be used with pneumatic fracturing and have most often been applied in fine-textured cohesionless soils such as silty sand. When injecting proppants or other solid media with pneumatic fracturing, the media are transported directly into the formation by the high velocity gas stream.

Pneumatic fracturing can be distinguished from two other technologies that also involve the injection of gas into geologic formations: air sparging and air injection. Both of these technologies force air through existing pores and fractures in the formation. In contrast, pneumatic fracturing dilates the formation and creates new or expanded pathways for transport.

Pneumatic fracturing has been applied in the vadose, saturated, and perched ground-water zones. For permeability enhancement, the technique has been applied in fine sands, silty sands, silts, clays, and various soil mixtures containing silt and clay, including saprolites. The permeability of sedimentary rock formations, including mudstones, siltstones, sandstones, and shale, have also been enhanced with pneumatic fracturing. When used for injection of liquid, granular, or gaseous supplements, essentially all soil grain sizes and some bedrock types are considered treatable with pneumatic fracturing including sands, gravels, and mixtures.

2.3.2 Hydraulic Fracturing

Hydraulic fracturing is performed by injecting high-pressure water or a polymer gel down a borehole to create subsurface fractures (Figure 2). For site remediation applications, fracture injections can be accomplished against the bottom of driven casing. Notching of the formation is done to nucleate a hydraulic fracture at the desired depth, and it is accomplished using a high- pressure water jet. This is followed by injection of the

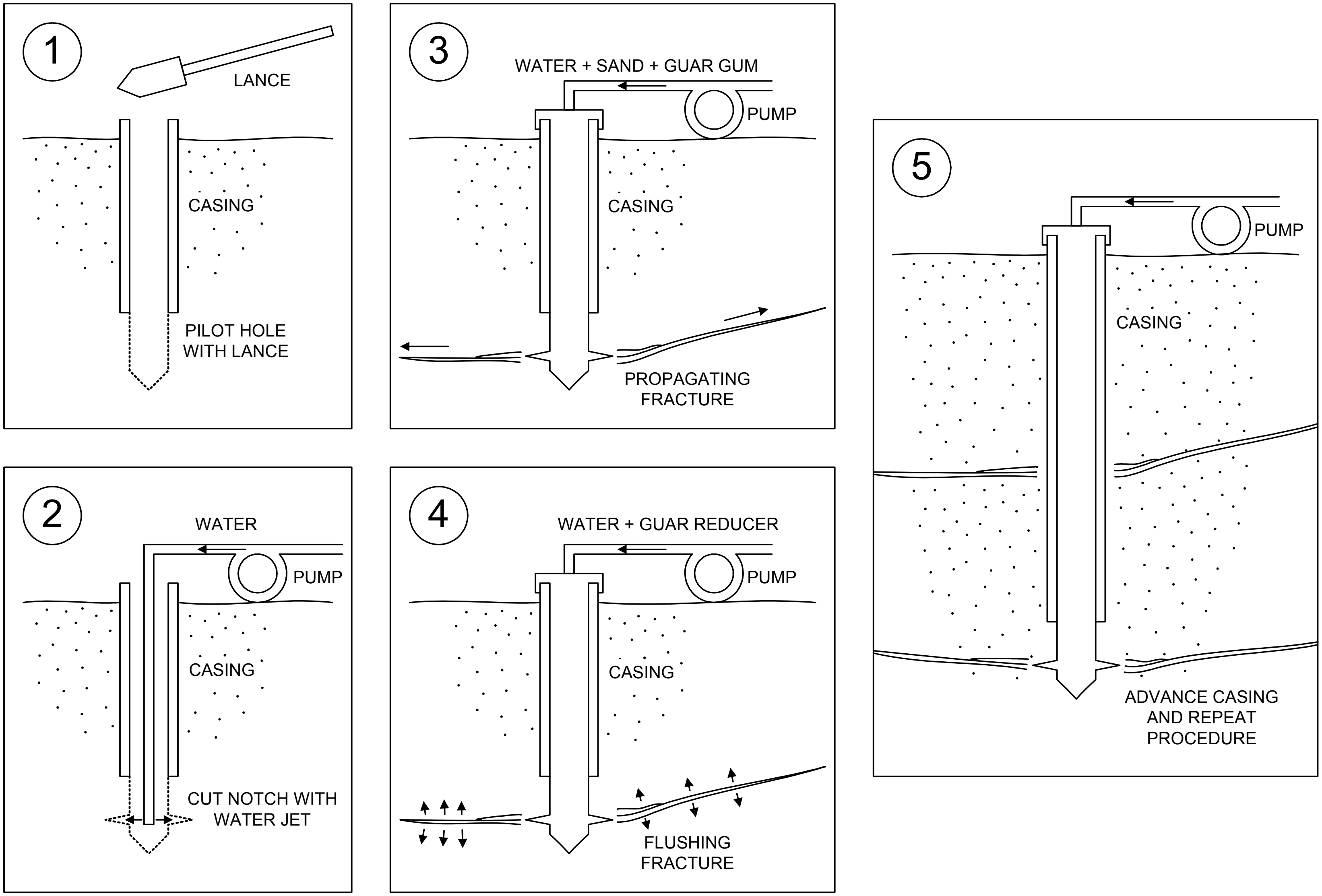

Figure 2. Method of Hydraulic Fracturing

hydraulic fracturing fluid, which typically consists of a mixture of water-based gel and sand or other proppant. Additional fracture wells are drilled at adjacent locations until the entire treatment zone is fractured. Hydraulic fracturing can also be accomplished in open bore bedrock wells using a straddle packer configuration. The vertical interval between fractures typically varies from 0.9 to 1.5 m (3 to 5 ft). Fracture propagation proceeds at a modest rate (0.1± m/sec), and a single injection normally takes 10 to 30 minutes. Standard equipment for hydraulic fracturing is available from the petroleum and water well industries, although the available equipment tends to be large and expensive. Therefore, scaled-down versions have been developed for site remediation.

Another variant of hydraulic fracturing involves creation of oriented vertical fractures that have been used to form permeable reactive barriers (PRBs). A series of wells are drilled at intervals along a line and hydraulic injections are made sequentially so that the vertical fractures overlap to form the barrier.

Hydraulic fracturing of bedrock formations is performed either with plain water or with propping agents such as sand or ceramic beads. In soil formations, proppants are almost always used with hydraulic fracturing. To keep the proppant suspended, special mixers and agitators are used along with a thickening agent, usually guar gum gel. The gel contains an enzyme that is designed to break down the gel to a fluid viscosity similar to water within 12 to 24 hours after injection. This facilitates flushing of the guar gum after the fracture is formed to assure its permeability. Liquid or granular supplements can be injected into the formation along with the pressurized fracturing fluid to complement various *in situ* remediation processes.

For site remediation, hydraulic fracturing has been be applied in the vadose, saturated, and perched hydrogeologic zones. For permeability enhancement, the technique has been effectively applied in cohesive soils such as clays, interbedded silt and clay, and saprolite. In the petroleum and water well industries, hydraulic fracturing is also used effectively in bedrock. A few applications of hydraulic fracturing in sedimentary rock have been reported for site remediation.

2.3.3 Blast Fracturing

Blast fracturing is performed by placing high explosives in open bedrock boreholes, and then detonating the explosives to create subsurface fractures (Figure 3). Standard drill and blast practice is used, including delayed firing and linear blasthole alignments (typically single or double line). Blastholes are drilled through the soil overburden and into the underlying bedrock. Blasthole spacing depends on the particular formation being treated, but typically ranges from 0.9 to 1.5 m (3 to 5 ft). Relatively large rock volumes are fractured during a single detonation. Water gel explosives are typically used since they are water-resistant.

Blast fracturing is used principally to enhance the permeability of the geologic formations. The technology is applied by creating a blasted-bedrock zone (BBZ) or a blasted-bedrock trench of fractured rock that is positioned transverse to movement of a

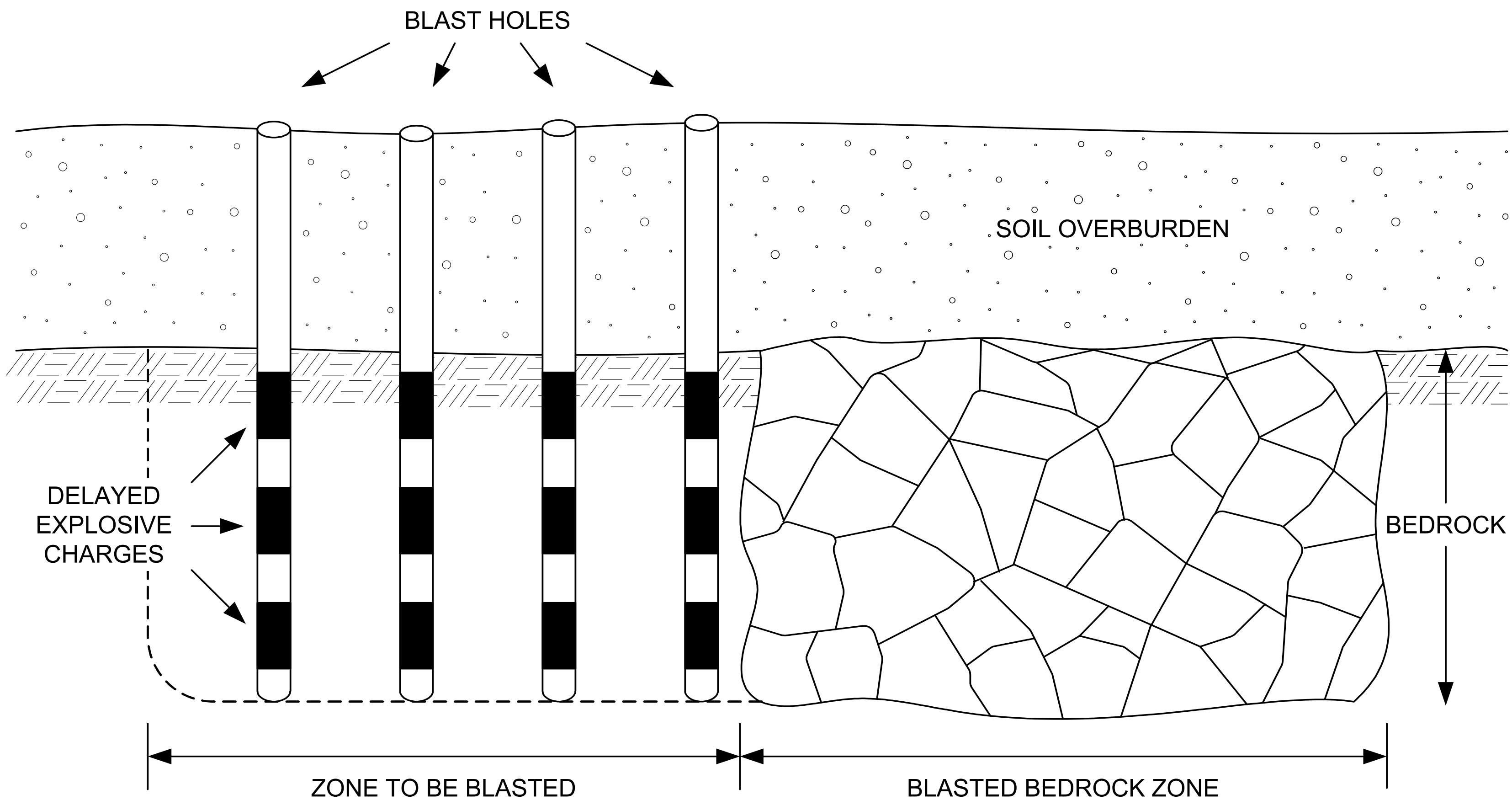

Figure 3. Method of Blast Fracturing

contaminant plume. Either linear or radial configurations are used depending on site requirements. Plume capture, control, and treatment is accomplished by installing pumping wells within the trench. Following creation of the fractured zone, liquid supplements to can be introduced to further enhance remediation. Emplacement of granular supplements such as iron powder into blast fractured zones is currently under study.

Blast fracturing relies on self-propping of the geologic formation in a manner similar to many pneumatic fracturing applications. The basis for self-propping is the Cubic Law, which demonstrates that fluid flows through open fractures can be substantial. See Section 2.3.1, "Pneumatic Fracturing," above for more discussion of self-propping.

For site remediation, all reported cases of blast fracturing have been applied to bedrock formations, especially hard rock such as crystalline granite and gneiss and competent sandstone and dolomite. Blast fracturing has most commonly been applied in the saturated zone, although vadose zone and perched zones can also be treated.

3.0 BENEFITS AND RESTRICTIONS OF FRACTURING TECHNOLOGIES FOR SITE REMEDIATION

3.1 BENEFITS OF FRACTURING TECHNOLOGIES

The fracturing technologies can benefit the remediation of contaminated soil and groundwater in several different ways. The principal benefits include:

- Increase in Effective Hydraulic/Pneumatic Conductivity of the Formation;
- Reduction of Formation Heterogeneities;
- Delivering of Liquid or Granular Supplements; and
- Use as a Retrofit Technique.

Each of these benefits is briefly described below.

1. Increase in Effective Hydraulic/Pneumatic Conductivity of the Formation. A principal use of fracturing is to increase the effective hydraulic and pneumatic conductivity of a geologic formation. To fully appreciate this beneficial mechanism of fracturing, a brief review of flow and transport concepts in geologic media is helpful. Fluid flow through soil and rock is most often modeled using Darcy's law, which assumes a uniform porous medium consisting of solid particles separated by interstitial voids or pore spaces (e.g., Freeze and Cherry, 1970). According to Darcy's law, the rate of fluid movement is directly proportional to formation hydraulic conductivity. Hydraulic conductivity, in turn, depends on the size and interconnectivity of the pore spaces. Coarse-grained soils have large, well-connected pore spaces, and thus they exhibit high fluid conductivity. In contrast, pore spaces in fine-textured soil such as silt and clay are much smaller, which greatly increases fluid friction and imparts much lower fluid conductivity. The small dimension of the pore spaces in fine-textured soils also facilitates inter-molecular attraction between the fluid and the particle, which retards fluid movement even further.

When a contaminant species is added to a ground-water flow regime, transport of the species will generally follow Darcy's Law if the soil is coarse-grained and the pore spaces are large. This is referred to as advective transport. However, in fine-grained soils the rate of Darcian advection is so low that, instead, diffusive transport begins to dominate (e.g., Domenico and Schwartz, 1990). Diffusive transport is modeled using Fick's Law of diffusion, which describes contaminant movement according to concentration gradients, i.e., from areas of higher concentration to areas of lower concentration. This is known as "diffusion-controlled" behavior, and it dominates the transport of contaminants in fine-textured soils, as well as in tight bedrock formations that do not contain many native fractures. As a consequence, when conventional remediation methods such as vapor extraction or product recovery are applied to low permeability formations, cleanups typically proceed at extremely slow rates.

An essential goal of all three fracturing techniques is to reduce the amount of diffusion-controlled behavior in the remediation process. This is accomplished by introducing a network of artificial fractures into the geologic formation that increases the overall hydraulic and pneumatic conductivity of the formation. This, in turn, allows a larger proportion of transport to occur by advection, which improves the process rate of the particular remediation technology that is being enhanced. The increase in formation conductivity caused by fracturing will vary according to formation type and the particular fracturing process and design that is used. Observed conductivity increases in artificially fractured formations have ranged from 50% to more than two orders of magnitude.

It is recognized that the increase in formation permeability or conductivity due to fracturing is an "effective" change rather than an intrinsic change. This is because a fractured formation will contain a network of highly conductive fractures interspersed with unfractured matrix blocks of soil or rock that are not initially affected. Nevertheless, fracturing shortens the diffusive pathways considerably, and access to contaminants is improved. The end result is that the coupled treatment technology can proceed more efficiently.

The most direct beneficial effect of fracturing on geologic formations is improved performance of installed wells, which is manifested by increased pumping rates (as measured by the specific capacity, for example). Fracturing also extends the radius of influence of wells. For example, wells installed in low permeability formations for recovery of vapors and liquids typically exhibit small lateral influences with a cone of depression that often measures 2 m (6.5 ft) or less. Fracturing normally extends the influence radius by at least several times. This results in a larger zone of capture for each individual well, so fewer wells are required to accomplish the remediation.

2. <u>Reduction of Formation Heterogeneities</u>. Essentially all natural geologic formations are heterogeneous to some degree. Heterogeneity is usually a consequence of formative geologic processes, as in a layered sequence of river sediments that exhibit various soil grain sizes. Heterogeneity may also result from post-depositional phenomena such as weathering, compaction or tectonic movements. Regardless of its origin, heterogeneity can lead to non-uniform cleanup and unsatisfactory results in remediation projects. Consider, for example, a vapor extraction site underlain by a sequence of sand and clay layers. Stripping of volatile organic compounds (VOCs) from the sand can be accomplished rather rapidly, while the clay will retain most of its contamination owing to diffusion-controlled behavior. In this situation fracturing has the potential to open the clay layer to vapor circulation and subsequent stripping of VOCs. Pressure gradients throughout the formation become more uniform after fracturing, and preferential air movement through the sand can be reduced. The end result is the geologic formation behaves more homogeneously and operational control of the remediation is improved.

Contaminated geologic formations containing native fractures are sometimes viewed as difficult to remediate, so the question can arise: how can artificial fracturing enhance contaminant removal? The answer is that native fractures are typically random causing preferential flow paths through the formation, which tends to isolate pockets of contamination. Artificial fractures, on the other hand, are beneficial since they are created in controlled patterns and densities, thereby providing access to contaminant pockets. All three fracturing technologies seek to establish more uniform flow and transport conditions within the formation, which ultimately accelerates remediation.

3. Delivering Liquid, Granular or Gaseous Supplements. The fracturing technologies are capable of delivering liquid, granular or gaseous supplements into the geologic formation to facilitate treatment of the contaminant. When using pneumatic or hydraulic fracturing, the supplements can be injected either during the fracturing event or after the fractures have been created. With blast fracturing the supplements must be introduced after creation of the blasted bedrock zone. A wide variety of liquid or granular media can be introduced for a number of different purposes. Use of fracturing to inject supplemental media is therefore not limited to low permeability geologic formations, since permeable formations such as coarse-grained sand and gravel or highly fractured bedrock can also benefit. In these applications, fracturing principally serves as a highly efficient delivery system. Additional discussion of the use of fracturing to deliver liquid and granular supplements is presented in Section 4.3 below.

Fracturing is capable of introducing selected gases into a geologic formation in addition to delivering liquid or granular supplements. With pneumatic fracturing gases can be delivered either during fracturing or by injecting into wells that have been stimulated by pneumatic fractures. It is possible to deliver gas in the form of foam during hydraulic fracturing, but the more common approach is to inject gas into wells after the fact. Establishment of a specific gaseous atmosphere may be useful in certain site remediation applications, such as providing oxygen to enhance aerobic bioremediation or nitrogen to assist anaerobic bioremediation.

4. Use as a Retrofit Technique. Another potential benefit of fracturing is it may be retrofitted to sites that are already under active remediation. A large number of remediation systems installed over the last decade have not “measured up” to the expected performance level of the original design. In some cases, fracturing can be used as a retrofit technique to enhance recovery rates or treatment rates. How fracturing is best employed at these sites will depend upon the configuration of the original remediation system, as well as the geology of the site. One approach is to install new fracture wells between the existing array of treatment wells. At some sites it is possible to perform pneumatic or hydraulic fracturing directly inside existing wells to enhance recovery rates. Wells are candidates for retrofit fracturing if they are constructed in open bedrock or if they contain screens that have been pressed in or grouted directly into the formation. Normally, fracturing is not feasible in wells constructed with gravel packs, since the fracturing fluid short circuits through the pack.

3.2 RESTRICTIONS OF FRACTURING TECHNOLOGIES

In the decade of experience in applying fracturing technologies to site remediation, some restrictions have become apparent. These include:

- Localized Contaminant Mobility; and
- Effect on Overlying Structures and Utilities.

Each of these restrictions is briefly described below.

1. Localized Contaminant Mobility. A principal benefit of fracturing is that it increases transport rate in a geologic formation, thereby allowing a contaminant to be treated or extracted more efficiently. Thus, within the fracture-enhanced zone the contaminant is mobilized locally. Since fracturing is typically applied in a low permeability geology, there is little risk of contaminant spreading since the enhanced zone is surrounded by low permeability materials. However, if a preferential pathway such as a sewer line traverses the site, it is possible that the contaminant could migrate along the pathway.

In all fracturing projects it is advisable to proceed with the primary integrated technology in a timely manner. Proper hydraulic and/or pneumatic controls along with contaminant collection and/or treatment systems should be installed and operational prior to fracturing, or alternatively, should be installed immediately following the fracturing activity. This practice will ensure that the increased contaminant mobility due to fracturing is used to remediate the site, and it should avoid unwanted migration. It is extremely important to employ consultants and fracturing vendors who have specific experience with hazardous site applications of fracturing techniques. The bottom line is that fracturing increases formation permeability in most applications, and it is essential to use this contaminant mobility to advantage.

2. Effect on Overlying Structures and Utilities. Since subsurface fracturing deforms the soil or rock surrounding the fracture, it has the potential to cause vertical movement or heaving at the ground surface. Therefore, the effects of fracturing on overlying active structures and utilities must be carefully evaluated. The amount of ground surface movement is related to a number of factors including the type of fracturing, depth of injection, number of fractures, and the geologic characteristics of the formation under treatment. Recent experiences have shown that fracturing in the vicinity of active structures and utilities is normally feasible as long as sound geotechnical design practices are followed. Additional discussion of the effects of subsurface fracturing on overlying structures and utilities is presented in Section 4.4 below.

4.0 TECHNOLOGY APPLICATION

4.1 EVALUATING SITES FOR FRACTURING: GEOTECHNICAL FACTORS

In evaluating potential sites for fracturing applications, it is important to consider a number of factors. These may be broadly characterized as geotechnical and chemical factors. This section discusses the geotechnical factors affecting or influencing fracturing projects. The chemical factors, which are more related to the particular remediation technology that is being coupled with fracturing, will be discussed in the next section.

Probably the most important geotechnical factor is the type of soil or rock that is to be fractured, although other factors must also be considered. Sielski (1999) presents a hierarchical order of geotechnical factors that are used to evaluate projects for pneumatic fracturing (see Figure 4). A similar hierarchy also applies to hydraulic fracturing and explosive fracturing projects. The main geotechnical factors for fracturing in soil formations (in hierarchical order) are formation type, depth, plasticity, relative density/consistency, secondary structure, and water table position. In rock formations the main factors are formation type, depth, fracture frequency/weathering characteristics, and water table position. The influence of each of these geotechnical factors on fracture behavior will now be briefly discussed.

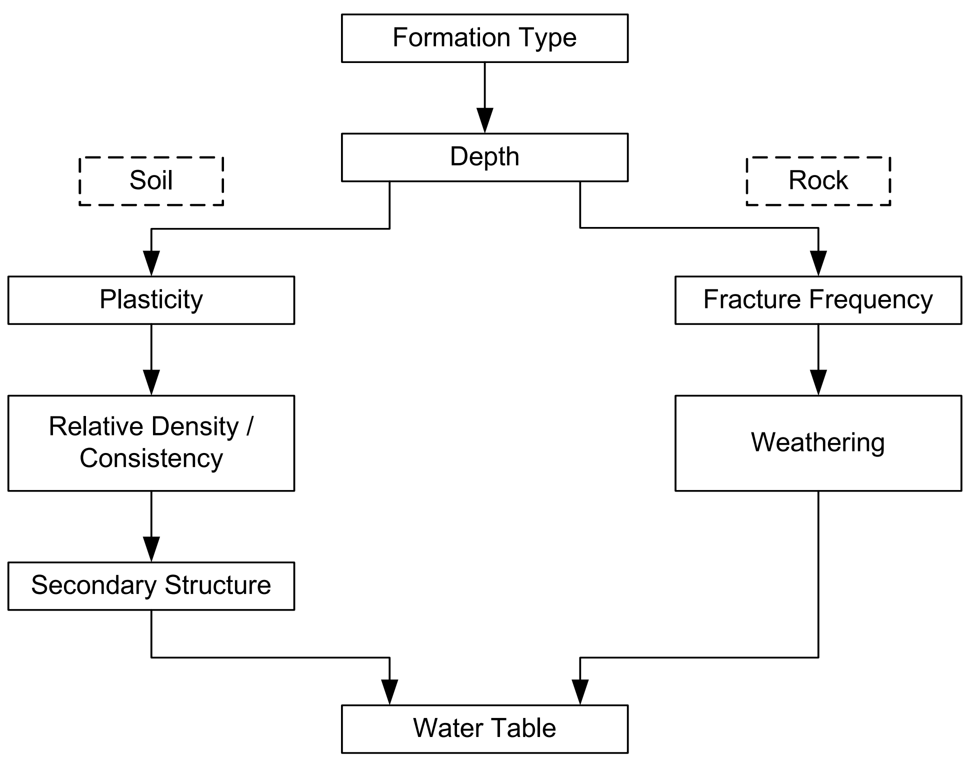

Figure 4. Hierarchy of Geotechnical Factors for Fracturing Projects
(after Sielski, 1999)

Formation Type. The type of geologic formation that will be fractured has a dominant influence on the results of the various fracturing technologies. Fine-grained soils such as silt and clay normally respond well to permeability enhancement by pneumatic fracturing or hydraulic fracturing. The permeability of tight bedrock formations can be increased by all three fracturing technologies. The initial pre-fracture permeability of the formation appears to play a significant role in the amount of permeability enhancement that may be expected from fracturing. The lower the initial permeability of the formation, the greater the expected increase in formation permeability. Conversely, if the initial permeability is higher, the observed improvement will be less. In this respect, there appears to be an upper limiting permeability that cannot be exceeded by fracturing. When using fracturing to deliver liquid or solid supplemental media (pneumatic or hydraulic only), a wider variety of formation types are treatable including sands, gravels, and highly fractured bedrock, and the upper limit concept does not apply.

It is important to thoroughly evaluate the geotechnical characteristics of the formation during the design phase of a fracturing project. Exploratory borings in the proposed treatment zone with continuous sampling or coring are always recommended. The borings are normally supplemented with geotechnical tests performed on collected samples of the geologic material to be fractured. The following geotechnical field and laboratory tests are used to evaluate soil and rock formations for fracturing projects:

<u>Soil Formations:</u>

- Detailed visual examination to assess structure including stratification, friability, secondary structure, and inclusions
- Grain size analysis
- Evaluation of consistency if cohesive, or relative density if cohesionless
- Natural moisture content
- Plasticity testing, including Atterberg limits
- Location of water table and perched water zones
- *In situ* permeability testing, e.g., slug, vapor extraction, pumping

<u>Rock Formations:</u>

- Detailed visual examination to assess lithology, joint frequency and orientation, degree of weathering, joint filling, and natural bedding
- Computation of recovery ratios and Rock Quality Designation (RQD)
- Strength testing (in some cases)
- Location of water table and perched water zones
- *In situ* permeability testing, e.g., slug, vapor extraction, pumping

If the geotechnical evaluation indicates that fracturing is applicable for a site, a pilot test is normally recommended to establish actual fracture behavior in the formation.

Depth. There is no theoretical maximum depth limit for initiating a fracture in a geologic formation as long as sufficient pressure and flow can be delivered to the fracture zone. In hydraulic fracturing the rule of thumb for estimating the injection pressure required to "lift the overburden" is 1 psi per foot of depth (7 kN/m^2 per 0.3 m of depth). In pneumatic fracturing the injection pressure required to lift the formation is typically two to three times higher on account of gas compressibility effects in the system. Both technologies require additional pressure to initiate a fracture, overcome the cohesive strength of the formation, and offset viscous friction losses in the equipment, delivery lines, and geologic formation. In blast fracturing satisfactory fractures are usually generated by loading about one pound of explosive per linear foot of blasthole.

To date, the target depths of most pneumatic and hydraulic fracturing projects have ranged from 3 to 15 m (10 to 50 ft). Blast fracturing has most often been applied at depths ranging from 6 to 20 m (20 to 65 ft). The deepest reported applications of pneumatic, hydraulic, and blast fracturing for site remediation purposes have been 13.7 m (45 ft), 22.9 m (75 ft), and 21.3 m (70 ft), respectively, and future applications are expected to extend to even deeper depths. For fracturing applications below a depth of around 25 to 30 m (80 to 100 ft), it may be advisable to use proppants since elevated overburden pressures can inhibit self-propping. The ability of a formation to self-prop depends both on the depth and the strength of the geologic material.

The minimum depth of fracturing is controlled by the ability to form a top seal during injection because there is a tendency for fractures to intersect or vent to the ground surface (known as "daylighting"). Whether shallow fractures will vent is usually related to the compaction history of the formation. For example, if the formation is dense and stratified, fracture injections as shallow as 1 m (3.3 ft) might be successful. However, in fill materials and loose natural soils, fractures tend to incline upwardly, even at deeper depths. The likelihood of surface venting reduces below a fracturing depth of about 3± m (10± ft). The shallowest reported applications of pneumatic, hydraulic, and blast fracturing for site remediation have been 0.9 m (3 ft), 1.2 m (4 ft), and 1.8 m (6 ft), respectively.

Plasticity. Plasticity is a measure of the cohesion of a soil, i.e., the tendency of the soil particles to stick to one another. A highly plastic soil will deform without cracking and retain its deformed shape, for example. Soil plasticity is attributable to the presence of clay minerals, and the degree of plasticity depends on the proportion and kind of clay minerals present. As a rule of thumb, if the percentage of clay in a mixed soil exceeds 30%, then clay will dominate its overall behavior. Soils that are rich in the clay mineral montmorillinite exhibit the highest plasticity, while the clay minerals illite and kaolinite impart medium and low plasticity, respectively.

Plastic soils are moisture sensitive with regard to their physical properties. For example, the strength of a plastic soil decreases with increasing moisture content. Also, a plastic soil will exhibit volume change in response to changes in moisture content: they shrink upon moisture loss and swell upon moisture gain. Soil plasticity is measured in the laboratory using the Atterberg Limits Tests (ASTM D4318-93), which involves varying the moisture content over a range and observing the behavior of the soil as it passes through semiliquid, plastic, semisolid, and solid states.

Plastic soils at low moisture contents usually respond well to fracturing since they behave in a brittle manner. As the moisture content of a plastic soil increases, fractures can still be propagated successfully. In projects involving a plastic soil with large shrink and swell potential, proppants may be appropriate to maintain a more consistent fracture aperture over time. Since many applications of fracturing rely on "self-propping" of the geologic formation, an important question is how do self-propped fractures behave in clay? Investigations have demonstrated that once a fracture is created in clay, it is permanent and does not heal upon swelling (e.g., Braunack et al., 1979; Hall, 2001). Rather, the fracture constricts temporarily and recovers when the moisture content drops due to natural conditions or operational controls. The investigations also demonstrated that the permeability of a fractured clay in a swelled state is higher than an unfractured clay in a swelled state. Swelling soils may actually be advantageous in some applications, since upon dessication shrinkage cracks will form that can substantially reduce diffusive distances. The final decision of whether to use proppants and/or moisture control in plastic soils will depend on the specific objectives of the project.

Relative Density/Consistency. Relative density is a term used to describe the firmness of cohesionless soils, e.g., sand. Consistency is an analogous term that is applied to cohesive soils, e.g., clay. The best method to determine relative density/consistency is through the use of the Standard Penetration Test or SPT (ASTM D1586-84), which consists of driving a split spoon sampler into the ground with a 63.5 kg (140 lb) hammer freely falling from a height of 750 mm (30 in). The blows on the sampler are recorded at 150 mm (6 in) intervals for a total penetration of 450 mm (18 in). The sum of the blows required to drive the spoon from 150 to 300 mm (6 to 18 in) is known as the standard penetration resistance, or N-value. The standard descriptors for soil consistency and relative density are summarized in Table 2, which also provides correlations with SPT and soil strength.

Table 2. Guide to Consistency and Relative Density of Soil
(after Peck et al. (1974) and U.S. Navy (1981)

Consistency – Clays			
Consistency	**SPT N-Value -**Blows/300 mm (Blows/ft)	**Field Identification Guide**	**Est. Unconfined Compressive Strength -** kN/m^2 ($tons/ft^2$)
Very soft	<2	Extruded between fingers when squeezed	Less than 24 (0.25)
Soft	2-4	Molded by slight finger pressure	24-48 (0.25-0.5)
Medium	4-8	Molded by strong finger pressure	48-96 (0.5-1.0)
Stiff	8-15	Readily indented by thumb, but penetrated only with great effort	96-192 (1.0-2.0)
Very stiff	15-30	Readily indented by thumbnail	192-384 (2.0-4.0)
Hard	>30	Indented with difficulty by thumbnail	Over 384 (4.0)

Relative Density – Sands		
Relative Density	**SPT N-Value -** Blows/300 mm (Blows/ft)	**Est. Angle of Internal Friction –** degrees
Very loose	0-4	Less than 28
Loose	4-10	28-30
Medium	10-30	30-36
Dense	30-50	36-41
Very dense	>50	41-44

Relative density and consistency are useful geotechnical indicators in designing fracturing projects since they can be correlated with two mechanical characteristics of a geologic formation: elastic modulus and state of geostatic stress. The influence of each of these characteristics on propagation of induced fractures will now be discussed.

Soils with low relative density/consistency that are loose or soft will have low elastic modulus. Such soils will tend to exhibit localized surface deformation around the injection point and modest propagation radii. Conversely, dense or hard formations are stiffer (high elastic modulus) and will typically exhibit less surface deformation but larger influence radii.

Relative density/consistency can also be an indicator of the state of geostatic stress within a soil formation. This is important since it is well known in the hydraulic fracturing industry that fractures tend to propagate perpendicular to the direction of the least principal geostatic stress (Hubbert and Willis, 1957). Geologic formations that are dense or hard tend to be "overconsolidated," which is a geotechnical engineering term meaning that the formation was formerly subjected to greater overburden stress than at present (an analogous condition in geology is thrust faulting). Overconsolidation is typically caused by overburden stress relief, but it may also result from desiccation or tectonic forces. In overconsolidated soil formations the least principal stress is vertical, so artificially induced fractures will tend to propagate in a horizontal plane. Conversely, soils with a loose density or soft consistency are typically "normally consolidated" or "underconsolidated," so fracture propagation tends towards the vertical.

Secondary Structure. Another factor that can influence the propagation and orientation of fractures in soil formations is secondary structure. Secondary structural features include planes of stratification, native fractures, relict bedding/foliation (saprolite), and root channels. Past anthropogenic disturbances caused by fill placement, previous excavations, abandoned boreholes, and buried structures can also impart secondary structure to a geologic formation. In some instances secondary structure will dominate the orientation and radius of induced artificial fractures, since the fractures may propagate along or be short-circuited by the secondary features.

Fracture Frequency/Weathering Characteristics. Fractures occur naturally in rock formations and originate from thermal and tectonic stresses, as well as unloading of overburden materials. Various types of fracture discontinuities may be encountered including cracks, joints, faults, and shear zones. In general, rock formations of the same lithology develop a somewhat similar fracture geometry. For example, basalt commonly exhibits vertical columnar joints, while shale exhibits horizontal bedding joints. In sedimentary rocks jointing patterns are normally related to the geologic strike and dip of the formation.

Blast fracturing is used to create new artificial fractures in bedrock formations. The pressures used for either pneumatic or hydraulic fracturing in site remediation are normally not sufficient to break intact rock, so these technologies are more dependent on existing fracture geometry. Thus, a principal effect of pneumatic and hydraulic fracturing is to dilate existing fractures, although pressures are high enough to extend existing fractures and create some new fracture surfaces. Dilation and extension of existing fractures is usually sufficient in remediation projects, since contaminants have typically concentrated within and adjacent to the existing fracture network.

Rock formations that are unweathered to slightly weathered will exhibit high strength and behave in a brittle manner. However, rock formations that are highly weathered will respond to fracturing like soil formations, and should be treated as such. Moderately weathered rock formations will exhibit behavior that is intermediate between the latter two conditions.

Water Table Configuration. Fracturing has been performed successfully in the vadose, perched and saturated ground-water zones. In general, the ability to fracture a geologic formation is not significantly affected by the location of the water table. For example, in pneumatic fracturing the increased unit weight of the saturated overburden will tend to decrease fracture radius. Conversely, saturation tends to reduce gas leakoff and improve pressure sealing, which increases fracture radius. The net result is that water table configuration has little effect on fracture propagation. Mostly, the water table affects the post-fracture behavior of the formation, and it may also affect how the fractured formation responds to a particular remediation technology. For example, if fracturing is being coupled with soil vapor extraction in a clay soil, high moisture content due to perched water could retard post-fracture airflows in the formation. However, if the same clay soil is fractured below the water table and the goal is to extract groundwater, saturation may only have a minimal effect. Fracture injection below the water table, however, will limit the ability to inject liquids and gases into geologic formations, since there is less available pore space for the introduced fluids.

4.2 INTEGRATING OTHER TECHNOLOGIES WITH FRACTURING

A wide variety of chemical contaminants are treatable with fracturing because the fracturing technologies are normally integrated with another primary technology. Thus, the contaminants that are treatable will depend on the target contaminants of the complementary technology. Table 3 lists twelve different *in situ* and ex situ technologies that either have been coupled with fracturing or can potentially be coupled with fracturing.

Case studies of technology integration with fracturing have been compiled by the Ground-Water Remediation Technologies Analysis Center (GWRTAC) and are summarized in their "S" Series Report TS-00-01, "Technology Status Report Hydraulic, Pneumatic, and Blast-Enhanced Fracturing" (Roote, 2000). The report contains project summaries for 86 pneumatic, hydraulic, and blast fracturing projects performed at the pilot- and full-scale. The report also provides an analysis of trends including integrated technologies, contaminant classes, site geology, and fracturing results. This "S" Series report can be downloaded in PDF format from the GWRTAC website at http://www.gwrtac.org.

Table 3. Technologies That Have Been Integrated with Fracturing

Legend: Y = Reported as field demonstrated, at least at a pilot-scale.
P = Not yet reported as field demonstrated, although should be feasible.
N = Not feasible.

Coupled Technology	Principal Contaminants Treated	Demonstrated with Pneumatic Fracturing	Demonstrated with Hydraulic Fracturing	Demonstrated with Blast Fracturing
Soil Vapor Extraction (SVE)	VOCs	Y	Y	P
Dual Phase Extraction (DPE)	VOCs	Y	Y	Y
Pump and Treat	Dissolved Phase Contaminants	Y	Y	Y
Product Recovery	LNAPLS	Y	Y	Y
Bioremediation	Various Organic Compounds	Y	Y	P
Permeable Reactive Walls or Zones	Various Organics	Y	Y	P
Chemical Reduction/ Oxidation	Various Organics and Inorganics	Y	Y	P
Air Sparging	VOCs	Y	Y	P
Electrokinetics	Various Organics and Inorganics	P	Y	N
In Situ Vitrification	Essentially any waste, including radioactive	Y	P	N
Thermal Treatment	VOCs, Semi-volatiles and Non-volatiles	Y	Y	N
Surfactant Flushing	Various Organics and Inorganics	P	P	N

The GWRTAC database (Roote, 2000) shows that pneumatic fracturing and hydraulic fracturing have most frequently been integrated with Soil Vapor Extraction (SVE) and Dual Phase Extraction (DPE). The most common technology integrated with blast fracturing has been pump and treat, which is also the next most common technology integrated with pneumatic and hydraulic fracturing. A number of projects coupling *in situ* bioremediation with either pneumatic or hydraulic fracturing have also been reported. Other technologies that have been integrated with fracturing include product recovery, air sparging, permeable reactive walls and zones, *in situ* chemical reduction/oxidation, *in situ* vitrification, and thermal enhancements. Additional information on the distribution of technologies that have been integrated with fracturing processes is shown in Table 7, Section 7.0, "Case Studies".

According to the GWRTAC database (Roote, 2000), the most common contaminant classes treated by fracturing are chlorinated solvents and petroleum hydrocarbons. The high frequency of fracturing with these contaminants is attributed to their widespread occurrence as well as the extensive use of fracturing to enhance SVE or DPE, rather than any special applicability. Other contaminant classes that have been treated by fracturing include unspecified organics, inorganic metals and radioactive waste. Additional information on the distribution of contaminant classes that have been treated with fracturing processes is shown in Table 7, Section 7.0, "Case Studies".

4.3 DELIVERY OF SUPPLEMENTAL MEDIA WITH FRACTURING

The use of fracturing at contaminated sites is not limited to permeability enhancement. The fracturing technologies can also function as delivery systems that introduce various kinds of treatment media, either liquid, granular, or gaseous, directly into the geologic formation. This is sometimes referred to as "engineered delivery," and it allows much better control of the spatial distribution of the media than just dumping it down a borehole. Thus, fracturing can be applied in a wide variety of geologic conditions, including formations that are already permeable such as sand and gravel or highly fractured bedrock. The following supplemental media have been injected with fracturing technologies:

- liquid nutrient and buffering solutions to enhance bioremediation;
- liquid or solid inocula to enhance bioremediation;
- chemically reactive solid media such as iron powder;
- electrically conductive solid media such as graphite to enhance *in situ* electrokinetics or *in situ* vitrification;
- liquid or solid oxygen-generating chemicals; and
- solid propping media to extend fracture longevity
- gases such as nitrogen and oxygen

When using pneumatic or hydraulic fracturing, supplemental media can either be introduced during the fracturing event or after the fractures have been created. Liquid supplements are the easiest to inject. With hydraulic fracturing, they can be mixed with the fracturing fluid (usually water or gel). With pneumatic fracturing, liquids are typically introduced into the gas stream to create varying liquid/gas ratios. At lower ratios, the liquid becomes atomized in the gas stream, while at higher ratios, the fracturing fluid can best be described as a gas-energized liquid. Liquids can also be injected into wells intersecting either pneumatic or hydraulic fractures.

Solid media can also be delivered to the geologic formation using either pneumatic fracturing or hydraulic fracturing. Injection of solid media is more complicated, since the media tends to settle out of the fracturing fluid. In general, the higher the specific gravity of the solid particle, the more difficult it is to inject. With pneumatic fracturing, solid media suspension is accomplished by maintaining high fluid velocity and controlling the ratio of solids to gas. With hydraulic fracturing the injection velocities are lower, so a thickening agent such as guar gum is used to increase the viscosity of the fracturing fluid. After the hydraulic fracture has been formed, the guar gum is decomposed with an enzyme and can be removed by flushing with water.

Both pneumatic and hydraulic fracturing have been used to inject reactive media such as iron powder into geologic formations to form reactive zones or barriers. This technique is an alternative to the permeable reactive barrier (PRB) technology, which places reactive media into excavated trenches (Gillham, 1995). Advantages of delivering reactive media by fracture injection include unlimited depth of installation and reduction of site disturbance. The hydraulic fracturing variant typically involves creation of oriented vertical fractures to form permeable reactive walls measuring up to a few centimeters in thickness. With pneumatic fracturing, the reactive media is injected horizontally into the formation at closely spaced vertical intervals to form a dispersed treatment zone measuring several meters in width. Depending on the nature of the geologic formation, the pneumatically injected media may mix with the native formation or may form discrete horizontal lenses. Techniques for injecting reactive media with pneumatic and hydraulic fracturing are evolving rapidly and are currently receiving considerable interest in the remediation industry.

Supplemental media can also be delivered into the subsurface with blast fracturing, although they must be introduced after creation of the blasted bedrock zone. As with the other fracturing technologies, liquid supplements are the easiest to distribute. The emplacement of granular supplements such as iron powder into blast fractured zones is currently under study.

4.4 EFFECT OF FRACTURING ON STRUCTURES AND UTILITIES

Since subsurface fracturing may cause vertical heaving of the ground surface, the effect on nearby active structures and utilities must be evaluated. The magnitude of ground surface movement is related to a number of factors including the type of fracturing, depth of injection, number of fractures at that location, and geologic characteristics of the formation under treatment. Depth is probably the most important factor. Experience has shown that significant surface heave, usually in the range of 1 to 3 cm (0.4 to 1.2 in), may be expected for shallow fracture injections of approximately 3 m (10 ft) depth or less. In contrast, little or no surface effect is normally observed for deeper fracture injections (approximately > 6 m (20 ft)). As might be expected, permanent surface heaves will be larger when injecting proppants or other solid media.

Ground deformation caused by the propagation of subsurface fractures has been most often modeled as an elastic plate in bending, (e.g., Perkins and Kern, 1961; Pollard and Johnson, 1973). Canino (1997) has developed an elastic deformation model to predict ground surface movements for pneumatic fracturing applications that was validated with field data from more than 40 different sites. Site geology was found to play an important role in the shape of the ground surface deformation. In general, soil formations that are soft or loose will deform more locally around the point of injection (see Table 2 for explanation of consistency/density descriptors of soil). In contrast, rock formations, as well as stiff and dense soil formations, tend to exhibit lesser amounts of surface heave around the point of injection. However, owing to their higher elastic modulus, heave influence in these formations generally extends to greater radii.

The materials and details of construction also play an important role in the ability of a building or utility line to sustain heaving movements. Most structures in good condition can tolerate a certain amount of differential movement. In fact, all structures experience a certain amount of seasonal movements due to normal moisture changes and thermal variations in the subsurface environment. The approach to fracturing in the vicinity of building and utilities is to keep ground deformations within the normal tolerable limits of building movement.

A suggested evaluation procedure for designing pneumatic fracturing projects in the vicinity of structures and utilities is presented in Table 4 that is extracted from Canino et al. (1998b). The evaluation procedure was developed using model analyses, as well as actual field experiences with pneumatic fracturing. The paper also presents criteria for allowable differential movements of various types of framing systems and materials, and it describes a highly instrumented field test of pneumatic fracturing conducted beneath a steel and masonry industrial building.

Essentially these same procedures are used when hydraulic fractures are created in the vicinity of sensitive structures.

Both pneumatic and hydraulic fracturing have been performed successfully in the vicinity of existing wells without causing damage, although fracture effectiveness may be reduced since the injected fluid can short-circuit through the well. In a few cases known to the author, existing wells have been damaged by nearby fracture injections, including annular breaching the grout seal and/or shifting the casing vertically. The potential of fracturing to affect existing wells will depend on the distance to the well, the robustness of well construction, and operational fracturing pressures. Consultants and vendors with specific experience in hazardous site applications of fracturing can best evaluate potential effects on existing wells.

When performing blast fracturing, the effect of transient blast-induced vibrations on the nearby buildings and utilities must also be evaluated. The depth of the fracturing and the distance to a potential receptor are important in explosive fracturing applications since vibratory effects diminish exponentially with distance in a geologic medium. The effect of blasting on nearby structures has been studied extensively for rock excavation in urban construction and mining, so guidelines are available for design (e.g., Dowding, 1985; Konon and Schuring, 1985). Reduced explosive charges can be specified to reduce effects on nearby structures and utilities. Vibration effects may limit the application of blast fracturing in close proximity to sensitive structures.

Table 4. Suggested Procedures for Designing Pneumatic Fracturing Projects in the Vicinity of Structures and Utilities
(modified from Canino et al., 1998b)

STEP 1 – Investigate the Facility Function: Define the function of the facility, and determine how critical are its operations. Of special interest are industrial processes with hazardous materials and sensitive machinery, which cannot tolerate movement.
STEP 2 – Review As-Built Information (including utilities): As-built drawings and other information should be consulted to establish the dimensions and composition of the structure and utilities. If as-builts are not available, exploratory test pits and cores may be necessary to determine actual dimensions of foundations and slabs. It is important to thoroughly investigate all utilities in the area, especially critical utilities such as natural gas, liquid fuels, and hazardous chemicals.
STEP 3 – Conduct and Document a Condition Survey: A walk-through of the facility should be conducted and the condition of the structure examined. Any existing cracks or other distress should be documented with photos, a video, or both. Strain telltales should be installed across selected joints and significant existing cracks.
STEP 4 – Establish Allowable Movement Criteria: Based upon information gathered in the previous steps, allowable movement criteria can be established using the values presented in Canino (1998b). This should be coordinated with the facility's structural engineer.
STEP 5 – Perform Fracture Injection Design: The most cost effective approach for minimizing potential effects of fracturing is to locate the injection wells a safe distance from footings and utilities. Design calculations should be performed to check the effect of heave on the structure using a suitable method (e.g., elastic plate-bending theory). Calculated heave values should be compared with allowable movement criteria, and fracture pressures and flow rates should be adjusted accordingly. If reliable soils data are not available, testing of recovered samples should be performed and evaluated by a geotechnical engineer.
STEP 6 - Pilot Test: If the results of the injection design analysis (i.e., Step 5) indicate that fracturing can be conducted safely, a field pilot test is recommended. The pilot test can be conducted outside the structure to assess the elastic properties of the geologic formation, or alternatively can be performed within the structure by gradually stepping up injection pressures and flow rates. Movement monitoring instrumentation (e.g., optical levels, tiltmeters, strain gages, and linear variable displacement transducers (LVDTs)) should be employed during the pilot test as appropriate.

4.5 FRACTURE MODELING

Modeling studies of fracturing processes can be broadly divided into two groups: fracture propagation and post-fracture response. Studies of fracture propagation focus on the actual fracture event with the goal of controlling and optimizing the fracturing process. Studies of post-fracture response deal with the behavior of the geologic formation after fracturing is completed, and they involve issues such as fluid flow and contaminant transport. A brief survey of pertinent fracture modeling studies follows.

Fracture Propagation. Because of its economic importance to the petroleum industry, investigators have studied propagation of hydraulic fractures in geologic formations for more than 50 years. A comprehensive summary of current hydraulic fracturing theory and practice in the petroleum industry is available in Gidley et al. (1989), and many of the classic hydraulic fracturing papers have been reprinted in Veatch et al. (1990). Information on water well stimulation by hydraulic fracturing is also available (e.g., Smith, 1989; Hurlburt, 1989). The application of hydraulic fracturing techniques to remediate hazardous waste sites commenced in the late 1980s (Murdoch, 1991), and a fracture propagation model for these applications has also been developed (Murdoch 1992b).

In the 1960s, the petroleum industry began using nitrogen and carbon dioxide gas at selected sites to energize hydraulic fracturing fluids and to avoid problems with water sensitive oil shales (Boren and Johnson, 1965; Black and Langsford, 1982). The application of gas or pneumatic fracturing to enhance contaminant removal at hazardous waste sites commenced in the late 1980s (Schuring et al., 1991; Schuring and Chan, 1992). Models for the initiation and propagation of pneumatic fractures were subsequently developed (King, 1993; Puppala, 1998). A computer model for analyzing geologic formations for pneumatic fracturing applications is also available (Sielski, 1999). The program, known as PF-MODEL, heuristically evaluates sites with regard to process applicability and then determines preliminary design parameters including predicted fracture radius. PF MODEL features a Windows based graphical user interface and includes a probabilistic knowledge base and extensive geotechnical defaults.

Essentially all propagation models for hydraulic fracturing and pneumatic fracturing are based on a solution of the continuity equation, i.e., the volume of the injected fluid is related to the volume of the generated subsurface fracture. For example, the numerical solution by Puppala (1998) couples three physical processes that determine the extent of fracture propagation. The first is pressure distribution in the fracture since the injected fluid loses energy due to frictional effects along the walls of the fracture. The second process is leakoff, which represents the fluid that leaks into the surrounding formation and is thus not available to propagate the main fracture. The third coupled process is the elastic deformation of overlying and underlying geologic materials, which must deform in order to propagate the fracture. The final radius of the fracture is determined when these three processes are balanced at a given fluid injection rate and for a specific set of formation properties.

In blast fracturing, fractures are propagated by large quantities of high-pressure gas released during detonation of the explosive material. In this respect the propagation mechanism of blast fracturing resembles pneumatic and hydraulic fracturing in that fractures are generated by a fluid. However, unlike the other fracturing processes, the driving pressures for blast fracturing exceed the strength of the geologic medium, and a high velocity shock or stress wave precedes the expanding gases that weakens the rock (Du Pont, 1980). Owing to the complexity of the explosive fracturing mechanism, analytical solutions are difficult, although a comprehensive numerical solution of gas-driven explosive fractures has been developed by Nilson (1981).

Post-fracture Response. After a geologic formation has been fractured, the ability to treat and/or remove contaminants *in situ* depends on the flow and transport characteristics of the fractured medium. Various aspects of post-fracture formation response have been modeled. One aspect is the flow characteristics of an open, self-propped fracture like that created by blast fracturing and many applications of pneumatic fracturing. Studies confirm that open fractures can efficiently transmit significant amounts of fluid on account of the Cubic Law, which states that the flow through an open fracture is proportional to the cube of the aperture (or thickness) of the fracture (e.g., Witherspoon et al., 1980; Nautiyal, 1994). The Cubic Law relationship emphasizes the high flow potential for even small fractures, and it explains why fractured bedrock can serve as an excellent aquifer. When propping agents are injected into a fracture, flow is governed by the first power of the aperture, i.e., Darcy's Law. However, since propped fractures typically have larger apertures than unpropped fractures, substantial flows are also transmitted.

A study by Hall (2001) examined the behavior of discrete fractures in clay soils when subjected to moisture fluctuations. An analytical model was developed relating moisture transfer rate, soil volume change, and associated changes in fracture aperture. The model was validated with laboratory tests and historic field data on expansive clay soils. The study showed that once a fracture is created in a plastic soil, it is permanent. Even if a fracture constricts temporarily due to swelling, the process is fully reversible and the fracture will recover as moisture is reduced due to natural conditions or operational controls. The investigation also demonstrated that the permeability of fractured clay in a swelled state is higher than an unfractured clay in a swelled state.

Another aspect of post-fracture response is the diffusion-controlled transport of contaminants within the formation. When a fracture network is created in a geologic formation, a "dual porosity" system (e.g., Barenblatt et al., 1960) is established so that flow and transport now occur both in the fractures and within the adjacent unfractured matrix blocks. In fine-grained soils, e.g., clay, silt, or bedrock, advection is the dominant transport mechanism in the fractures, while diffusion dominates in the matrix blocks. As long as fluid flow is maintained through the fracture network, diffusive gradients are established in the matrix blocks that will ultimately control the final cleanup of the formation. Predictive solutions based on the advection-diffusion mechanism have been developed for problems associated with nuclear waste disposal (Tang, 1981; Chen, 1986). More recently, Ding et al. (1999b) developed an analytical transport model for pneumatically fractured geologic formations and a procedure for determining related transport parameters such as retardation factors and diffusion coefficients (Ding et al., 1999c). The model can be used to predict contaminant removal rate and residual concentration in the treated formation.

4.6 REGULATORY ISSUES

The regulations and permitting requirements vary among of the three fracturing technologies. For pneumatic fracturing, no special permits are required since the gas injections are done in short bursts of 15 to 20 seconds. For hydraulic fracturing a permit may be required for the injection of the guar gum gel and enzyme. This requirement will vary with regulatory jurisdiction. When either pneumatic or hydraulic fracturing is used to deliver supplemental media into the geologic formation such as inocula, chemical reactants, or oxidizers, the regulations of the Underground Injection Control (UIC) program under the Federal Safe Drinking Water Act will apply. Responsibility for the UIC varies across the United States. Some states have been delegated complete or partial enforcement responsibility, while in other states the UIC program is administered by EPA Regional Offices.

Blast fracturing is regulated like any other commercial blasting operation, so permits are required in every jurisdiction. At some locations building code regulations may also apply with regard to vibration monitoring and protection of nearby structures and utilities. Engineering seismographs can be employed to measure vibration levels and help control blasting operations.

One concern that was expressed by some regulators during early applications of pneumatic and hydraulic fracturing was possible downward migration of the fractures. Geomechanical theory suggests that pneumatic and hydraulic fractures initiated at relatively shallow depths (<30 m (<100 ft)) will either continue horizontally or propagate upward towards the ground surface (e.g., Narendran and Cleary, 1983). Extensive *in situ* monitoring over the years has confirmed that this is the case. Blast fracturing creates stress waves that can conceivably cause downward propagation of a fracture. However, the majority of the blast effort is directed laterally and upwardly from the shot holes so propagation of downward fractures is unlikely. In order to avoid possible consequences, this can be handled in practice by leaving a buffer zone of unfractured rock beneath the blast trench.

5.0 TECHNOLOGY RESULTS

5.1 METHODS OF EVALUATION

The results of subsurface fracturing projects can be measured in a variety of ways. The more common methods of evaluation include:

- Change in effective permeability or conductivity of the formation;
- Change in the radius of well influence;
- Change in mass removal rate of the contaminant;
- Extent of fracture; and
- Production rate of fracturing and delivery rate of liquid or granular supplements.

Each of these evaluation methods will now be briefly discussed.

Change in effective permeability or conductivity of the formation. Probably the most common measure of fracturing effectiveness is increase in effective permeability or conductivity of the formation. During early applications of the fracturing technologies, rather elaborate field tests were run to measure permeability increases accurately, especially during sponsored research demonstrations. In recent years the use of elaborate permeability testing has declined somewhat due in part to the fact that such tests are expensive, and also since fracturing is now accepted as beneficial for many geologic formations. Comparative permeability tests now tend to be short term if they are run at all. A number of permeability test and data analysis methods have been used at fracturing sites, and results can vary according to the method selected. It is recognized that the observed increase in formation permeability or conductivity due to fracturing is an "effective" change rather than an intrinsic change. This is because a fractured formation contains a network of highly conductive fractures interspersed with unfractured matrix blocks of soil of lower permeability.

Another approach for evaluating the effectiveness of fracturing is to compare the specific capacity of a well before and after fracturing. Specific capacity is a method for estimating well productivity, and it is calculated by dividing the discharge rate by the observed drawdown. Specific capacity shows good correlation with formation permeability or conductivity and is somewhat simpler to evaluate.

Change in the radius of well influence. Since most fracturing applications are aimed at enhancing subsurface transport, a useful measure of fracture effectiveness is the observed change in radius of well influence. This is usually evaluated by applying a constant suction head or drawdown at selected wells prior to fracturing and recording the influence at outlying wells in order to establish a baseline. Following fracturing, the test is repeated to evaluate the change in influence at outlying wells. Substantial increases in radius of well influence are commonly associated with all three fracturing technologies.

Change in mass removal rate of the contaminant. When fracturing increases the permeability of a contaminated geologic formation, it follows that the mass removal rate of the contaminant should also increase. Many case studies of fracturing have confirmed such increases. However, the mass removal rate often increases at a lesser proportion than the permeability. This is attributed to two principal reasons. First, unfractured blocks of soil or rock will always remain between adjacent fracture levels, so contaminant extraction from these blocks is still diffusion-controlled. That is, fracturing does not eliminate diffusion, it just shortens the diffusive paths. A second reason for lower mass removal rates is depletion of contaminant source in near vicinity to the fracture network. This explains why initial mass concentrations in the effluent immediately following fracturing are usually high compared to baseline, but may taper off rather rapidly (in the petroleum industry with hydraulic fracturing this is known as "flush production"). Nevertheless, at fractured sites where long-term measurements have been made, mass removal rates typically remain elevated at least several times above baseline.

Extent of fracture. An approach for determining the extent of fracture is to measure the vertical heave of the ground surface. Devices that measure ground surface heave include optical levels, laser levels, electronic tiltmeters, and linear variable differential transducers (LVDT's) (Canino, 1998a). Surface effects of fracturing decline rather rapidly as the depth of fracturing increases on account of the ability of the overlying formation to absorb strain deformation. Fracturing applications involving injection of solid media or proppants will cause the largest permanent heave. Alternatively, it is possible to drill cores or probes around the fracturing well to delineate the extent of fracture, and on some "clean site" demonstrations fractures have actually been exposed by excavation. For projects involving the injection of iron powders, geophysical resistivity methods have been used to detect the extent of iron emplaced in the fractures (Hocking et al., 1998).

Production rate of fracturing and delivery rate of liquid or granular supplements. When pneumatic fracturing or hydraulic fracturing are used as a delivery system for liquid or solid media, other criteria are normally used to measure effectiveness. One important criterion is accuracy of distribution, i.e., does the media reach the targeted location? A second criterion is delivery rate, since this directly affects technology cost.

5.2 SUMMARY OF FRACTURING RESULTS

A review of the 86 case studies reported in Roote (2000) was undertaken to assess the general capabilities of the three fracturing technologies. The results of this review are summarized in Table 5, which gives the range and average of reported values for permeability/conductivity, mass removal rate, fracture radius, and radius of well influence. The data sources varied widely and included published papers, EPA summaries, and information furnished by vendors. Many of the case studies (38%) did not furnish any quantitative data in these evaluation categories, so they are not reflected in the table. For blast fracturing, only permeability/conductivity increases are shown since the other evaluation categories do not apply.

The overall similarity of results produced by the three fracturing techniques as shown in Table 5 is notable. All categories exhibit a wide range of quantitative results suggesting that applicability of a particular fracturing process is highly site dependent. A comparison of the computed averages for the three fracturing techniques indicates that performance in most categories falls within a relatively narrow range of ±20%. This confirms the writer's long held belief that there is an upper limit of effective permeability that any artificial fracturing process can achieve, and this hypothesis will be further investigated now that substantial performance data is available.

Since all three fracturing technologies can achieve similar end performance, the choice seems to depend on site specific factors such as geology, project objectives, presence of overlying structures, regional vendor availability, and cost. Clearly, the main determining factor for success of any fracturing application is properly matching the process design and layout with the geologic conditions at the site.

Some comments are offered for the data trends shown in Table 5. First, the evaluative test methods differed significantly among the reported fracturing projects. For example, hydraulic conductivity can be measured by several different methods, and results can vary according to the method selected. Therefore, all data presented in the Table 5 should be considered approximate. A second comment is that for a particular fracturing type, e.g., hydraulic, no attempt was made to separate individual vendors who may practice different variants, and all data for particular fracturing type have been lumped together. A third comment is that there is not always a clear distinction between fracture radius and radius of well influence. The former is the physical extent of the fracture propagation during injection, while the latter is the extent of detectable influence of the fracture, which typically exceeds the propagation radius. A final comment is that the evaluative testing for most projects was relatively short term having been conducted over a period not exceeding a few weeks in most cases. A very limited number of projects reported long term performance, probably on account of the expense involved and also since fracturing is generally accepted as beneficial.

The similarities and differences among the three fracturing technologies and their variants have been described throughout this report. A definitive comparison of the relative capabilities of the technologies is difficult since the three technologies have never been compared under controlled conditions at the same site to the writer's knowledge. Certainly, all three technologies have demonstrated that they are viable and beneficial for enhancing site remediation. In light of the findings of this report and the increasing use of fracturing for remediation, further research is warranted to more fully evaluate the relative merits of the various fracturing technologies.

Table 5.
Summary of Fracturing Results from Case Studies[1]

	Range of Reported Results	Average of Reported Results
Pneumatic Fracturing		
Increase in Permeability/Conductivity	1.5 to 175 times	28 times
Increase in Mass Removal Rate	3 to 25 times	10 times
Fracture Radius	1.4 to 10.7 m (4.5 to 35 ft)	4.9 m (16 ft)
Increase in Radius of Well Influence	1.4 to 30 times	8 times
Hydraulic Fracturing		
Increase in Permeability/Conductivity	5 to 153 times	34 times
Increase in Mass Removal Rate	5 to 10 times	8 times
Fracture Radius	1.0 to 7.6 m (3.3 to 25 ft)	4.9 m (16 ft)
Increase in Radius of Well Influence	1.3 to 9 times	5 times
Blast Fracturing		
Increase in Permeability/Conductivity	0.7 to 100 times	39 times

[1] Note: Data extracted from project summaries contained in "S" Series Report TS-00-01, "Technology Status Report Hydraulic, Pneumatic, and Blast-Enhanced Fracturing" by D. Roote, 2000.

6.0 TECHNOLOGY STATUS, COST, AND VENDORS

6.1 TECHNOLOGY STATUS

All three of the fracturing technologies, i.e., pneumatic fracturing, hydraulic fracturing, and blast fracturing, are commercially available for site remediation. There are differences, however, with respect to the *in situ* and ex situ technologies that have been integrated with each kind of fracturing. The commercial status of each is described below.

6.1.1 Pneumatic Fracturing

Commercially, pneumatic fracturing has been most extensively applied to enhance physical treatment processes including vapor extraction, dual phase extraction, product recovery, and pump and treat. Pneumatic fracturing has also been successfully coupled with aerobic bioremediation, including biostimulation and bioaugmentation (Fitzgerald and Schuring, 1992; Venkatraman et al., 1998; Walsh et al., 2000). Field installations of permeable reactive treatment zones containing iron powder have also taken place (Schnell et al., 1998; Schnell, 2001). Other technologies that have been coupled with pneumatic fracturing are chemical reduction/oxidation and thermal treatment. In addition, a field pilot demonstration that integrates pneumatic fracturing with *in situ* vitrification (ISV) has been completed (McGonigal, 1995). Experience with performing pneumatic fracturing in the vicinity of active structures and utilities is increasing rapidly.

6.1.2 Hydraulic Fracturing

Most commercial applications of hydraulic fracturing have involved enhancement of physical treatment processes, including vapor extraction, dual phase extraction, product recovery, and pump and treat. Hydraulic fracturing has also been successfully coupled with bioremediation (Davis-Hoover et al., 1992; Davis-Hoover et al., 1993). Hydraulic injection of iron powder to form permeable reaction walls has been applied at a commercial scale (Hocking, 1998; Siegrist et al., 1999). Chemical reduction/oxidation has also been coupled with hydraulic fracturing. A variant of hydraulic fracturing known as the "Lasagna Process," which forms an *in situ* electrokinetic cell for removal of contaminants, has been demonstrated in the field (Ho et al., 1995; Chen and Murdoch, 1999).

6.1.3 Blast Fracturing

Subsurface blasting technology has been available for many years in the fields of construction, mining, and well drilling. Most commercial applications of blast fracturing have involved enhancement of product recovery or pump and treat systems installed in saturated bedrock formations (Loney et al., 1996; Edwards et al., 1997).

6.2 COST AND POTENTIAL SAVINGS

The cost of fracturing will vary according to the size of the project, the depth of fracturing, and how fracturing will be integrated with the primary remediation technology. It is always advisable to contact a consultant or vendor involved with fracturing for accurate costing of a project.

For permeability enhancement, costs for pneumatic fracturing are often estimated per fracture level. Recent data suggest that unit costs for pneumatic fracturing range from $250 to $400 per fracture. Hydraulic fracturing is normally estimated per well on the assumption that three to five hydrofractures will be made. The cost per well typically ranges from $1000 to $1500. The unit costs for pneumatic and hydraulic fracturing normally do not include drilling, well installation and long distance mobilization. Also, if the project involves fracturing in the near vicinity of active structures and utilities, there may be additional costs for geotechnical analysis and monitoring. When costing pneumatic fracturing or hydraulic fracturing projects, the total number of fractures can be estimated quite easily for a given volume of soil or rock to be treated by: (1) assuming a fracture radius (normally 3 to 6 m (10 to 20 ft)); (2) assuming a vertical fracturing interval (normally around 0.6 m (2 ft) for PF and 1.5 m (5 ft) for HF); and (3) counting the fractures needed to treat the impacted volume of soil or rock. It is important to note that the preceding costs of fracturing do not include those costs associated with the primary remediation technology such as soil vapor extraction.

When pneumatic fracturing and hydraulic fracturing are used to deliver supplemental media into the geologic formation, additional costs are involved. One of these costs is for the liquid or solid media to be injected. Another cost is for the add-on equipment that will be used to deliver the media. Since both of these costs will vary widely according to project specifics, it is best to contact a consultant or vendor for cost information.

Since blast fracturing is normally applied in a trench configuration, it is estimated on a linear foot basis. The unit cost of blast fracturing normally ranges from $120 to $200 per linear foot of blast trench. Cost variables include the height of the trench (vertical dimension) and depth of overburden. The cost includes drilling and blasting but does not include well installation.

The costs of pneumatic, hydraulic and blast fracturing cited above do not include the cost of engineering controls that may be required to mitigate potential effects on nearby structures and utilities due to ground heaving and vibration. Such costs will depend on the degree of site development and distance to potential receptors.

The cost of applying the various fracturing technologies must be weighed against their potential cost savings. Specific areas where fracturing can reduce the costs of site remediation include:

Reduction in the number of remediation wells. Since fracturing can increase formation permeability, the radius of influence of each treatment well is similarly increased. Thus, well spacing can be expanded and fewer wells need to be drilled. In formations that have a low to moderate permeability, fracturing can reduce well drilling and installation costs substantially. For example, if well spacing can be doubled, from say 4 m to 8 m (13.1 ft to 26.2 ft) by the application of fracturing, then the number of wells can be reduced by 75%. This will produce a similar savings in the capital costs associated with well construction.

Reduction in treatment time. Fracturing also has the potential to reduce the treatment time of a remediation project, either by increasing contaminant mobility or allowing for the introduction of liquid or solid supplements. Operational costs are therefore reduced in proportion. Since operational costs often represent the majority of a clean-up budget, significant savings can be realized. For example, if fracturing increases transport rate in the geologic formation by several times, which is typical, it would be conservative to expect that clean-up time and operational costs can be reduced by 50% or more.

Comparison with Other Alternatives. In some cases fracturing may provide the only feasible way to remediate a site with *in situ* methods. In these situations, the potential savings are more difficult to define. One approach is to compare fracturing with excavation and disposal, unenhanced pump and treat, or another ex situ method that is feasible for the site. The cost of fracturing can also be weighed against the risks and liabilities of no action or natural attenuation.

6.3 VENDORS

Vendors that currently provide services of pneumatic fracturing, hydraulic fracturing, and blast fracturing are listed in Table 6. Vendors within the same category, e.g., pneumatic fracturing, may use special variants of the fracturing technique. A number of the fracturing process variants are protected by U.S. and foreign patents.

Table 6.
Current Principal Fracturing Vendors

Company Information	Point of Contact	Fracturing Type
ARS Technologies, Inc. 271 Cleveland Ave. Highland Park, NJ 08904 Phone: 732-296-6620 Fax: 732-296-6625 e-mail: jjl@arstechnologies.com WebSite: www.arstechnologies.com	John Liskowitz	Pneumatic Fracturing Media Injection
Foremost Solutions, Inc. 350 Indiana Street Golden, CO 80401 Phone: (303) 271-6117 Fax: (303) 278-0642 e-mail: foremost@earthlink.net Web Site:	Seth Hunt	Hydraulic Fracturing Media Injection
FracRite Environmental Ltd. 6 Stanley Place S.W. Calgary, Alberta Canada T2S 1B2 Phone: 403-620-5533 Fax: 403-287-7092 e-mail: fracrite@home.com	Gordon Bures	Hydraulic Fracturing Media Injection
FRx, Inc. P.O. Box 37945 Cincinnati, OH 45222 Phone: 513-469-6040 Fax: 513-469-6041 e-mail: wslack@frx-inc.com Web Site: FRx-Inc.com	William Slack	Hydraulic Fracturing Media Injection
Golder Sierra Ltd. 3730 Chamblee Tucker Road Atlanta, GA 30341 Phone: 770-496-1893 Fax: 770-934-9476 e-mail: ghocking@golder.com Web Site: www.golder.com	Grant Hocking	Hydraulic Fracturing Media Injection
Haley & Aldrich of New York 200 Town Centre Drive, Suite 2 Rochester, NY 14623 Phone: (716) 321-4207 (716) 359-9000 Fax: (716) 359-4650 e-mail: vbd@haleyaldrich.com Web Site: www.haleyaldrich.com	Vince Dick	Blast-Enhanced Fracturing
Pneumatic Fracturing, Inc. 1718 Springtown Road Alpha, NJ 08865-4634 Phone: 908-387-0373 Fax: 908-387-1370 e-mail: pfinc@entermail.net	Deborah L. Schnell	Pneumatic Fracturing Media Injection

7.0 CASE STUDIES

The Ground-Water Remediation Technologies Analysis Center (GWRTAC) has compiled 86 case studies of pilot- and full-scale fracturing projects in their "S" Series Report TS-00-01, "Technology Status Report Hydraulic, Pneumatic, and Blast-Enhanced Fracturing" (Roote, 2000). This database is companion to the present report, and the case studies will not be repeated here. The project summaries were assembled from readily available information in the literature as well as from personal communications with involved vendors and researchers. The compiled database is a "snapshot" of pilot- and full-scale applications of the fracturing technologies in the public and private sectors over the last decade. This "S" Series report can be downloaded in PDF format from the GWRTAC website at http://www.gwrtac.org.

The division of projects in the GWRTAC database among the various fracturing technologies is currently:

- Pneumatic Fracturing – 37 projects
- Hydraulic Fracturing – 27 projects
- Blast Fracturing – 22 projects

In addition to providing technical summaries of the fracturing projects, the "S" Series report analyzes various trends reported in the case studies. Some of these trends are listed in Table 7, and the reader is referred to the report for additional details. Geographically, fracturing projects have been reported in 26 different U.S states and Canadian provinces, although there has been a decided concentration of applications in New Jersey, New York, Ohio, Alberta, and Colorado, which reflects the regional influence of the principal vendors of the fracturing technologies. Other countries with reported fracturing applications include Belgium, England, and Denmark.

Table 7.
Summary of Technology Trends in Reported Fracturing Case Studies
(extracted from Roote, 2000)

Technology Trend	Approximate Distribution of Projects
Project Scale of Fracturing Projects	48% Full-Scale/Commercial 44% Pilot/Field Demonstration 8% Scale Unknown
Primary Integrated Technology	41% SVE/DPE 19% Pump and Treat/Plume Control 15% Not Specified 10% Bioremediation 7% Other 5% Product Recovery 3% Permeable Reactive Barriers/Zones
Environmental Media Targeted	33% Groundwater Contamination 27% Both Soil and Groundwater Contamination 24% Soil Contamination 11% NAPL Removal 5% Unspecified
Contaminant Class	30% Organics – VOCs – Halogenated 19% Organics – VOCs – BTEX 14% Organics – VOCs – PetroleumHydrocarbons 4% Organics – VOCs – Non-halogenated 3% Organics – LNAPL 2% Organics – Inorganics – Metals 28% All Other
Hydrogeologic Setting	39% Vadose Zone 31% Unconfined Aquifer 2% Confined Aquifer 28% Other
Maximum Depth of Fracturing	6% <3 m (<10 ft) 40% >3 m and <7.6 m (>10 ft and <25 ft) 22% >7.6 m and <15.2 m (>25 ft and <50 ft) 9% >15.2 m and <30.5 m (>50 ft and <100 ft) 1% >30.5 m (>100 ft) 22% Unspecified

Note: Not all listed categories are mutually exclusive; a project may be counted more than once for some technology trends.

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