

GUIDANCE DOCUMENT

Use of Permeability Enhancement Technology for Enhanced In Situ Remediation of Low-permeability Media

ESTCP Project ER-201430

NOVEMBER 2019

Kent Sorenson
Dung Nguyen
Nathan Smith
CDM Smith

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14. ABSTRACT Remediation of contaminants in low-permeability lithologies (hydraulic conductivities of approximately 10 ⁻⁵ centimeters per second [cm/s] or lower) is a significant challenge for many sites, with conventional technologies often failing. Environmental Permeability Enhancement Technology (PET), also known as environmental soil fracturing, is a technology that has shown promise for emplacement of solid (U.S. patent number 7,179,381) or liquid phase amendments into low-permeability lithologies (silts, clays, and some bedrock formations), where standard approaches such as permeation injections (conventional injections into existing pore space) typically fail. This document has been developed under the Environmental Security Technology Certification Program (ESTCP) and is associated with project ER-201430, <i>A Rigorous Demonstration of Permeability Enhancement Technology for In Situ Remediation of Low-permeability Media</i> . The purpose is to: 1) demonstrate appropriate uses of PET for various contaminants and lithology; 2) provide guidance on design, implementation, and monitoring of the technology once it has been selected for use; and 3) provide details necessary for procurement of an effective technology implementation.					
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ACRONYMS

>	greater than
3D	three dimensional
bgs	below ground surface
cm/s	centimeter per second
DNAPL	dense non-aqueous phase liquid
DoD	Department of Defense
DOE	Department of Energy
DPI	direct-push injection
DPT	direct-push drilling technology
EC	electrical conductivity
EPA	U.S. Environmental Protection Agency
ERT	electrical resistivity tomography
ESTCP	Environmental Security Technology Certification Program
EZVI	emulsified zero-valent iron
GFAFB	Grand Forks Air Force Base, Site TU504
gpm	gallon per minute
HPE	hydraulic permeability enhancement
ISCO	in situ chemical oxidation
ISCR	in situ chemical reduction
ISRD	in situ reductive dechlorination
LCAAP	Lake City Army Ammunition Plant, Site 17D
NAPL	non-aqueous phase liquid
PET	permeability enhancement technology
PPE	pneumatic permeability enhancement
psi	pound per square inch
ROI	radius of influence
TCE	trichloroethene
TOC	total organic carbon
USACE	U.S. Army Corps of Engineers
VOC	volatile organic compound
ZVI	zero-valent iron

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1.0 INTRODUCTION

The Environmental Security Technology Certification Program (ESTCP) Project Number ER-201430 involved the demonstration and validation of permeability enhancement technologies (PETs) (i.e., environmental fracturing), including hydraulic permeability enhancement (HPE) and pneumatic permeability enhancement (PPE) to improve the delivery of remediation amendments to low-permeability zones. This demonstration project provided a rigorous comparison of the costs and benefits of the hydraulic and pneumatic approaches for enhanced amendment delivery and distribution in low-permeability media, and an analysis of the state-of-the-art tiltmeter and other advanced geophysics monitoring tools to delineate the emplaced fracture networks. The ultimate goal of this demonstration project was to develop a guidance document that does the following:

- Outlines the technical and financial advantages and disadvantages of PET.
- Describes available monitoring technologies and discusses what they can and cannot do.
- Provides remediation project managers with information to help them select and appropriately procure the optimal in situ remediation amendment injection and monitoring techniques for low-permeability sites.

1.1 PURPOSE OF THE DOCUMENT

The Department of Defense (DoD) has many contaminated sites in complex hydrogeological settings and with unique contaminant characteristics where aquifer restoration to maximum contaminant levels or other cleanup criteria within a reasonable timeframe might be extremely difficult. For example, in the presence of a dense non-aqueous phase liquid (DNAPL), technologies specific to treatment of the dissolved components of the contaminants are limited by the DNAPL dissolution rates. This can result in contaminant persistence on the order of hundreds of years. In geologic settings of low hydraulic conductivity, such as tight clays and fractured rocks, effective and uniform delivery of remediation amendments to the zones of interest is rarely achieved using conventional techniques. Collectively, these sites present significant technical and financial challenges to DoD (and other federal site owners) due to the long remedial timeframe and high cleanup costs.

This document has been developed under ESTCP and is associated with project ER-201430, *A Rigorous Demonstration of Permeability Enhancement Technology for In Situ Remediation of Low-permeability Media* (CDM Smith 2019). Remediation of low-permeability lithologies (hydraulic conductivities approximately 10^{-5} centimeters per second [cm/s] or lower) is a significant challenge for many sites, with conventional technologies often failing. Environmental PET, also known as environmental soil fracturing, is a technology that has shown promise for emplacement of solid (U.S. patent number 7,179,381) or liquid phase amendments into low-permeability lithologies (silts, clays, and some bedrock formations), where standard approaches such as permeation injections (conventional injections into existing pore space) typically fail.

To date, limited guidance is available to environmental project managers for both implementation of PET and monitoring technologies that are appropriate during its application. Therefore, this document is intended to provide users with technical information to do the following:

- Determine appropriate use of PET for various contaminants and lithology.

- Provide guidance on design, implementation, and monitoring of the technology once it has been selected for use.
- Provide details necessary for procurement of an effective technology implementation.

This document has been developed using findings from project ER-201430 and information gathered from published reports and studies that describe similar applications of PET.

1.2 OVERVIEW OF PERMEABILITY ENHANCEMENT TECHNOLOGIES

The treatment of recalcitrant contaminants trapped in low-permeability soils can be a difficult and costly endeavor. Traditional injection methods that rely on distribution of treatment agents through existing pore space to induce chemical or microbial interaction with contaminants have been shown to be ineffective and time-consuming when implemented at sites with impacted low-permeability soils. In situ delivery technologies that can enhance treatment amendment delivery to low-permeability soils are of special interest to site managers who wish to dramatically reduce the time needed to reach minimum contaminant thresholds in soils and groundwater.

PETs provide a tool that can increase the bulk aquifer soil hydraulic conductivity, increase contact with contaminants, dramatically increase the radius of influence (ROI) of amendments, and potentially connect existing fractures, all of which facilitate enhanced in situ remediation in low-permeability formations. PETs tend not to add significantly to up-front or life-cycle costs. They generally require fewer wells and less time to accomplish cleanup goals (Department of Energy [DOE] 1998), both of which contribute to decreased life-cycle costs.

Originally developed by the oil and gas industry to increase production yields in deep reservoirs, PET was adopted in the late 1980s as a useful tool to aid in remediating contaminated soil and groundwater (U.S. Environmental Protection Agency [EPA] 1993, 1994). Continued study of the logistics and impacts of hydraulic and pneumatic fracturing both above and below the water table continued throughout the 1990s (Anderson et al. 1994, Frank and Barkley 1995, Murdoch 1995, Walden 1997, Siegrist et al. 1999, Venkatraman et al. 1998, DOE 1998), and numerous studies have since implemented PET strategies at pilot- and full-scale sites in conjunction with other technologies such as chemical oxidation and reduction, bioremediation, soil vapor extraction, and pump and treat (Wong and Alfaro 2001, Murdoch and Slack 2002, Bures et al. 2017, Strong et al. 2004, Christiansen et al. 2007, Christiansen et al. 2010, Scheutz et al. 2010, Swift et al. 2012, Bures et al. 2015, Tzovolou et al. 2015). Many of these studies have shown that PETs were able to substantially increase contaminant removal and degradation rates from low-permeability soils at contaminated sites where traditional remediation techniques have previously failed or would have been too costly or time-consuming to achieve similar results. A summary of the literature review done on PET is provided in **Appendix A**.

Based on the offerings of several of the larger remediation injection companies in the United States and North America, the three most prevalent in situ PET-like methods in use today are pressurized direct-push injection (DPI), HPE, and PPE. Pressurized DPI is commonly used because of its low initial cost, but distribution of amendments using this technique is often uncontrolled and unverified, leading to potentially low treatment efficacy and higher life-cycle costs. In addition, it

rarely includes viscosity modifiers or injection of sand as a proppant, and therefore provides no long-term enhancement of permeability, so is not truly a PET. In recent years, other technologies have been developed or refined to address the challenge of achieving more effective distribution of treatment amendments in low-permeability and fractured media. These technologies include HPE and PPE, both of which can quickly emplace a large volume of amendments throughout both high and low-permeability media with relative ease. Additionally, advancements in tiltmeter monitoring for high resolution mapping of the subsurface distribution of amendments have been made, some of which allow site investigators to use fast-turnaround data for optimization and confirmation of the selected PET strategy. These technologies are described in detail in the following subsections.

1.2.1 Hydraulic Permeability Enhancement

HPE relies on delivery of viscous fluids under high pressures to the wall of soil borings to initiate a soil fracture in the formation, followed by continued pumping and delivery of fluids to further propagate the initiated fracture. Prior to creation of a hydraulic fracture, the field team will typically prepare the injection fluid in large on-site containers. This mixture usually contains silica sand to act as a proppant within the soil formation, the treatment amendment(s) (e.g., zero-valent iron [ZVI]), and a low- or high-viscosity cross-linking gel (e.g., guar gum) for suspension of the sand and treatment amendment(s). When using high-viscosity gels, the sand proppant will help maintain the integrity of the fractures that can otherwise become restricted or closed entirely (particularly in plastic geologic materials), can emplace high permeability pathways and conduits throughout low-permeability formations, and will increase the bulk hydraulic conductivity to allow for more effective injection or extractions in the future.

While the treatment mixture is being thoroughly mixed, a soil boring is drilled to the desired depth for distribution of the treatment agent. When using direct-push drilling technology (DPT), boreholes that will have multiple hydraulic fracture initiation points should use a top-down approach to avoid or minimize continued propagation of previously initiated fractures (unless desired). When a straddle packer is used in an open borehole, either a bottom-up (more preferred) or top-down approach can be used. The pre-mixed low- or high-viscosity mixture is then injected into a borehole at a pressure high enough to overcome the in situ confining stress and the material strength of a geologic formation, resulting in the formation of a tensile parting of the soil, or fracture. **Figure 1-1** provides a visual perspective on the processes involving HPE where a series of long, depth-discrete fractures were initiated using the top-down approach.

The shape and direction of hydraulic fractures has been extensively studied, and these types of fractures typically exhibit the following characteristics (DOE 1996, Wong and Alfaro 2001, Murdoch and Slack 2002, Bures et al. 2003, Christiansen 2010):

- Gently dipping, asymmetric, and elongate to an elliptical shape with respect to the injection boring
- Near horizontal close to the borehole
- Propagate perpendicular to the minimum principal stress
- Dip towards the injection borehole between 10 and 35 degrees
- Tend to not be steeply dipping, at least in low-permeability horizons

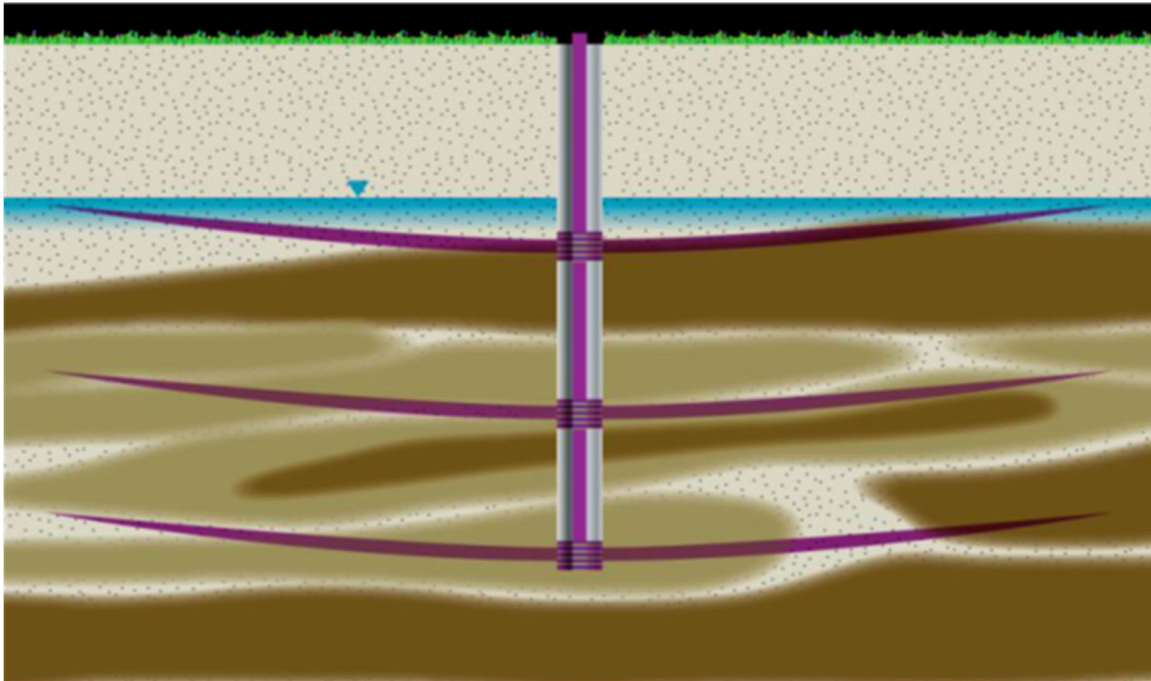


Figure 1-1: An Illustration of HPE

The distances that the fractures typically propagate using hydraulic fracturing are highly dependent on individual site lithology and injection pressures and volumes and can range from 9 to 80 feet from the initiation borehole (Murdoch 1995, Wong and Alfaro 2001, Bures et al. 2003, Strong et al. 2004, Christiansen et al. 2010, Swift et al. 2012, Bures et al. 2015). The thicknesses of the emplaced sand-filled fractures typically range from 1 to 3 centimeters (Siegrist et al. 1999, Scheutz et al. 2010). If liquid amendments (e.g., soluble carbon, potassium permanganate) were injected into the target zones in these fractures, diffusion of these amendments will take place into the surrounding low-permeability soils (Scheutz et al. 2010), developing favorable geochemical conditions for enhanced treatment and degradation rates in both the low- and high-permeability soils. A solid amendment, such as ZVI or chitin, would accomplish a similar objective, and occupy the newly created transmissive fractures, creating an interweaving and complex web of highly reducing soil zones for both biotic and abiotic contaminant degradation. Studies have shown that combining both liquid and solid phase amendments into the injection fluid can have substantial impacts on reducing contamination mass (Swift et al. 2012). Lastly, if fluid or free-product recovery is the goal of a remediation effort, fluid recovery from hydraulically fractured sites has been shown to increase from 10 to 1,000 times baseline levels, with increases in pumping ROI of over 10 times baseline (DOE 1996).

1.2.2 Pneumatic Permeability Enhancement

PPE has been used to successfully deliver treatment amendments and increase fluid and gas extraction rates at sites with low-permeability soils contaminated with gasoline and chlorinated solvents (Anderson et al. 1994, Sankar et al. 1998, Strong et al. 2004, Christiansen et al. 2010).

PPE generally involves applying a high-pressure gas stream to the borehole wall to develop and/or enhance existing natural fractures present in the lithology, followed by pumping of amendments into the fractures by either aerosolizing the amendment (atomized delivery) or fluid pumping (hybrid approach). PPE is conducted by first drilling a cased or uncased borehole and using an air packer to isolate a small (typically 2-foot) section of the borehole. PPE of the formation is then conducted by injecting gas in this isolated interval to generate pressures to overcome the in situ confining stress and the material strength of a formation such that numerous small fractures are formed (EPA 1995, Christiansen et al. 2010). This typically occurs when gas flow rates exceed the natural permeability of the formation. The injection pressures required to initiate these fractures typically increases with depth and injection rate (DOE 1996), and the injections are typically done in 30-second intervals. The result is the enhancement and connection of existing fractures and planes of weakness (e.g., bedding planes) and the propagation of a dense fracture network surrounding the in situ delivery boring. This result is potentially beneficial when delivering amendments to zones of tightly packed or low-permeability soils (Frank and Barkley 1995, DOE 1996). Once a target geologic zone has been adequately pneumatically fractured, injection of a liquid treatment amendment can be performed (Sankar et al. 1998, DOE 1996, Strong et al. 2004, Christiansen et al. 2010, Arnason et al. 2014). This would entail blending of a liquid amendment above ground into a nitrogen gas stream to become atomized using an atomization apparatus, which is a down-hole injection assembly that consists of an injection nozzle with straddle packers that isolate and focus the injection to the target interval. More recent applications, including under ESTCP ER-201430, have used the hybrid approach, where amendments are hydraulically pumped into the pneumatically fractured borehole immediately following the fracturing process. Note that if emplacement of a solid treatment is desired, HPE must be used. PPE alone cannot be used to effectively emplace solid amendments. While it has been claimed that the hybrid PPE approach can be used to emplace solid amendments, there is a lack of data supporting this claim.

Using PPE, amendment is typically distributed between 6 and 25 radial feet from the initiation borehole, depending on site-specific conditions (Anderson et al. 1994, Arnason et al. 2014). Other technologies, such as bioventing, product recovery, and SVE systems, can also be more efficiently used when the formation is pneumatically fractured (Anderson et al. 1994, Frank and Barkley 1995, Ding et al. 1999). At sites where the geology is conducive to dilated existing or newly created fractures staying open (sites with silts and clays), the fracture network generated via PPE has the potential to enhance the overall effective bulk permeability of the formation and extends the ROI for injection, thus enhancing in situ treatment (Schuring, 2002). Vapor extraction flow rates have been observed to increase from 15 to 30 times that of unfractured wells in PPE applications (DOE 1998). **Figure 1-2** provides a visual schematic of the processes involving PPE where a series of hairline fractures are initiated at the depths of interest.

The nature of PET induced by PPE is thought to be quite different from HPE. HPE has the advantage of a larger in situ delivery radius for liquid or solid amendment delivery, and propped fractures that can be used for multiple injections or extractions. Users of PPE can expect to produce a smaller, but denser fracture network to deliver liquid amendments for similar up-front costs.

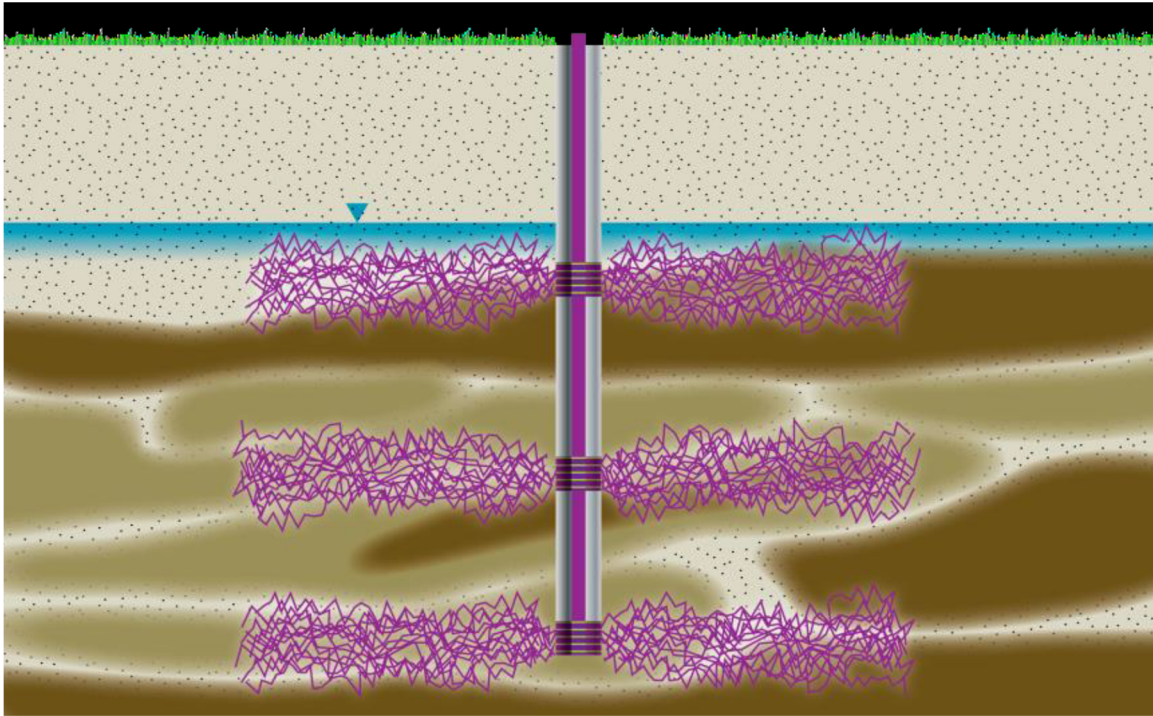


Figure 1-2: An Illustration of PPE

1.2.3 Tiltmeter Monitoring

Tiltmeters have been used at sites where PET activities have created fracture networks with the intention of gaining an understanding of the spatial geometry of the fractures without the need for excavation or borehole confirmation (Wong and Alfaro 2001, Bures et al. 2003, Strong et al. 2004). Tiltmeters contain two tilt sensors (on orthogonal axes) and precision electronics; much more sophisticated tilt meters operate on the same principle as a carpenter's level (Dunnicliff 1993). As the tiltmeter tilts, the gas bubble must move to maintain its alignment with the local gravity vector. The movement of the gas bubble within the conductive liquid causes a change in the total resistance between the electrodes. This resistance change is measured with a resistance bridge or voltage divider circuit to precisely detect the amount of tilt. While simple in theory, the instruments are remarkably sensitive. Using sophisticated electronics and signal processing, tiltmeters are able to achieve a resolution on the order of nanoradians. This is equivalent to the tilt produced by lifting one end of a rigid beam spanning from New York to San Francisco by less than 1 inch. To meet this resolution, proper installation and operation of the instruments are required. The instruments must be adequately coupled to solid earth and significantly isolated from the large thermal fluctuations of the earth's surface. This is accomplished by setting up ground-surface-mounted tiltmeters in a concentric array.

The changes in resistance created by tilting the bubble sensor are electronically converted to a voltage that is proportional to the tilt of the instrument. The voltage is then recorded either by a local data acquisition unit at each tiltmeter site or via cable to a central data acquisition system for the whole tiltmeter array. Data acquisition is often accomplished with remote data acquisition at each tiltmeter site because it removes the need to run cables over the surface area surrounding the well boring. Real-time monitoring and analysis can still be performed with remote data acquisition

units using radio telemetry to send the data to a central computer system for display and analysis. Remote data acquisition units have sufficient storage capabilities to allow periodic data acquisition with a portable computer.

After tiltmeter data are collected and analyzed to determine the tilt vectors due to the fracture stimulation, an inverse problem is solved to determine the nature of the source that produced the observed tilt field. Various models exist that predict surface deformations due to subsurface disturbances. Currently a dislocation model is used to calculate the theoretical surface deformation (and therefore tilt field) due to hydraulic fractures with arbitrary orientation, dimensions, and location. The resulting output is then converted into a dynamic, three-dimensional (3D) graphical output that can be viewed in any perspective in space and can be manipulated to view individual fracture configurations as well as the fracture network as a whole. Real-world, tiltmeter demonstrations, such as from Wong and Alfaro (2001), have observed that tiltmeter-predicted fracture geometries conformed closely with actual site fracture placement (which can be found through excavation or analysis of confirmation borings). During implementation of ESTCP ER-201430, tiltmeters were used to monitor both hydraulically and pneumatically generated fracture networks with a high degree of accuracy when compared to data collected from confirmation borings. Tiltmeter-predicted fracture intercept depths were generally confirmed within 1 to 3 feet of actual fractures identified visually or using various tracers.

1.2.4 Other High-Resolution Characterization Tools

Other high-resolution characterization tools including direct-push electrical conductivity (EC) and electrical resistivity tomography (ERT) may be useful to aid validation of amendment delivery via PET, although their use is not as well documented or verified as that of tiltmeters.

1.2.4.1 Direct-Push Electrical Conductivity

EC logging is used for high-resolution characterization of hydrostratigraphic conditions in unconsolidated media (Schulmeister et al. 2007). Direct-push EC probes typically operate using a four-electrode Wenner array, passing current through the outer two electrodes and measuring voltage across the inner two electrodes. The sensors are capable of collecting 20 measurements per second and collect data at a vertical resolution of 0.05 foot. Clayey materials tend to have higher electrical conductivity and charge characteristics compared to sandy or gravelly soils. The high vertical resolution of the probe readings allows the user to identify fine-scale features, such as low-permeability clay or silt lenses or sand stringers, which are important for transport of injected amendments in the subsurface. The electrical conductivity of the groundwater also affects the conductivity measurements, but the conductivity of groundwater is typically relatively constant over the scale of a shallow, unconsolidated aquifer. By injecting an electrically conductive tracer or amendment solution and measuring electrical conductivity before and after injection activities, intervals impacted by the tracer can be evaluated using the direct-push probes, thereby delineating the vertical distribution of injected amendments.

1.2.4.2 Electrical Resistivity Tomography

ERT is a geophysical visualization technique used to study hydrogeological characteristics of the subsurface. Resistivity, an inherent property of all materials, measures the degree to which a

material resists the flow of an electrical current. As resistivity depends on chemical and physical properties such as saturation, concentration, and temperature, ERT can be used to monitor natural and anthropogenic processes responsible for changes in such properties (Daily et al. 1992). In the context of in situ remediation, ERT can aid in monitoring active remedial progress and provide insights into material emplacement and deformational processes, both of which are relevant to in situ treatment technologies in general and PET in particular (Halihan et al. 2005, Wilkinson et al. 2008). However, uses of this technology, such as from Wong and Alfaro (2001), have shown that ERT was unsuccessful in mapping individual hydraulic fractures.

2.0 TECHNOLOGY CONSIDERATIONS

PET offers unique benefits to address the many challenges present at contaminated sites with low hydraulic conductivity. This section provides considerations for applying the technology, including its advantages and limitations.

2.1 GENERAL CONSIDERATIONS

A variety of factors may influence the selection of PET at a given site. This section provides a discussion of general factors to be considered, including site-specific contaminant profile and lithology. In addition, the importance of a well-developed conceptual site model and gaining the appropriate regulatory acceptance are discussed herein.

2.1.1 Contaminant Profile

PETs are generally implemented to achieve improved amendment delivery and distribution for in situ remediation in low-permeability lithologies. Therefore, any contaminants that can be treated in situ using treatment techniques such as in situ reductive dechlorination (ISRD), in situ chemical oxidation (ISCO), or in situ chemical reduction (ISCR) can be subject to PET. These aforementioned techniques, along with other less common in situ treatment technologies including cometabolism, can be used to address a variety of site contaminants such as chlorinated solvents, petroleum hydrocarbons, and metals.

2.1.2 Lithologies

As previously mentioned, PETs are most often implemented at low-permeability sites where conventional injection techniques cannot be performed with a high degree of success. Typically, the subject technologies are conducted at sites with a bulk hydraulic conductivity of approximately 10^{-5} cm/s or lower, often associated with silts, clays, and a variety of bedrock formations such as siltstone and claystone. For example, HPE was performed at the F.E. Warren Air Force Base, Former Atlas Missile Site No. 12 in Colorado to mitigate impacts from chlorinated volatile organic compounds (VOCs) (Swift et al., 2012). The former missile site complex is underlain by silty sandstone bedrock sediments affected by trichloroethene (TCE) at a concentration of 4,000 micrograms per liter or more, plus associated VOCs. Over 100 tons of a ZVI/complex carbon treatment amendment (EHC-G™) was emplaced via HPE into deep bedrock sediments to attain optimal distribution throughout the contaminant plume. PET was conducted in nine pre-drilled boreholes to deliver the amendment slurry at 5-foot increments between depths of 35 and 63 feet below ground surface (bgs) in bedrock. Amendment distribution was distributed to greater than (>) 50 feet in sedimentary rock and chlorinated VOC concentrations were reduced below target levels of 100 parts per billion in less than 2 years, facilitating transition to monitored natural attenuation. Conventional injections were not even attempted in this setting because of the low-permeability bedrock.

In addition to facilitating treatment in low-permeability media, PETs can also be used to overcome the high degree of lithologic heterogeneity that cannot be effectively addressed by conventional injection techniques. Such heterogeneity generally leads to preferential amendment distribution into high-permeability but less-contaminated zones rather than the low-permeability counterpart

containing the majority of the contaminant mass. For example, at the Bountiful/Woods Cross Superfund Site, Operable Unit 1 in Bountiful, Utah, conventional injection approaches were employed for almost 10 years to address a source area with elevated concentrations of TCE and/or its degradation constituents (hundreds of parts per million concentrations). The conventional injection techniques employed (injections through permanent wells) were inadequate because of the high degree of lithologic heterogeneity observed at the site (interbedded sand, silt, and clay). HPE was performed in 2017 to facilitate emplacement of sand and ZVI. Within 3 months of completing the sand/ZVI emplacement, complete degradation of TCE and daughter products was achieved with no apparent contaminant rebound as of November 2018 (CDM Smith 2018).

In addition, PETs can be used in high-permeability lithologies including sand, where emplacement of a solid amendment such as ZVI or EHC is desired. It has been observed during implementation of PETs at several high-permeability sites with fine-grained sands that the solid amendments may not be distributed very far from the injection location, as the native materials may serve as a filter pack. High-permeability lithologies can also allow much steeper soil fracturing because the soil “fabric” provides little resistance to the pressurized injection fluid as it moves toward low pressure at ground surface. In nearly all cases, it is recommended that detailed lithologic logging and contaminant profiling be performed to assess the applicability of the subject technologies at a given site prior to full-scale design and field implementation. In some cases, pilot-scale testing might also be appropriate to determine how injections behave in a higher-permeability lithology.

2.1.3 Conceptual Site Model

Similar to the design and implementation of any in situ treatment technology, having a detailed and well-developed conceptual site model is key to success of PET implementation. Specifically, a detailed conceptual site model allows for identifying data gaps, focusing the data collection efforts, and prioritizing treatment areas (vertically and laterally) within the context of the overall site-specific remedial objectives. PET is well-suited to sites with groundwater contamination trapped in low-permeability zones. This includes highly heterogeneous sites where contaminant transport into higher permeability groundwater flow zones is diffusion-limited. PET can also be used to emplace solid-phase amendments regardless of permeability. In most cases, the cost of obtaining the necessary data to create a conceptual site model or update an existing one is insignificant compared to that associated with the design and full-scale implementation of PETs. Performing a remedial design and conducting field implementation on the basis of an inadequate conceptual site model generally result in unsatisfactory treatment effectiveness, prolonged remedial timeframe, and substantially higher project life-cycle cost.

2.1.4 Regulatory Acceptance

Because of the negative perceptions sometimes associated with hydraulic fracturing, regulatory agencies and other parties involved in a remediation project may be reluctant to implement PETs at a given site. The common misunderstandings of PETs can usually be overcome via education on the drastic differences between environmental fracturing for remediation purposes and hydraulic fracturing used in the oil and gas industry. While the objective of hydraulic fracturing in the oil and gas industry is to extract natural resources, the goal of PET is to increase the bulk hydraulic conductivity, improve amendment delivery ROI, and to ultimately enhance contaminant degradation. During hydraulic fracturing for extraction of natural resources in situ, fractures are initiated vertically under very high pressure ranging between 1,000 and 10,000 pounds per square

inch (psi). Anti-corrosion chemicals used in these applications can contaminate groundwater if not properly managed. On the other hand, environmental fracturing performed for remediation purposes is generally conducted in horizontal planes at relatively lower pressures ranging between 100 and 1,000 psi using substantially less volume (hundreds to thousands of gallons). In most cases, non-toxic and food-grade materials can be used for remediation purposes. Communicating the key differences between hydraulic fracturing in the oil and gas industry and environmental fracturing in the remediation field can be effectively done via presentations and/or webinars similar to that shown in **Appendix B**. In many cases, detailed work plans and permit applications describing the amount of fracture fluid to be emplaced and demonstrating the non-toxic, food-grade nature of the fracturing fluid to be used are needed to obtain the necessary regulatory acceptance. In instances where community acceptance of the proposed remedy using PETs is needed, the aforementioned presentations and/or webinars on environmental fracturing must be revised as appropriate to address an audience that may not be familiar with the environmental engineering field.

2.2 SITE-SPECIFIC CONSIDERATIONS

In addition to the general design considerations discussed in **Section 2.1**, several site-specific conditions must be reviewed carefully at the planning stage, including proximity to sensitive facilities or formations, presence of non-aqueous phase liquid (NAPL), and previous site remediation activities. These conditions can affect the potential applicability or effectiveness of PET at a given site. Therefore, such review of site-specific conditions can facilitate go/no-go decision making and allow for adjustment of the remedial design at the planning stage.

2.2.1 Underground or Nearby Utilities

While the pressure typically required for fracture initiation during PET is relatively low, ranging between 100 and 1,000 psi, such pressure is sufficiently high to cause potential damage to nearby utilities or infrastructure. For example, the structural integrity of a nearby monitoring well (including its well screen and grout seal) may be susceptible to damage if intercepted by fractures initiated from a PET location at close proximity. Similar to other in situ treatment technologies, considerations should be made with respect to the type of amendment used and nearby underground utilities. For example, ISCO amendments such as peroxide should not be used in PET applications at sites where fuel lines are present close to the remediation area and within the target vertical treatment depth. Also, utility corridors intersected by a PET injection can become conduits for transport of injected fluid to undesirable receptors such as surface water.

It should be noted that the orientation of the fractures initiated during PET cannot be controlled. Therefore, there is a possibility that highly angled or even completely vertical fractures will be initiated during field implementation. In general, higher degrees of soil consolidation or the presence of sub-horizontal bedding planes will lead to low-angle fractures, but it is not possible to predict fracture orientation perfectly (E² Inc., 2008). The possibility of high-angle fractures needs to be considered during the planning stage and/or the remedial design of PET at sites where, for example, an underlying, uncontaminated aquifer may be connected and become contaminated unintentionally as a result of the technology implementation. Note that proper design and engineering control measures can be taken to mitigate such contaminant migration concerns.

2.2.2 Presence of NAPL

Similar to conventional in situ treatment technologies, the presence or absence of NAPL must be verified during the pre-design investigation stage as it is a significant remedial design and implementation consideration. A clear understanding of the phase distribution of NAPL in the subsurface is critical in remedial planning, design, and implementation. PET can be applied to provide greater access to residual NAPL for in situ treatment, or in some cases, for extraction of free-flowing NAPL. However, at sites where free-flowing NAPL is present and a high risk of NAPL migration to undesirable locations as a result of PET exists, PET should only be implemented with great care, if at all.

2.2.3 Previous Remedial Activities

A comprehensive review of remedial activities previously performed at a site where PET is being considered should be conducted. Subsurface disturbances from prior remedial action, such as excavation, drilling, and well installation, may result in creation of subsurface voids and preferential pathways that can ultimately lead to undesirable PET outcomes (surfacing, poor amendment distribution, and subsidence). In most cases, a phased approach to PET should be used to avoid committing significant resources to a field activity that is highly site-specific.

3.0 SELECTION OF AN EMPLACEMENT TECHNOLOGY

As discussed in **Section 2**, site-specific considerations should be taken into account when determining the potential for and suitability of PET at a given site. **Figure 3-1** can be used to facilitate the selection process for PET. As with all in situ remediation technologies, a reasonable understanding of the conceptual site model, including site lithology, hydrogeology, nature and extent of contamination, treatment objective, and environmental receptor, in accordance with ASTM method E1689-95(2014) must be in place. Commercially available high-resolution characterization tools can be used to obtain pertinent site-specific physiochemical information as shown in **Table 3-1**. Once it is determined that PET is the appropriate remediation implementation approach at a given site, the proper treatment amendment followed by the proper amendment emplacement methodology must be selected. A discussion regarding treatment amendment selection is provided in **Section 4**. This section pertains to the selection of the proper amendment emplacement methodology once a treatment amendment has been selected for a given site. Specifically, a discussion regarding emplacement of sand for improved bulk hydraulic conductivity and repeatable aqueous injection as well as emplacement methodologies for solid versus aqueous amendments is provided herein.

3.1 SOLID AMENDMENT EMPLACEMENT

If emplacement of a solid amendment such as ZVI or EHC via PET is desired at a site, HPE is the preferred method based on previous project performance evaluation. A side-by-side pilot study comparing the two PETs was performed at the Hunters Point Naval Shipyard in San Francisco, California in 2010, where emplacement of ZVI into borrowed fill and serpentinite bedrock materials was desired to aid abiotic degradation of TCE (Alliance, 2010). Note that the hybrid pneumatic/hydraulic approach was employed where nitrogen gas was first used to aid fracture initiation pneumatically followed by hydraulic emplacement of the ZVI slurry. Emplacement of a solid amendment such as ZVI or EHC cannot be performed using the “pure” pneumatic approach to PET. Results from this pilot study indicate that:

- PPE, even when implemented in its hybrid approach, was more susceptible to amendment surfacing than its hydraulic counterpart.
- The HPE approach was more effective than the hybrid PPE approach with respect to volume of amendment emplaced, radius of distribution, and contaminant degradation.

This result is not surprising for two reasons. First, low-viscosity fluids such as water (or especially gases) cannot carry a solid-phase amendment more than a few centimeters when traveling at the velocities achieved during subsurface injection. Second, these low-viscosity injection fluids tend to “leak off” into the formation through existing pore spaces, and the soil grains filter out any solid-phase amendment, preventing migration with the injection fluid. **Only the high-viscosity injection fluid used during HPE can carry solid-phase amendments long distances in the subsurface.**

Is permeability enhancement appropriate for a site. If so, what type?

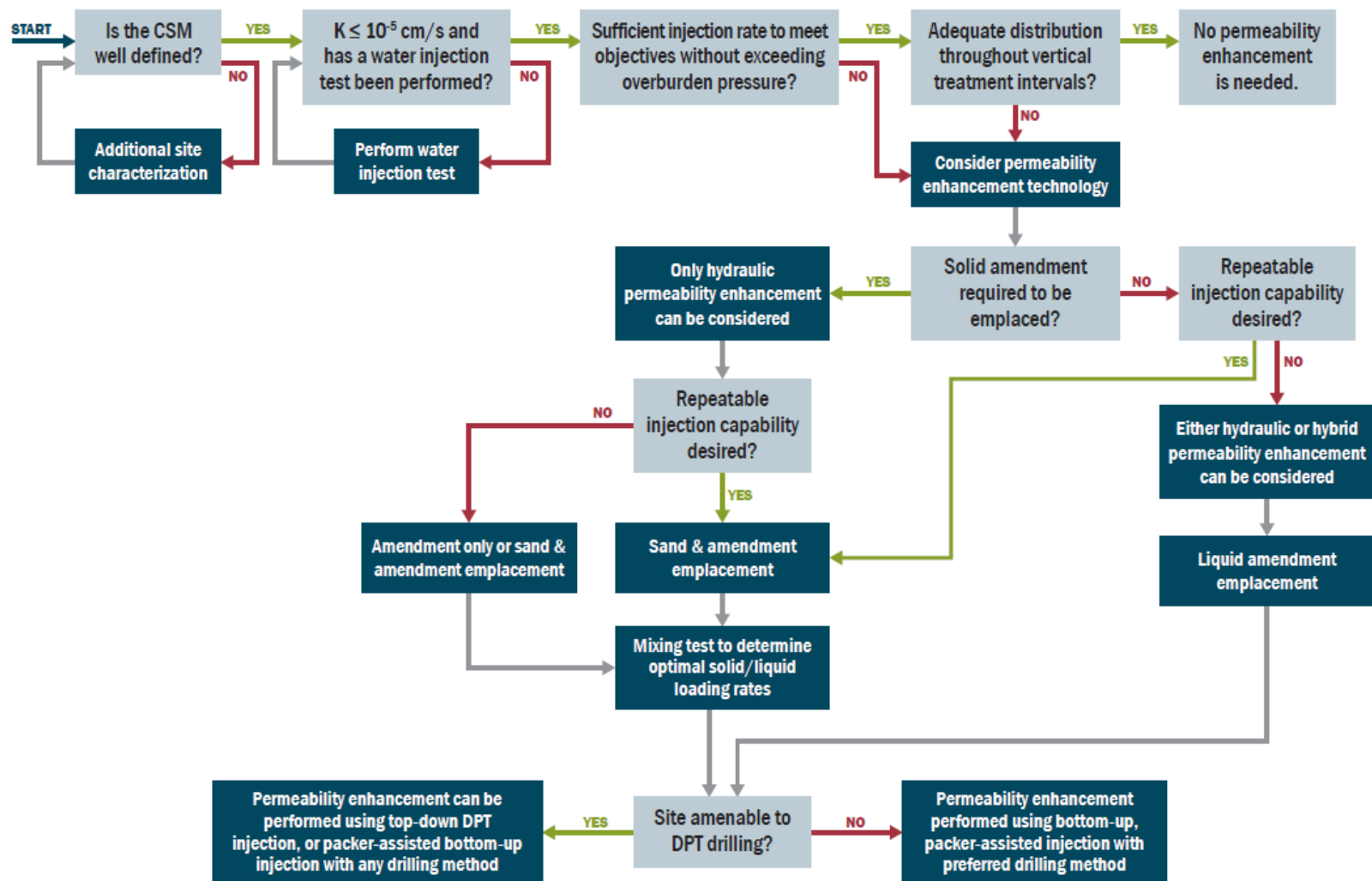


Figure 3-1. Permeability Enhancement Selection Approach

Category	Type of Information Provided	Specific Information Provided	Technology Type	Example Technology
High-Resolution Site Characterization Tool	Physical Properties	Surface Geologic Properties	Microgravity	
			Radar/Radio Wave Technologies	Ground Penetrating Radar (GPR)
				Very Low Frequency (VLF)
				Electromagnetic (EM) Conductivity
			Seismic Technologies	High Resolution Seismic Reflection (2D or 3D)
				Seismic Refraction
				Multi-Channel Analyses of Surface Waves (MASW)
				Geophysical Tomography
			Electrical Technologies (Resistance)	Electrical Resistivity Tomography (ERT)
				Electrical Resistivity Imaging (ERI)
				GeoTrax CSM (Aestus method)
			Electrical Technologies (Current)	Willowstick
				Induced Polarization (IP)
		Downhole Geologic Properties	Electrical Resistance Technologies	Magnetometric Resistivity
				Induction Resistivity (Conductivity Logging)
				Resistivity (Elog)
			Seismic Technologies	Seismic Tomography
				Full Wave Form Seismic
			Radar/Radio Wave Technologies	GPR Cross-Well Tomography
		Geologic and Hydraulic Properties	DPT-Based In Situ Logging	Hydraulic Profiling Tool (HPT) with Electrical Conductivity (EC) Logging
				High-Resolution Piezocone (HRP) with GeoVis
				Waterloo Advanced Profiling System (Waterloo APS)
				Cone Penetrometer Testing (CPT and CPTu)
		Hydraulic Properties	Well and Aquifer Tests	Downhole Flow Technologies
				Colloidal Borescope Flowmeter
				Saline Tracing – In-well Flow
				Heat Tracing – In-well Flow with Fiber Optic Tracing
				Active Line Source Profiling
				FLUTe Hydraulic Profiling
				High-Resolution Passive Profiler
				Horizontal-to-Vertical Spectral Ratio (HVSr)
				Hydrophysical Logging
		Hydraulic Properties of Fractured Rock	Heat-Pulse Flowmeter	
			Stratigraphic Logging Technologies	Optical Televiewer
				Video Log
				Natural Gamma Log
				Neutron (porosity) Logging
				Nuclear Magnetic Resonance Logging
			Fracture Mapping Technologies	Acoustic Televiewer
				Caliper Log
				Temperature Profiling
	Chemical Properties	Subsurface Contaminant Profiling		Membrane Interface Probe (MIP)
				Dye-Laser Induced Fluorescence (LIF) – Targost
				Dye-Laser Induced Fluorescence (LIF) – Ultraviolet (UV) fluorescence (UVOST)
				Optical Image Profiler (LNAPL)

Table 3-1. Commercially Available Standard and High-Resolution Site Characterization Tools

High-Resolution Site Characterization Tool	Chemical Properties (continued)	Subsurface Contaminant Profiling (continued)		SCAPS LIF
				Passive Fluxmeter
				FLUTe-NAPL, FACT
				Raman Spectroscopy
				Vertical Seismic Profiling
	Natural Attenuation Potential	Biotic and Abiotic Degradation	Aquifer Attenuation Capacity for Abiotic Degradation	Magnetic Resonance Testing
			Evaluation of Degradation	Microbial Diagnostics
		Specific Isotope Analysis (CSIA)		
		NAPL Degradation Tracers (MapTrap, FossilFuelTrap, Thermal NSZD)		
	Standard Site Characterization Tool	Physical and Chemical Properties	Solid Media Sampling and Analysis Methods	
			CoreDFN	
Groundwater Sampling and Profiling – Contaminant Profiling Technologies			FACT FluteTM	
			Straddle packer sampling	
			ZONFLO-Hydraulic sampling system	
			Hydrosparge (SCAPS)	
			Co-Solvent Injection/Extraction; or Precision Injection/Extraction PIX Probe	
			Conservative Tracer Tomography	
			Partitioning Tracer Tomography	
Groundwater Sampling – Multilevel Well Sampling			Westbay	
			Solinst	
			Fact Systems (FLUTe)	
			Barcad	
			ZIST	
			CMT (Continuous Multichannel Tubing)	
			Vertebrae (Horizontal multi-increment sampling)	
Soil Vapor Characterization Approaches			Waterloo Membrane Sampler (passive sorbent method)	
			Vapor-Phase Tomography	

Table 3-1. Commercially Available Standard and High-Resolution Site Characterization Tools

3.2 LIQUID AMENDMENT EMPLACEMENT

Unlike emplacement of a solid amendments, both the hydraulic and the pneumatic (pure or hybrid) approach to PET can potentially be used for effective distribution of an aqueous amendment into low-permeability materials, though the nature of the distribution will differ. Specifically, HPE can be used to directly or indirectly emplace an aqueous amendment. For example, if one-time injection is desired, the aqueous amendment solution can be emplaced (with or without a high-viscosity injection fluid) during fracture initiation. Following such initiation, the fractures are likely largely collapsed, rendering the PET a one-time event.

As part of the DoD-funded ESTCP field demonstration project ER-201430, an aqueous amendment injection was performed using the hydraulic approach to PET at GFAFB TU530 in Grand Forks, North Dakota in 2016 to overcome the intrinsically low-permeability glacial till present at the site (CDM Smith 2019). Results from this field demonstration indicate that:

- The target injection volume of approximately 130 gallons per enhancement interval was achieved at all three depth-discrete intervals of 12-, 15-, and 18-feet bgs at all four PET initiation points.
- Very minimal surfacing (less than 5 gallons) was observed despite the very shallow target injection intervals. Amendment delivery into nearby monitoring wells was visually observed. Uniform vertical amendment distribution was also observed as indicated by elevated fluorescein concentrations in soil in depth-discrete intervals at several post-enhancement confirmation borings.
- No significant changes in hydraulic conductivities were observed following HPE at GFAFB; this was expected since no sand proppants were injected to create permanent high-permeability flow pathways within the target treatment zone. It should be noted that an injection rate of approximately 10 gallons per minute (gpm) was achieved during HPE, which is two orders of magnitude higher than previously achieved at the site using conventional injection techniques (between 0.1 and 0.35 gpm).
- Highly reducing conditions characteristic of sulfate-reduction were observed following HPE at GFAFB. Compared to baseline conditions, orders-of-magnitude increases in TOC concentrations, coupled with depleted dissolved oxygen, very low oxidation-reduction potential, elevated ferrous iron, and complete or near-complete sulfate reduction, were observed at many of the nearby monitoring wells. Significant reduction in contaminant concentrations was observed.
- Using a direct-push drill rig in combination with a proprietary injection tip connected to GeoTactical Remediation's standard pumping and mixing for HPE, the effective ROI of the HPE at GFAFB was estimated to be at least 10 feet, which is an order-of-magnitude higher than what was achieved previously using direct-push injection. This approach successfully provided the benefits of rapid, low-cost drilling with the ROI and vertical injection control of HPE.

HPE can also be used to facilitate emplacement of a fine-grained silica sand. In the presence of the silica sand, once initiated, the various interconnected fractures created during HPE are permanently propped by the sand particles. The sand-propped fracture network allows for an opportunity for the fracture boreholes to be converted into injection wells, facilitating repeatable injection events on an as-needed basis.

While a direct comparison study of the two emplacement methodologies in the same lithology has not been performed, the DoD-funded ESTCP field demonstration project ER-201430 provided insights into the distribution and degradation performance of each technique. Specifically, a pilot study was performed at the Lake City Army Ammunition Plant, Site 17D (LCAAP) in Independence, Missouri in 2016. Emplacement of sand followed by injection of an aqueous amendment into sand-propped fractures was targeted in the hydraulic demonstration cell, whereas the hybrid PPE approach using nitrogen gas for fracture initiation followed by hydraulic emplacement of the aqueous solution was targeted in the second demonstration cell at LCAAP. Note that the same volume of aqueous amendment solution was injected into each demonstration cell. Results from this demonstration project indicate that:

- Approximately 80 percent of the target solid amendment volume was achieved within the hydraulic demonstration cell; amendment surfacing observed was likely attributable to subsurface preferential pathways resulting from past site disturbances. Subsurface conditions within the hybrid PPE and the HPE demonstration cells were very different: an undocumented and previously unknown former TCE dump pit was present in the hydraulic demonstration cell. Because of this pit, this area was highly disturbed and then backfilled, with a significant amount of NAPL present. In contrast, the hybrid PPE area had never been disturbed. Regardless, the target aqueous amendment injection volume was achieved in the HPE demonstration cell. Note that the target injection volume was also achieved in the hybrid PPE cell.
- Significant increases in TOC were observed in both soil and groundwater following PET within the hydraulic demonstration cell despite amendment surfacing issues. On the other hand, while achieving the target amendment injection volume, no significant increases in TOC in soil were observed within the hybrid PPE demonstration cell. Some increases in TOC concentrations in groundwater were observed within the hybrid demonstration cell, albeit transient and at significantly lower levels than those observed in the hydraulic demonstration cell.
- Highly reducing conditions were established in both the hybrid PPE and the HPE demonstration cells following enhancement. These geochemical changes were accompanied by significant changes in contaminant concentrations in several monitoring wells within the ROI of PET within both demonstration cells. The extent of contaminant reduction varied significantly as the baseline concentrations in groundwater within the two demonstration areas were vastly different; relatively low benzene, toluene, ethylbenzene, xylene, and chlorinated solvent concentrations were observed in the hybrid monitoring wells, whereas NAPL was seen in all new HPE cell monitoring wells.
- The estimated ROIs of liquid injection for the hybrid PPE and the HPE demonstrations are 10 and 25 feet, respectively, based on the overall evaluation of groundwater chemistry and contaminant profiles over time and results of the post-enhancement soil confirmation sampling. Therefore, it is very important to recognize that a much higher density of injection locations is required for the hybrid PPE approach than for the PPE approach.

3.3 SAND EMPLACEMENT

Sand emplacement performed using HPE is intended to increase the bulk hydraulic conductivity of the treatment area and create a permanent sand-propped fracture network that can later be used for subsequent, repeatable (if needed) aqueous amendment injections. In some cases, it may be appropriate to hydraulically emplace a solid treatment amendment such as ZVI or EHC concurrently with sand to achieve increased hydraulic conductivity and treatment in the new preferential flow path simultaneously. Note that changes in bulk hydraulic conductivity are expected to be minimal when a solid amendment such as ZVI or EHC is emplaced without sand. Therefore, if repeatable injections of an aqueous amendment are desired, emplacement of silica sand is recommended. Note that inclusion of sand in the PET fluid will reduce the solid mass loading rate of the treatment amendment.

Proper sand placement using HPE requires the use of a cross-linked gel to provide sufficient viscosity to carry the sand for the entire length of the soil fracture. A “blender-stall” test can be used to determine how much sand can be loaded into the gel. This same test can be used to determine the maximum mass loading rate for any particular solid-phase amendment being injected, either alone or in combination with sand. The viscosity of the gel can be adjusted if necessary to increase or decrease mass loading.

4.0 PERMEABILITY ENHANCEMENT REMEDIAL DESIGN

4.1 DOSING AND AMENDMENT SELECTION

A variety of commercially available solid and aqueous amendment products can be used for PET applications. For solid amendments, ISCR reagents such as ZVI and EHC are generally used to promote abiotic degradation of chlorinated solvents, whereas ISCO solid amendments such as permanganate granules can be used to promote chemical oxidation of a variety of soil and groundwater contaminants. To keep the solid amendment suspended in solution during and throughout the PET processes rather than settling out due to gravity or due to reactivity between the amendment and the delivery fluid, the compatibility between the chosen amendment product and the delivery fluid components must be tested at the bench scale. The maximum achievable solid loading rate may vary even for the same product category with different grades and specifications and thus should also be subject to bench-scale testing during the planning phase. In most cases, the PET vendors can very easily perform the aforementioned testing via a simple mixing test. Note that under select regulatory environments, a solid amendment dosage expressed in terms of the amount of the treatment amendment per amount of soil requiring treatment must be achieved as a satisfactory performance metric. In these instances, the lateral and vertical spacing of the PET boreholes may need to be adjusted accordingly. More complex bench-scale treatability testing may be required to determine the optimal dosing requirements and associated amendment longevity. Note that inclusion of a solid amendment into a PET delivery fluid is a patented process (U.S. patent number 7,179,381) and thus must be procured properly, from a licensed vendor.

Similar to solid amendments, a variety of commercially available aqueous amendments can be used to promote ISRD, ISCO, or ISCR reactions. ISRD amendments are often categorized as oil-based substrates and soluble substrates. ISCO aqueous reagents such as concentrated peroxide, permanganate, and persulfate can be used to promote chemical oxidation. ISCR amendments such as emulsified zero-valent iron (EZVI) have been previously emplaced analogous to liquids via PET, though EZVI is a suspension of a solid and not just a liquid (it is not clear how well understood the distribution of ZVI is from such injections of EZVI.) Note that, in contrast to solid amendments, emplacement of an aqueous amendment into low-permeability materials using PETs generally does not require a delivery fluid. Therefore, bench-scale testing for material compatibility is not often needed. However, in many cases, a bench-scale treatability study to determine optimal amendment dosage, amendment longevity, and any potentially adverse geochemical changes is beneficial.

4.2 LATERAL AND VERTICAL SPACING

Amendment surfacing via naturally occurring or manmade vertical conduits notwithstanding, the lateral radius of distribution resulted from HPE is a function of the injection volume and the fracture aperture. The fracture aperture (the “thickness” of a fracture opening initiated during PET) is a function of the materials being emplaced, the manner in which fracture initiation occurs, and the surrounding lithology. In general, the apertures of fractures initiated via HPE are larger than those associated with the pneumatic counterpart technique. However, as described in **Section 2**, PPE tends to create more of a “web” of fractures from a single initiation point rather than an individual injection plane. Therefore, a theoretical prediction of distribution radius is problematic for the pneumatic technique. Experience suggests a rule of thumb of 10 feet be used when

designing for PPE, with the understanding it can vary depending on the subsurface formation. For HPE design purposes (not for predicting actual injection orientation), the injection volume required to achieve a certain radius of distribution during HPE can be estimated using the following simplifying assumptions:

- During PET, an opening (i.e., fracture) is initiated in the subsurface by the pressurized fluid that simultaneously fills it with the fracturing amendment.
- The fracture is propagated equally in all directions from the fracture borehole (i.e., length-to-width aspect ratio of 1), resulting in radial amendment distribution.
- The fracture initiated is completely horizontal.
- The volume of amendment required is determined by multiplying the squared radius of distribution by the fracture thickness (i.e., aperture of the fracture initiated during propagation), which may vary depending on the amendment type and site-specific lithology.

Note that professional judgement and data obtained from prior projects are often used to estimate the fracture apertures. Experience suggests that an average fracture aperture for HPE ranging between 0.5 and 0.8 inch can be expected. In many cases, the effective ROI will be larger than the initial radius of distribution. In the case of an aqueous amendment injection, the extent of influence beyond the radius of distribution will be a function of the matrix permeability, viscosity and mobility of solution, chemical gradient, and groundwater flow. In the case of a solid-phase amendment injection, the extent of influence beyond the radius of distribution will be a function of matrix permeability, solubility and mobility of dissolved amendment, chemical gradient, and groundwater flow. In reality, fractures often have an aspect ratio >1 and some degree of dip. The majority of fractures are anticipated to have dip angles of 15 to 35 degrees, although completely horizontal or vertical dip angles have also been observed. Therefore, it is often recommended that overlapping of theoretical ROI is planned. Experience obtained from the ESTCP demonstration project and several others indicate that in many geologic formations, 1 cubic meter of injection fluid will provide an effective ROI of about 20 to 25 feet, but that tends to increase with the degree of consolidation of the formation.

As previously mentioned in **Section 4.2**, the lateral and vertical spacing of the PET boreholes and depth-discrete enhancement intervals, respectively, may need to be designed with respect to the amendment dosage requirements specified by the regulatory agency. Regardless of such dosing requirements, the minimal vertical spacing between depth-discrete PET intervals depends on the emplacement methodology used and the site-specific lithology and hydrogeology. For top-down emplacement methodology using DPT, for example, a vertical spacing as close as 1 to 2 feet may be achieved. When a straddle packer assembly is used for bottom-up emplacement methodology, a larger vertical spacing ranging between approximately 3 and 4 feet is generally required. Because the vertical spacing requirements are dictated by the overburden pressure (for top-down emplacement methodology) or the straddle packer configuration (for packer-assisted, bottom-up emplacement methodology), there are no major discrepancies between HPE and PPE with respect to vertical spacing of permeability enhancement intervals.

4.3 HPE CONSIDERATIONS

Several factors must be taken into consideration when planning for field implementation of HPE:

- HPE can be performed using the top-down or bottom-up emplacement methodology.
- Top-down emplacement methodology is usually used at sites that are amenable to DPT, where the PET downhole tooling can be attached to the DPT drilling rods. In this instance, the skin friction between the subsurface materials and the drilling rods and the overburden/hydrostatic pressure are relied upon to create a seal. Amendment emplacement is first performed at the shallowest target interval of interest. Upon completion of the shallowest interval, the PET tooling and the DPT drilling rods are advanced further to the next depth interval of interest. The same process is repeated until all depth-discrete intervals are permeability-enhanced.
- At sites with more consolidated lithologies that are not amenable to DPT or at sites where DPT drilling can be performed but a proper seal cannot be maintained, the bottom-up emplacement methodology can be used. In most cases, a straddle-packer assembly consisting of two inflatable packers and an injection element straddled between the two packers is required to facilitate depth-discrete amendment emplacement. An open borehole is generally pre-drilled to the appropriate specifications (the borehole diameter has to be smaller than the maximum allowable inflatable diameter of the packers and the total depth has to account for the length of the bottom packer) using sonic or rotary drilling techniques. Hollow-stem auger drilling technology is not often preferred as a smooth borehole (to prevent uneven packer inflation and potential damage) is desired. Depending on the site-specific geology, surface casing may be required to prevent material sloughing into the open borehole. In addition, the borehole may be calipered to ensure diameter consistency throughout and mitigate potential packer blowout in washed-out zones.
- Because of the low compressibility of water, water-inflatable packers are preferred to gas-based packers because the former are substantially safer than the latter.
- Injection hoses and aboveground injection wellhead tooling compatible with the drilling equipment are required to facilitate high-velocity transfer of the injection solution from the mixing skid to the borehole subject to PET.
- Proprietary delivery fluid chemistry is required to achieve the desired solid amendment loading rate. In addition to keeping the solid amendments of interest suspended in the PET solution throughout the entire fracture initiation and propagation process (proprietary guar and polymer-based cross-linker), the unique chemistry (an enzyme breaker) of the delivery fluid system is designed to facilitate in situ breakdown of the fluid carrier following amendment emplacement in the target treatment zone.
- The use of triplex pumps capable of mixing and pumping high-viscosity slurries at a high rate and pressure, as well as pertinent monitoring instrumentation, is recommended. Specifically, a monitoring technique capable of providing near real-time interpretation of the fracture network generated as a result of permeability enhancement implementation such as tiltmeter should be employed to the extent practicable.

4.4 PPE CONSIDERATIONS

Several factors must be taken into consideration when planning for field implementation of the PPE:

- Because of the high potential for leak-off during PPE (at least during the gas-based fracture initiation process), the bottom-up emplacement methodology using a straddle- or triple-packer assembly is recommended.
- The third packer of the triple-packer assembly is positioned in the vadose zone and on top of the straddle-packer assembly used to isolate the depth-discrete injection interval of interest. The top packer is intended to minimize amendment surfacing. However, with the use of this top packer, vertical amendment short-circuiting to the borehole might actually happen between the top and the second packer without being detected. Because of the lack of real-time monitoring during PET, the use of the top packer may lead to overestimating the success of pneumatic fracture initiation processes and should be evaluated on a case-by-case basis. For this reason, it is also imperative to perform adequate aboveground and/or underground monitoring or post-enhancement confirmation sampling (soil and/or groundwater) to verify amendment delivery and distribution in the subsurface.
- Pure PPE can only be used to deliver aqueous amendments, and mass loading is limited by the need to aerosolize the liquid. The hybrid approach is often used even for liquid amendment injection into low-permeability media, but without the vertical control of PPE. Note that such a hybrid approach is still sometimes advertised as PPE. Solid amendments have been emplaced in a two-stage, hybrid approach where gas-based fracture initiation is first performed followed by hydraulic emplacement of the solid amendments of interest. However, distribution of solids in a liquid suspension that does not have the high viscosity of a cross-linked gel will be very limited due to settling out (gravity) and filtration by the soil in the unpropped pneumatic fracture. It is also important to note that incorporation of a solid amendment into a high-viscosity fluid for hydraulic emplacement is a patented process (U.S. patent number 7,179,381). Therefore, remedial project managers should seek and obtain the necessary information to make informed decisions at the planning/procurement stage of a PET project.
- Gas-inflatable packers instead of water packers are most often used during implementation of PPE. Proper health and safety measures should be taken as appropriate.

5.0 PERMEABILITY ENHANCEMENT IMPLEMENTATION

5.1 PROCUREMENT CONSIDERATIONS

Regulatory requirements vary by state, but the sometimes negative perception of hydraulic fracturing for oil and gas could lead to regulatory hold-ups with implementation in some states. Proper education of reviewers to explain the significant differences between environmental PET and fracturing typically used in oil and gas production might be necessary. **Attachment B** is provided as an example of a presentation that has been used to help inform stakeholders about this technology. As with many newer technologies, project managers who are considering use of PET should build time into review and approval schedules to accommodate extra meetings and regulatory interface. Some states have started to require fracturing-specific permitting and project managers should determine if those rules apply. It should be noted that for some states, almost all of the chemical reagents used for HPE (including the silica sand, the shear-thinning fluid, and the polymer-based crosslinkers) are on the approved list of chemicals to be used for in situ treatment applications and should be stated as such to avoid unnecessary delays due to the permitting process.

HPE and PPE require highly specialized, proprietary equipment for proper application. Few vendors are available who can properly implement the technologies. Furthermore, emplacement of solid-phase amendments (e.g., ZVI) is patented under U.S. patent number 7,179,381. As stated previously, a variety of drilling vendors claim they can provide fracturing service, but the methods used and results are not comparable to what is performed by those with specialty equipment and patents. Care should be taken when selecting a vendor; inquiries should be made as to whether the potential vendors are licensed under applicable patents for implementing the technologies. Experience in PET must be provided and evaluated as part of the procurement process.

Because of the limited number of vendors, scheduling of work should be completed as soon as possible once PET is selected as an appropriate remedial option. While this demonstration project did not experience any challenges with scheduling the work, as PET becomes a more widely accepted technology, the availability of equipment may become a limitation. Similarly, coordination between drillers and PET vendors should be initiated early to ensure equipment and personnel availability as well as compatibility between the drilling and the PET equipment.

Close coordination between the project technical team, the contracting officer, and the remedial project manager will be required to procure a vendor who is capable of achieving the desired results. Detailed performance specifications must be developed during the procurement stage and conformance with such specifications must be verified during field implementation. A combination of advanced geophysics monitoring techniques such as tiltmeters and conventional soil and groundwater sampling can be used to facilitate such verification. Some examples of specification details that should be included are:

- A cross-linked, high-viscosity gel (e.g., cross-linked guar) shall be used as the delivery fluid when emplacement of a solid amendment is desired.
- The vendor shall have the capability to perform PET using either the top-down or bottom-up emplacement methodology, with or without packer assistance, and using a variety of conventional drilling techniques suitable to the site-specific geological conditions.

- The vendor shall have the capability of performing a “blender-stall” or equivalent mixing test to determine chemical compatibility and optimal mass loading of solids for a given gel.
- An enzyme breaker shall be used to break the cross-linked gel after emplacement.
- All delivery fluid components shall be non-hazardous and biodegradable.
- The vendor shall have the capability of performing tiltmeter geophysics (see **Section 5.2**), including inverse modeling of the results, in order to provide a 3D visualization of the injection network.
- The vendor shall provide such visualization of the initiated fracture network in a timely manner to facilitate real-time decision making.
- The vendor shall provide the appropriate injection equipment (i.e., triplex pumps or equivalent) capable of injecting a high-viscosity slurry at a high injection rate (>10 gpm) and high pressure (>100 psi).
- The vendor shall provide ancillary monitoring equipment capable of producing real-time pressure versus flow rate curves to facilitate confirmation of fracture initiation and subsequent field decisions.

5.2 PERFORMANCE MONITORING REQUIREMENTS AND RECOMMENDATIONS

A variety of conventional and advanced geophysical methods can be used to facilitate performance monitoring during and following PET applications. These methods and associated performance success criteria are summarized in **Table 5-1**. A brief discussion regarding how these different techniques can be used at a given site is provided below.

5.2.1 Conventional Methods

Periodic monitoring of basic parameters such as water levels and wellhead pressures, and collection of grab groundwater samples that may be under pressure as a result of PET applications, can provide useful and real-time insights on radius of distribution. Deformation in ground surface may also occur and can be monitored during PET by performing a surface survey. Note that the surface survey can only provide marginal evidence of fracture initiation and subsurface amendment emplacement. Details pertinent to the fracture network with respect to the fracture length, orientation, and aperture, for examples, cannot be elucidated using this method.

In instances where a solid or aqueous amendment can be visually observed (e.g., sand, EHC), measured using a field instrument (e.g., fluorescein), or qualitatively detected (e.g., ZVI using a magnet), soil confirmation sampling using conventional drilling and sampling techniques represents a useful and cost-effective way to verify amendment delivery and distribution in the subsurface both laterally and vertically. Similarly, performance monitoring can be performed at nearby monitoring wells to facilitate evaluation of remedial progress with respect to changes in geochemical conditions, contaminant profile, and microbiology, for example. Monitoring of an anionic or fluorescent tracer added to the fracture fluid or amendment-specific parameters such as TOC, persulfate, or total iron can also provide yet another line of evidence of delivery.

Type	Approach	Assessment Type	Performance Indicator	Example
Permeability enhancement monitoring		Emplacement volume	80% of target emplacement volume achieved	Calculations of actual amendment injected divided by target volume
		Visual observation of amendment delivery in nearby wells	Visual detection of emplaced amendment or sand	Observation of amendment in confirmation boreholes
Conventional	Conventional soil sampling	Visual soil confirmation in nearby boreholes following permeability enhancement	Visual/field observation of sand, tracer, and/or amendment during confirmation sampling	Fluorescent tracer used during permeability enhancement can be analytically measured in the field using a fluorometer ZVI or sand emplaced can be observed visually or detected using a magnet
		Analytical soil confirmation in nearby boreholes following permeability enhancement	Increase in amendment concentration by a factor of 2 relative to baseline level if baseline concentration is not highly elevated	Increase in TOC when an organic amendment is emplaced or increase in total iron when ZVI is emplaced
	Hydraulic testing	Aquifer testing in wells subject to permeability enhancement	Approximately an order-of-magnitude in bulk hydraulic conductivity	Hydraulic conductivity estimates via slug tests or pumping tests obtained pre- and post- permeability enhancement
	Conventional groundwater sampling	Changes in redox conditions observed at wells impacted by the permeability enhancement or downgradient of the target treatment zone	Appropriate changes to redox, dependent on amendment emplaced	Development towards reducing conditions typical of sulfate or methanogenic conditions when an organic amendment is emplaced for bioremediation purposes Increase in DO and ORP when a chemical oxidant is emplaced for chemical oxidation applications
		Contaminant concentration in wells directly impacted by the permeability enhancement or downgradient of the target treatment zone	Declining concentrations of contaminants (typical goal is at least 50% reduction)	Evaluation of contaminant trends over time based on groundwater sampling
		Amendment concentration (or electrical conductivity) in wells directly impacted by the permeability enhancement or downgradient of the target treatment zone	Increase in amendment concentration by a factor of 10 relative to baseline level if baseline concentration is not highly elevated	Increase in TOC when an organic amendment is emplaced or increase in ferrous iron when ZVI is emplaced
		Visual observation of amendment delivery in nearby wells	Visual detection of emplaced amendment	Color change to milky white for emulsified oil; gray or black for ZVI
	Advanced geophysics	Tiltmeters	Changes in amendment concentrations in soil where predicted	Increase in amendment concentrations by a factor of 2 (relative to baseline level) within 1 to 3 feet of the tiltmeter-predicted depth-discrete intervals where the initiated fracture network intercepts the confirmation borehole
Injection radius of influence			80% of the target injection radius of influence	Radius of influence greater than 15 feet is typical
Visualization of fracture network			Tiltmeter data should provide capability to develop three-dimensional visualization of the entire fracture network. This visualization should indicate sufficient distribution and connectivity of the fractures to address target treatment zone	See Figure 5-1
Electrical resistivity tomography		Visualization of amendment distribution	These methods are still under development and may be appropriate at sites with low background electrical conductivity	–

Table 5-1. Performance Indicators for Permeability Enhancement

While these conventional PET monitoring methods can be performed with relative ease and cost, they provide only limited, discrete observations of amendment delivery as opposed to an understanding of the full three-dimensional distribution achieved through PET applications. For example, visual observations at nearby monitoring wells may provide information regarding the lateral extent of the PET applications. However, the vertical distribution of the emplaced amendment cannot be determined. While some of vertical information may be elucidated via analysis of confirmation soil samples, these samples represent only a few discrete points in the treatment area, and quantitative analytical results are generally not available in real-time. In contrast, more advanced performance monitoring techniques are available to provide a detailed 3-D visualization of the fracture network to support rapid evaluation of treatment amendment distribution performance via PET. These are discussed in the subsequent section.

5.2.2 Advanced Geophysical Methods

Tiltmeter geophysics used in combination with PET provide a dramatic improvement in the understanding of 3-D amendment distribution in the subsurface. Tiltmeter arrays can be set up at the surface to allow for two-dimensional and 3D mapping of the fracture network generated by PET. A specialized inverse model analysis and interpretation is needed to generate the aforementioned fracture network maps. While the process is time-consuming in both the setup (could take up to 1 hour per fracture interval during field application) and data analysis (several days), such renderings of the interconnected fracture network are critical in strategically placing different components of a remedial system both laterally and vertically. Results from the ESTCP field demonstration project ER-201430 and several other projects utilizing tiltmeter monitoring indicate that such geophysics monitoring technique provides a non-intrusive and cost-effective way to accurately predict the lateral and vertical extent of fractures emanating from a PET borehole. In fact, the ER-201430 results demonstrated that the lateral extent of injections corresponded very well with confirmation soil borings and groundwater data, and that the vertical depth of injection planes (fractures) predicted by the tiltmeter geophysics was within 1 to 3 ft of the depth observed in 92% of confirmation borings (CDM Smith 2019). This demonstrates that the amendment distribution estimated by images such as **Figure 5-1** are highly reliable with appropriate application of this technique.

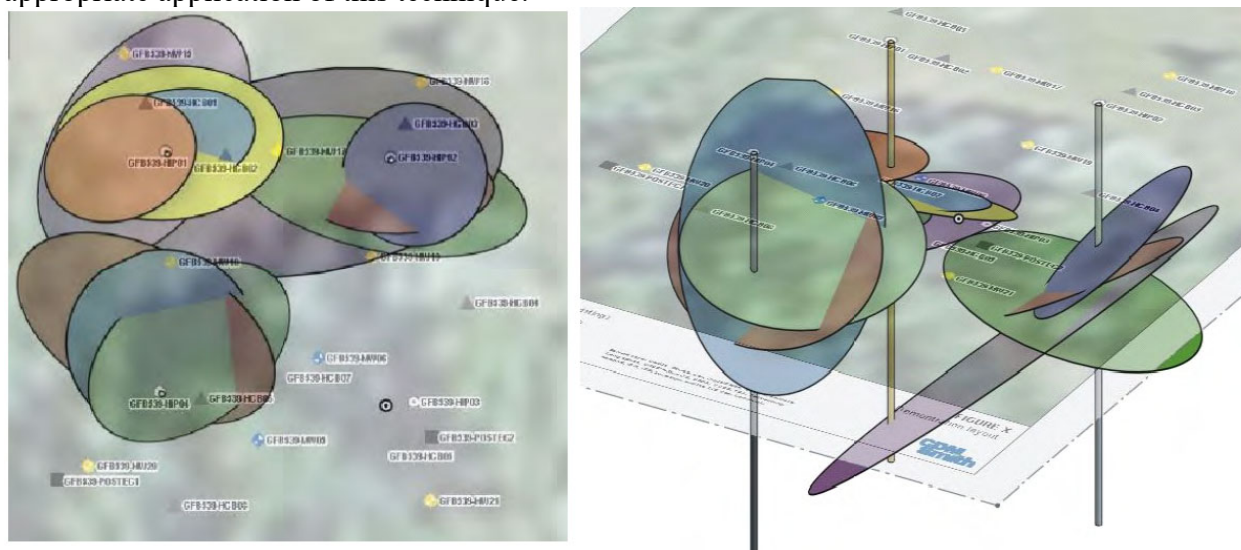


Figure 5-1. 3D Visualization of the Fracture Network Generated at the Grand Forks Air Force Base Site TU504 as part of ER-201430

Advanced geophysics monitoring techniques such as ERT can also be performed in situ during and after PET to provide time-lapsed images of amendment delivery. ERT results obtained during the ESTCP field demonstration project ER-201430 in some cases provided a general indication of zones of significant amendment distribution. However, the results did not provide the high resolution of tiltmeter geophysics. In addition, the ERT monitoring system installation and deployment in the currently available configuration were cumbersome and expensive. The significant contrast in conductivity required for proper ERT imaging renders the technology inapplicable at sites with elevated background conductivities, including coastal and historic seabed sites. Further development of ERT is needed before it can be recommended for wide use in this application.

Similar to ERT, EC logging relies on the significant contrast in conductivity between the injection fluid and background levels and thus is susceptible to the same aforementioned restriction in terms of applicability. In addition, EC logging may be depth- and lithology-limited since it is a DPT-based monitoring technique. However, unlike ERT, EC can be performed very quickly and cost-effectively; however, the accuracy of EC logging as a fracture network monitoring tool has not been comprehensively evaluated as part of ESTCP field demonstration project ER-201430 or in contemporary literature.

5.3 POTENTIAL IMPLEMENTATION ISSUES

This section provides a discussion of the potential implementation issues associated with use of PET in the field.

5.3.1 Nonstandard Equipment Required for Implementation

As discussed above, specialty equipment is required, and adequate time should be built into the schedule to ensure availability at the desired time.

5.3.2 Health and Safety Considerations

Some applications of PET are performed under relatively high pressures. Therefore, it is imperative that all personnel involved in field implementation be familiar with the health and safety concerns associated with pressurized injections and are qualified to operate, supervise, and provide inputs as necessary. Proper health and safety requirements should be applied to protect workers from injury, including limiting access to the immediate vicinity of injection equipment and drilling locations, ensuring avoidance of high-pressure hoses, and general awareness of the ongoing activities. Other health and safety hazards that are often associated with implementation of PETs including the use of heavy equipment; slips, trips, and falls; and potential undesirable exposure to treatment chemicals (e.g., silicosis from ZVI powder or silica sand, exposure to corrosive materials such as peroxide and persulfate). Note that these hazards are present for any conventional injection of these treatment reagents and can generally be mitigated using proper planning and engineering controls.

5.3.3 Amendment Surfacing

Amendment surfacing can be observed during implementation of both hydraulic and hybrid PET. Hydraulic surfacing is generally a gradual seeping of material to the ground surface, although more rapid releases of fluid could occur if short circuiting occurred from shallow initiation depths. Note that significant surfacing as a result of HPE applications was only observed at LCAAP as part of the ESTCP demonstration project. Approximately 100 gallons of surfaced amendment were observed at the site during HPE application at target depths of approximately 40 to 50 feet bgs; the surfacing was likely attributable to past subsurface disturbances that created preferential pathways to the surface. The amendment was containerized in drums and subsequently disposed of properly off-site. Note that HPE was also performed at GFAFB as part of this ESTCP project. Despite the very shallow fracture initiation depths ranging between 10 and 20 feet bgs, very little (less than 5 gallons) amendment surfacing was observed at this Site. Therefore, in most cases, amendment surfacing can be mitigated with relative ease.

Pneumatic surfacing is generally more sudden due to use of high-pressure gas to initiate the fractures. For example, during implementation of PPE at LCAAP in this demonstration, the seal between the upper packer and soil failed and a burst of soil and gas was observed around the drill rod. The vendor prohibits personnel access near the drill location during application, which prevents injury in this situation. To avoid the significant amendment surfacing observed when the pure PPE approach was used, the hybrid PPE approach with fracture initiation by the nitrogen gas stream followed by hydraulically induced emplacement of the liquid amendment was used at LCAAP. In addition to the health and safety concern associated with the high pressures, surfacing can also result in release of concentrated remediation amendment solutions. Therefore, proper spill control should be available on-site to mitigate surfacing.

5.3.4 Monitoring Issues

While not proprietary, tiltmeters are specialty equipment that require trained operators to use them properly. Because of the highly sensitive nature of the tiltmeters, any disturbance requires recalibration/resetting of the instrument. Thus, care must be taken when working around tiltmeters, which is sometimes difficult considering the operations involved in PET (number of people, drill rigs, and equipment). Fortunately, the instruments are relatively easy to reset, but if not handled properly, data quality could be affected. The data provided by tiltmeters has proven to be unmatched in terms of documenting amendment distribution. However, because of their high sensitivity, the proper setup of tiltmeters requires some time (approximately 1 hour per PET location). Proper location of the tiltmeter array is required, including accurate measurements of distance and orientation from the PET initiation point. This can add time to the mobilization, and potentially slow operations on-site. Because of the short duration of PPE fracture initiation, the resolution of tiltmeter readings may not be appropriate for monitoring all pneumatic injections. Tiltmeters record changes every 10 seconds, which may not be sufficiently frequent enough to capture short-term changes during pneumatic injections. Nevertheless, at LCAAP, the tiltmeters appeared to capture the pneumatic injections fairly well (CDM Smith 2019).

Monitoring techniques requiring a significant difference in electrical conductivity or resistivity between the water present in the formation and the injection fluid such as ERT or EC may be limited at sites with high background conductivity (i.e., coastal sites or historic sea beds). At these

sites, salt solutions that are sufficiently conductive to provide the proper conductivity/resistivity contrast may inhibit biological activity or may induce density-driven flows. However, at ERT-compatible sites, this technique presents a potential for real-time monitoring and visualization of amendment delivery in the subsurface, albeit at lower spatial resolution than tiltmeters provide. Similarly, at sites where DPT drilling is feasible, EC logging can be used to monitor the vertical and lateral distribution of amendment with a high degree of efficiency and low cost.

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Appendix A – Summary of Literature Review

Citation	Year	Site	Fracture Method	Contaminant Type				NAPL Presence?	Lithologies				Emplacement Strategy					
				VOCs	TPHs	BTEX	Jet Fuel		Sand / Gravel	Silt / Clay	Bedrock	Glacial Till	Air	Sand	Dye	Solid Amendment	Aqueous Amendment	
North Wind Services, LLC. 2017. Final Remedial Action-Construction Report F.E. Warren AFB Former Atlas E Missile Site 12. July.	2015-2017	Atlas 12, CO	Hydraulic	X					X	X	X					X	X	Continued on next page
Swift, D., J. Rothermel, L. Peterson, B. Orr, G.H. Bures, and J. Weidhaas. 2012. Remediating TCE-Contaminated Groundwater in Low-Permeability Media Using Hydraulic Fracturing to Emplace Zero-Valent Iron/Organic Carbon Amendment. Remediation, 22: 49–67. doi:10.1002/rem.21310.	2012	Atlas 12, CO	Hydraulic	X							X					X	X	
Bures, G., T.J. Williams, E. Mance, and C. Clark. 2015. In Situ Chemical Oxidation in Clays using Hydraulic Fracturing. September.	2015	Edmonton, Canada	Hydraulic	X						X				X			X	
Tzovolou, D.N., M.A. Theodoropoulou, D. Blanchet, F. Haeseler, M. Jeczalik, T. Kasela, W. Slack, and C.D. Tsakiroglou. 2015. Environmental Earth Sciences, September 2015, Volume 74, Issue 6, pp 4907–4925	2015	Kluczewo airport, Poland	Hydraulic				X	X		X			X					
Arnason, J.G., M. Harkness, and B. Butler-Veytia. 2014. Evaluating the Subsurface Distribution of Zero-Valent Iron Using Magnetic Susceptibility. Groundwater Monitoring & Remediation 34, No. 2 pp 96-106.	2014	Anonymous Industrial Facility, Southeastern U.S.	Hydraulic, Pneumatic, DPT	X					X	X						X	X	
Lee, A., S.H. Abrams, E. Moskal, S. Ciambuschini, and D. Moss. 2013. Chemical and Biological Reduction of PCE by Pneumatic Fracturing and Injection of ZVI in Saprolite. Remediation, 23: pp 7-21. doi:10.1002/rem.21363.	2013	Maryland	Pneumatic	X				X	X	X	X					X		
Sheutz, C., M.M. Broholm, N.D. Durant, E. Begtrup Weeth, T.H. Jorgensen, P. Dennis, C.S. Jacobsen, E.E. Cox, J.C. Chambon, and P.L. Bjerg. 2010. Field Evaluation of Biological Enhanced Reductive Dechlorination of Chloroethenes in Clayey Till. Environmental Science & Technology, 2010, Vol. 44, No. 13, pp 5134–5141.	2010	Odense, Denmark	Hydraulic	X					X	X		X		X			X	

Citation	Year	Site	Depth Ranges				Radius of Influence				Downhole Method			Monitoring Techniques						
			<6ft (<2m)	6-20ft (2-6m)	20-40ft (6-12m)	>40ft (>12m)	<6ft (<2m)	6-20ft (2-6m)	20-40ft (6-12m)	>40ft (>12m)	Packer	Top-Down	Others	Tiltmeter	EC	ERT	other?	Borehole Logging	Trenching	
North Wind Services, LLC. 2017. Final Remedial Action-Construction Report F.E. Warren AFB Former Atlas E Missile Site 12. July.	2015-2017	Atlas 12, CO			X	X				X	X			Not available						Continued on next page
Swift, D., J. Rothermel, L. Peterson, B. Orr, G.H. Bures, and J. Weidhaas. 2012. Remediating TCE-Contaminated Groundwater in Low-Permeability Media Using Hydraulic Fracturing to Emplace Zero-Valent Iron/Organic Carbon Amendment. Remediation, 22: 49–67. doi:10.1002/rem.21310.	2012	Atlas 12, CO			X	X				X	X		X							
Bures, G., T.J. Williams, E. Mance, and C. Clark. 2015. In Situ Chemical Oxidation in Clays using Hydraulic Fracturing. September.	2015	Edmonton, Canada		X	X			X				X	Not available							
Tzovolou, D.N., M.A. Theodoropoulou, D. Blanchet, F. Haeseler, M. Jeczalik, T. Kasela, W. Slack, and C.D. Tsakiroglou. 2015. Environmental Earth Sciences, September 2015, Volume 74, Issue 6, pp 4907–4925	2015	Kluczewo airport, Poland		X			Not available				Not available			Not available						
Arnason, J.G., M. Harkness, and B. Butler-Veytia. 2014. Evaluating the Subsurface Distribution of Zero-Valent Iron Using Magnetic Susceptibility. Groundwater Monitoring & Remediation 34, No. 2 pp 96-106.	2014	Anonymous Industrial Facility, Southeastern U.S.		X				X	X			Top-Down & Bottom-Up					Magnetic Susceptibility	X		
Lee, A., S.H. Abrams, E. Moskal, S. Ciambuschini, and D. Moss. 2013. Chemical and Biological Reduction of PCE by Pneumatic Fracturing and Injection of ZVI in Saprolite. Remediation, 23: pp 7-21. doi:10.1002/rem.21363.	2013	Maryland		X	X	X		X		X	X	Bottom-Up	Not available							
Sheutz, C., M.M. Broholm, N.D. Durant, E. Begtrup Weeth, T.H. Jorgensen, P. Dennis, C.S. Jacobsen, E.E. Cox, J.C. Chambon, and P.L. Bjerg. 2010. Field Evaluation of Biological Enhanced Reductive Dechlorination of Chloroethenes in Clayey Till. Environmental Science & Technology, 2010, Vol. 44, No. 13, pp 5134–5141.	2010	Odense, Denmark			X			X			Not available			X					X	

Citation	Year	Site	Notes	Findings/Summary
North Wind Services, LLC. 2017. Final Remedial Action-Construction Report F.E. Warren AFB Former Atlas E Missile Site 12. July.	2015-2017	Atlas 12, CO	Approximately 8 acres, Frac-Rite was contractor, 51 wells were sampled	Post-fracturing TOC ranged from 2.8 to 34 mg/L. Baseline TCE plume with TCE >100 ug/L has been significantly reduced in size, but the lower concentration plume areas are not degrading as effectively. The core plumes identified during baseline sampling has been reduced to a single localized hot spot around one well. Concentration-based mass reduction estimates there hass been approximately 90% reduction in TCE mass on site.
Swift, D., J. Rothermel, L. Peterson, B. Orr, G.H. Bures, and J. Weidhaas. 2012. Remediating TCE-Contaminated Groundwater in Low-Permeability Media Using Hydraulic Fracturing to Emplace Zero-Valent Iron/Organic Carbon Amendment. Remediation, 22: 49–67. doi:10.1002/rem.21310.	2012	Atlas 12, CO	Field pilot test (April/May 2009) to emplace ZVI and organic carbon into fine-grained sandstone to remediate TCE-contaminated groundwater followed by two years of monitoring.	"Geophysical monitoring and inverse modeling show that the network of amendment-filled fractures extends throughout the aquifer volume targeted in the pilot test zone. Two years of subsequent groundwater monitoring demonstrate that amendment addition resulted in development of geochemical conditions favorable to both abiotic and biological TCE degradation, that TCE concentrations were substantially reduced (i.e., greater than 90 percent reduction in TCE mass), and that the primary degradation processes are likely abiotic. The pilot-test data aided in re-evaluating the conceptual site model and in designing the full-scale remedy to address a larger portion of the TCE-contaminated groundwater plume."
Bures, G., T.J. Williams, E. Mance, and C. Clark. 2015. In Situ Chemical Oxidation in Clays using Hydraulic Fracturing. September.	2015	Edmonton, Canada	A fracture network was emplaced within the solvent plume area of the site in October, 2006 using the Frac Rite™ process. A total of 3,715 litres of Oxytek™ solution was injected into wells in November, 2006. Approx 30 tons of sand was emplaced. A total of 8,825 litres of KMnO4 slurry at approximately 4% solution by weight was injected into wells in 2007. An additional 18,000 litres of a 12% solution oxidant of NaMnO4 was injected during 12 injection events in 2008 and 2009.	"After 18 injections of peroxidant solutions over three years, the groundwater PCE plume at the former dry cleaner site has been reduced to concentrations below risk-based derived criteria . Elevated concentrations of PCE persist in core wells centered near the former source area due to leaching of PCE and other chlorinated aliphatics from the clay matrix into fracture pathways."
Tzovolou, D.N., M.A. Theodoropoulou, D. Blanchet, F. Haeseler, M. Jeczalik, T. Kasela, W. Slack, and C.D. Tsakiroglou. 2015. Environmental Earth Sciences, September 2015, Volume 74, Issue 6, pp 4907–4925	2015	Kluczewo airport, Poland	A bioventing pilot test was performed on one cell of the vadose zone of a low permeability and fractured site. Air was injected and extracted through hydraulic fractures that were installed to enhance effectively the horizontal permeability of the soil. Soil samples were collected from seven depths of twelve wells of the pilot Cell.	"Due to the heterogeneous nature of the porous matrix over a broad range of pore sizes (from 1 nm to 1 mm), the rate of intrinsic biodegradation of jet fuel in matrix was limited. The main pollutant removal mechanism was the ventilation in which most volatile hydrocarbons vaporized and diffused toward the gas phase that was flowing along the preferential flow pathways. Hydraulic fractures facilitated and accelerated the pollutant remediation rate by enhancing the interconnectivity of the porous matrix with natural fracture systems or any other type of natural preferential flow pathway. " Hydrocarbon reduction was higher than 75% in the sandy soils, but NAPL removal efficiency in the low k layers was low.
Arnason, J.G., M. Harkness, and B. Butler-Veytia. 2014. Evaluating the Subsurface Distribution of Zero-Valent Iron Using Magnetic Susceptibility. Groundwater Monitoring & Remediation 34, No. 2 pp 96-106.	2014	Anonymous Industrial Facility, Southeastern U.S.	A pilot study using pneumatic fracturing was performed in January of 2009, followed by side-by-side pilot studies of direct injection and hydraulic fracturing in September of 2010. Fullscale implementation of the EHC biobarrier using direct injection occurred during the spring of 2012.	"[Magnetic susceptibility] represents a useful approach for determining the subsurface distribution of ferromagnetic amendments such as ZVI that is highly sensitive, quantitative, and objective." "When used in support of side-byside pilot studies, it was effective in mapping amendment distribution and differentiating performance between various delivery methods (pneumatic fracturing, hydraulic fracturing, and direct injection) for delivery of EHC. Most importantly, it was used to verify EHC distribution during full-scale application and provide significant understanding of the way changes in process variables impacted the emplace-ment process during direct injection."
Lee, A., S.H. Abrams, E. Moskal, S. Ciambruschini, and D. Moss. 2013. Chemical and Biological Reduction of PCE by Pneumatic Fracturing and Injection of ZVI in Saprolite. Remediation, 23: pp 7-21. doi:10.1002/rem.21363.	2013	Maryland	A commercial brownfields redevelopment site in Maryland. A 20,000-square-foot source area impacted with PCE at concentrations greater than 15,000 ug/L was treated. A hybrid pneumatic approach was used to fracture and emplace amendments, with amendment delivery achieved using hydraulic fracturing pressures.	" An average ZVI dosage of 0.0024 iron-to-soil mass ratio within the overburden zone led to a 75 percent decrease in PCE mass in less than one year. For the weathered bedrock zone, an average 0.0045 iron-to-soil mass ratio resulted in a 92 percent decrease in PCE mass during the same period. The reducing environment and hydrogen generated by the ZVI may have stimulated Dehalobacter populations, as evidenced by concentrations up to 10E4 cells per milliliter measured within the treatment area despite a groundwater pH as high as 9."
Sheutz, C., M.M. Broholm, N.D. Durant, E. Begtrup Weeth, T.H. Jorgensen, P. Dennis, C.S. Jacobsen, E.E. Cox, J.C. Chambon, and P.L. Bjerg. 2010. Field Evaluation of Biological Enhanced Reductive Dechlorination of Chloroethenes in Clayey Till. Environmental Science & Technology, 2010, Vol. 44, No. 13, pp 5134–5141.	2010	Odense, Denmark	Hydraulic fracturing was used to emplace a green colored sand fracture within the clayey till at approximately 7.5 m bgs. The location and orientation of the fracture was determined by advancing a combination of core and auger borings in a high-density sampling network. A 208 L batch mixture of site groundwater, Newman Zone, lithium bromide tracer, and KB-1 was injected into the test plot into a sand-filled hydraulic fracture.	The fracture distribution was nonuniform. The observed fracture thickness typically ranged from a few mm to a few cm. "Fermentation of the ERD solution caused the establishment of a dechlorinating bioactive zone in the fracture within 1 month of injection. By 148 days, all the cDCE in the fracture was dechlorinated to ethene. Analysis of a clay core from Day 150 indicated that electron donor and fermentation products diffused from the fracture at least 10 cm into clay and that stimulated dechlorination occurred in the clay in the presence of Dehalococcoides (7.9-104 cells g–1). Comparison of chloroethene profiles in the Day 150 core to modeled diffusion profiles indicated degradation occurred in a bioactive zone extending approximately 5 to 6 cm into the clay matrix. These data suggest that a bioactive zone established in a sandfilled fracture can expand into the adjacent clayey till matrix and facilitate mass transfer from the matrix to the bioactive zone.""...by Day 540, all cDCE and VC in the clayey till within an apparent distance of 22cm of the fracture was completely degraded and at least partially by dechlorination to ethene and ethane."

Citation	Year	Site	Fracture Method	Contaminant Type				NAPL Presence?	Lithologies				Emplacement Strategy					
				VOCs	TPHs	BTEX	Jet Fuel		Sand / Gravel	Silt / Clay	Bedrock	Glacial Till	Air	Sand	Dye	Solid Amendment	Aqueous Amendment	
Christiansen, C. M., I. Damgaard, M. Broholm, T. Kessler, K.E. Klint, B. Nilsson, and P.L. Bjerg. 2010. Comparison of Delivery Methods for Enhanced In Situ Remediation in Clay Till. Ground Water Monitoring & Remediation, No. 4, Fall 2010, 30: pp. 107–122. doi:10.1111/j.1745-6592.2010.01314.x	2010	Vasby, Denmark	Hydraulic, Pneumatic, DPT							X		X		X (hydraulic only)	X			Continued on next page
Christiansen, C.M., C. Riis, S.B. Christensen, M.M. Broholm, A.G. Christensen, K.E.S. Klint, J.S.A. Wood, P. Bauer-Gottwein, and P.L. Bjerg. 2008. Characterization and Quantification of Pneumatic Fracturing Effects at a Clay Till Site. Environmental Science & Technology, 2008, Vol. 42, No. 2, pp 570–576.	2008	Denmark	Pneumatic	Not available						X			X		X			
Bures, G., K.S. Sorenson, J.P. Martin, R.F. Reinke. 2015. "BIO-FRACING™ FOR ENHANCED IN SITU BIOREMEDIATION OF CHLORINATED SOLVENTS IN LOW-PERMEABILITY SEDIMENTS. September.	2003	Distler Brickyard Superfund Site	Hydraulic	X					X	X				X		X		
Wong, R.C.K. and M.C. Alfaro. 2001. Fracturing in low permeability soils for remediation of contaminated ground, Canadian Geotechnical Journal, 2001, 38(2): 316-327	2001	Battle Lake, Canada	Hydraulic	Not available					X	X		X		X				
Siegrist, R.L., R.K. Lowe, L.C. Murdoch, T.L. Case, and D.A. Pickering. 1999. In Situ Oxidation by Fracture Emplaced Reactive Solids. Journal of Environmental Engineering 125, No. 5: 429–440.	1999	DOE Portsmouth, Ohio	Hydraulic	X												X		
Siegrist, R.L., W.W. Slack, T.C. Houk.1998. X-231A demonstration of in-situ remediation of DNAPL compounds in low permeability media by soil fracturing with thermally enhanced mass recovery or reactive barrier destruction. 407 p. CONTRACT AC05-96OR22464, Report.	1998	Portsmouth	Hydraulic	X				X	X	X			X	X		X		

Citation	Year	Site	Depth Ranges				Radius of Influence				Downhole Method			Monitoring Techniques						
			<6ft (<2m)	6-20ft (2-6m)	20-40ft (6-12m)	>40ft (>12m)	<6ft (<2m)	6-20ft (2-6m)	20-40ft (6-12m)	>40ft (>12m)	Packer	Top-Down	Others	Tiltmeter	EC	ERT	other?	Borehole Logging	Trenching	
Christiansen, C. M., I. Damgaard, M. Broholm, T. Kessler, K.E. Klint, B. Nilsson, and P.L. Bjerg. 2010. Comparison of Delivery Methods for Enhanced In Situ Remediation in Clay Till. Ground Water Monitoring & Remediation, No. 4, Fall 2010, 30: pp. 107–122. doi:10.1111/j.1745-6592.2010.01314.x	2010	Vasby, Denmark	X	X			X (DPT)	X (pneumatic)	X (hydraulic)		X (pneumatic)	X (DPT, hydraulic)						X	X	Continued on next page
Christiansen, C.M., C. Riis, S.B. Christensen, M.M. Broholm, A.G. Christensen, K.E.S. Klint, J.S.A. Wood, P. Bauer-Gottwein, and P.L. Bjerg. 2008. Characterization and Quantification of Pneumatic Fracturing Effects at a Clay Till Site. Environmental Science & Technology, 2008, Vol. 42, No. 2, pp 570–576.	2008	Denmark		X	X		X					Bottom-Up						X	X	
Bures, G., K.S. Sorenson, J.P. Martin, R.F. Reinke. 2015. "BIO-FRACING™ FOR ENHANCED IN SITU BIOREMEDIATION OF CHLORINATED SOLVENTS IN LOW-PERMEABILITY SEDIMENTS. September.	2003	Distler Brickyard Superfund Site			X	X			X		Not available			X				X		
Wong, R.C.K. and M.C. Alfaro. 2001. Fracturing in low-permeability soils for remediation of contaminated ground, Canadian Geotechnical Journal, 2001, 38(2): 316-327	2001	Battle Lake, Canada		X				X			X	X		X		X			X	
Siegrist, R.L., R.K. Lowe, L.C. Murdoch, T.L. Case, and D.A. Pickering. 1999. In Situ Oxidation by Fracture Emplaced Reactive Solids. Journal of Environmental Engineering 125, No. 5: 429–440.	1999	DOE Portsmouth, Ohio	X	X			Not available					X						X		
Siegrist, R.L., W.W. Slack, T.C. Houk.1998. X-231A demonstration of in-situ remediation of DNAPL compounds in low permeability media by soil fracturing with thermally enhanced mass recovery or reactive barrier destruction. 407 p. CONTRACT AC05-96OR22464, Report.	1998	Portsmouth	X	X				X				X						X		

Citation	Year	Site	Notes	Findings/Summary
Christiansen, C. M., I. Damgaard, M. Broholm, T. Kessler, K.E. Klint, B. Nilsson, and P.L. Bjerg. 2010. Comparison of Delivery Methods for Enhanced In Situ Remediation in Clay Till. Ground Water Monitoring & Remediation, No. 4, Fall 2010, 30: pp. 107–122. doi:10.1111/j.1745-6592.2010.01314.x	2010	Vasby, Denmark	The testing was carried out at an uncontaminated part of a farm site, previously used for storage of chlorinated solvents. Pneumatic fracturing used atomization approach with nitrogen carrier gas. Hydraulic fracturing approach was completed using a cross-linked sand/guar gel using rudimentary downhole tooling. DPT injection was performed at pressures exceeding fracturing pressures but included injection of only an aqueous tracer solution.	"Results show that pneumatic fracturing with nitrogen gas and propagation pressures of 1 to 9 bar had a distribution radius of less than 2 m, and produced dense networks of tracer-filled natural fractures above the redox boundary (0 to 3 m b.s.) and widely spaced, discrete, induced, tracer-filled subhorizontal fractures at depth (>3 m b.s.). Direct-push delivery at pressures of 8 to 30 bar had a distribution radius of approximately 1 m, distributed tracer primarily in natural fractures above the redox boundary and in discrete, closely spaced (but not merging) induced fractures below the redox boundary. Hydraulic fracturing with a sand-guar mixture at pressures of 0 to 6 bar produced an elliptical, asymmetrical, bowl-shaped fracture with a physical radius of approximately 3.5 m at 3 m b.s."
Christiansen, C.M., C. Riis, S.B. Christensen, M.M. Broholm, A.G. Christensen, K.E.S. Klint, J.S.A. Wood, P. Bauer-Gottwein, and P.L. Bjerg. 2008. Characterization and Quantification of Pneumatic Fracturing Effects at a Clay Till Site. Environmental Science & Technology, 2008, Vol. 42, No. 2, pp 570–576.	2008	Denmark	"The study applied injection of five tracers with different characteristics (bromide, uvitex, fluorescein, rhodamine WT, and brilliant blue), subsequent tracer-filled fracture documentation via direct and indirect methods, and geological characterization of the fractured site. The direct documentation methods consisted of Geoprobe coring, augering, and excavation."	"Mass balance showed tracer was distributed within 2 m of the fracturing well, mainly in existing fractures above the redox boundary (2 to 4 m.b.s.; 5 to 10 cm spacing). Spacing of observed tracer-filled fractures was large (>1 m) at greater depths. In this trial, pneumatic fracturing was able to spread tracer into both previously hydraulically active and inactive natural fractures of a basal clay till. However, at depths below the redox boundary, the distance between activated fractures is large, and the pneumatic fracturing technology is, therefore, in its present state not considered able to overcome the mass transfer limitations set by diffusion in the this type of low-permeability matrix at depth."
Bures, G., K.S. Sorenson, J.P. Martin, R.F. Reinke. 2015. "BIO-FRACING"™ FOR ENHANCED IN SITU BIOREMEDIATION OF CHLORINATED SOLVENTS IN LOW-PERMEABILITY SEDIMENTS. September.	2003	Distler Brickyard Superfund Site	This work followed a field pilot which fractured silty sands and silty clays to empalce 325 lbs of Chitin and 1,550 lbs of sand into 3 fractures within a TCE/cis source area.	Estimated coverage of the Chitin mixture was 75%. Placement efficiency of the Chitin/sand was 97% in the silty sands, and 99% in the silty clays. "Tiltmeter fracture mapping showed that 50% of the fractures (of the 36 total inc. pilot) were near-horizontal to gently dipping (35 deg or less). Fractures in the upper clay were mostly moderately dipping (36 to 60 deg), and fractures in the silty sand were moderate to steeping dipping. Sulfate concentrations were typically below 20 mg/L across the site from 40-60 mg/L pre-test. Ferrous iron, VFAs, and methane increased, and ORP is methanogenic. Groundwater sampling data show TCE and cis-DCE concentrations that have decreased to near or below maximum concentration levels in all of the original pilot test wells since full scale chitin fracturing at the site in May, 2003, while ethene increased." "The full scale in situ application of fracture-enhanced bioremediation of chlorinated aliphatic hydrocarbons using a chitin as a solid phase, electron donor amendment was determined to be technically and commercially feasible. A total (inc. pilot) of 5,145 lbs of chitin and 19,420 lbs of frac sand were successfully emplaced; fracturing resulted in an increase of an order of magnitude in hydraulic conductivity; distribution of chitin by hydraulic soil fracturing provided good to excellent lateral and vertical coverage within the contaminant source area"
Wong, R.C.K. and M.C. Alfaro. 2001. Fracturing in low permeability soils for remediation of contaminated ground, Canadian Geotechnical Journal, 2001, 38(2): 316-327	2001	Battle Lake, Canada	"Sand-propped hydraulic fractures were placed from vertical and horizontal wells at a test facility. Field excavations were conducted to expose the fractures and inspect their distribution and geometry. ERT and tiltmetering was also done to attempt to map the fractures."	"Fractures that were mapped by field excavation were found to be near horizontal, implying that the soil formation is overconsolidated. It was also observed that the sand "proppant" was thicker at locations where the soil layers were relatively weak or contained weak fissures. Electrical resistivity tomography (ERT) was also conducted in an attempt to map the fractures. There was no indication that fractures were being mapped by this geophysical technique. Fracture mapping based on tiltmeter data analyses conformed closely with the actual fracture placement in the vertical well but did not properly predict the actual fracture placement in the horizontal well"
Siegrist, R.L., R.K. Lowe, L.C. Murdoch, T.L. Case, and D.A. Pickering. 1999. In Situ Oxidation by Fracture Emplaced Reactive Solids. Journal of Environmental Engineering 125, No. 5: 429–440.	1999	DOE Portsmouth, Ohio	Fracture emplacement was monitored, and soil and ground water conditions were characterized. After 3, 10, and 15 mo of emplacement, continuous cores were collected and morphologic and geochemical data were taken across the fracture zones	"Controlled degradation tests were completed using site ground water with TCE concentrations near 53, 144, and 480 mg/L, equivalent to 0.5, 1.2, and 4.1 g TCE per kg media, respectively. The iron-filled fractures formed a discrete reactive seam less than 1 cm thick, wherein the Eh decreased and reductive dechlorination could occur, but effects in the adjacent silty clay soils were negligible. Though the emplaced iron exhibited some surface corrosion after extended emplacement in the subsurface, its reactivity was unaffected. Iron from the fractures degraded TCE at efficiencies of as much as 36% after 24–48 hr of contact, which is consistent with Fe0 packed bed degradation half-lives of 1 to 2 hr. The permanganate-filled fractures yielded a diffuse reactive zone that expanded over time, reaching 40 cm in thickness after 10 mo. Throughout this oxidizing zone, the degradation efficiency was >99% after 2 hr of contact for dissolved TCE at 0.5 and 1.2 mg TCE per g of media. When exposed to higher TCE loadings (i.e., 4.1 mg per g), degradation efficiencies after 10 mo dropped to 70% as the TCE load exceeded the oxidant capacity remaining. These efficiencies and rates are consistent with oxidation stoichiometry and previously determined half-lives of <2 min for permanganate oxidation of TCE. In both test cells there were no marked effects on the chemistry or contamination levels in the ground water beneath the cells."
Siegrist, R.L., W.W. Slack, T.C. Houk.1998. X-231A demonstration of in-situ remediation of DNAPL compounds in low permeability media by soil fracturing with thermally enhanced mass recovery or reactive barrier destruction. 407 p. CONTRACT AC05-96OR22464, Report.	1998	Portsmouth	"Utilized subsurface manipulation of the low k soils through soil fracturing with thermally enhanced mass recovery or horizontal barrier in place destruction." "A set of four test cells was established at the X-231A land treatment unit at the DOE PORTS plant in August 1996 and a series of demonstration field activities occurred through December 1997."	Hydraulic methods appear to be more suited to low permability media like silt and clay deposits than pneumatic methods. If the fractures can be spaced closeley together, they can be used to enhance recovery of VOCs, deliver and distribute treatment agents, and placement of treatment media.

Citation	Year	Site	Fracture Method	Contaminant Type				NAPL Presence?	Lithologies				Emplacement Strategy						
				VOCs	TPHs	BTEX	Jet Fuel		Sand / Gravel	Silt / Clay	Bedrock	Glacial Till	Air	Sand	Dye	Solid Amendment	Aqueous Amendment		
Murdoch, L.C. Forms of hydraulic fractures created during a field test in overconsolidated glacial drift. 1995. Quarterly Journal of Engineering Geology and Hydrogeology, 28, 23-35. February.	1995	Cincinnati, Ohio	Hydraulic	No contamination					X	X		X		X					Continued on next page
Anderson, D.B., B.M.Peyton, J. J. Liskowitz, C. Fitzgerald, and J.R. Schuring. 1994. Enhanced in situ bioremediation with pneumatic fracturing. In: Applied Bioremediation of Petroleum Hydrocarbons. R.E. Hinchee, J.A., Kittel, H. Reisinger. Battelle Press, Columbus, OH, USA	1994	Tinker AFB	Pneumatic	X				X	X	X	X		X						

Citation	Year	Site	Depth Ranges				Radius of Influence				Downhole Method			Monitoring Techniques						
			<6ft (<2m)	6-20ft (2-6m)	20-40ft (6-12m)	>40ft (>12m)	<6ft (<2m)	6-20ft (2-6m)	20-40ft (6-12m)	>40ft (>12m)	Packer	Top-Down	Others	Tiltmeter	EC	ERT	other?	Borehole Logging	Trenching	
Murdoch, L.C. Forms of hydraulic fractures created during a field test in overconsolidated glacial drift. 1995. Quarterly Journal of Engineering Geology and Hydrogeology, 28, 23-35. February.	1995	Cincinnati, Ohio	X	X				X	X	X		X							X	Continued on next page
Anderson, D.B., B.M.Peyton, J. J. Liskowitz, C. Fitzgerald, and J.R. Schuring. 1994. Enhanced in situ bioremediation with pneumatic fracturing. In: Applied Bioremediation of Petroleum Hydrocarbons. R.E. Hinchee, J.A., Kittel, H. Reisinger. Battelle Press, Columbus, OH, USA	1994	Tinker AFB		X	X			X		X		X					Surface heave and vacuum tests			

Citation	Year	Site	Notes	Findings/Summary
Murdoch, L.C. Forms of hydraulic fractures created during a field test in overconsolidated glacial drift. 1995. Quarterly Journal of Engineering Geology and Hydrogeology, 28, 23-35. February.	1995	Cincinnati, Ohio	Hydraulic injection of guar gum, sand, enzyme to break down guar, KCL 3%, and dyes for identifying fractures.	" Hydraulic fractures as long as 13 m were created at depths of 2 m in overconsolidated silty clay glacial drift. The vicinity of each fracture was excavated, typically revealing a continuous fracture whose geometry was defined by four zones: a vertical fracture adjacent to the parent borehole; a flat-lying fracture in the vicinity of the borehole; a gently dipping fracture that assumes a preferred direction of propagation away from the borehole; a vertical fracture that intersects the ground surface. The hydraulic fractures were gently dipping with a preferred direction of propagation that apparently was controlled by loading of the ground surface; the fractures propagated away from a back hoe parked next to the parent borehole. Sand pumped into some of the fractures formed permeable layers that could increase flow into or out of low-permeability soils or rock, suggesting that sand-filled hydraulic fractures could have a variety of geotechnical or environmental applications."
Anderson, D.B., B.M.Peyton, J. J. Liskowitz, C. Fitzgerald, and J.R. Schuring. 1994. Enhanced in situ bioremediation with pneumatic fracturing. In: Applied Bioremediation of Petroleum Hydrocarbons. R.E. Hinchee, J.A., Kittel, H. Reisinger. Battelle Press, Columbus, OH, USA	1994	Tinker AFB	Pneumatic fracturing technology was demonstrated at two field sites at Tinker Air Force Base, Oklahoma City, Oklahoma in August 1993.	"Tests were performed to increase the permeability for more effective bioventing, and evaluated the potential to increase permeability and recovery of free product in low permeability soils consisting of fine grain silts, clays, and sedimentary rock. Pneumatic fracturing significantly improved formation permeability by enhancing secondary permeability and by promoting removal of excess soil moisture from the unsaturated zone. Post-fracture airflows were 500% to 1,700% higher than pre-fracture airflows for specific fractured intervals in the formation. This corresponds to an average pre-fracturing permeability of 0.017 Darcy, increasing to an average of 0.32 Darcy after fracturing. Pneumatic fracturing also increased free-product recovery rates of number 2 fuel from an average of 587L (155 gal) per month before fracturing to 1,647 L (435 gal) per month after fracturing."

Appendix B – Example Permeability Enhancement Presentations

A Rigorous Demonstration of Permeability-Enhancement Technology for *In Situ* Remediation in Low Permeability Media at the Camp Pendleton Site 1115

Prepared for:

Marine Corps Base Camp Pendleton

Prepared By:

Kent Sorenson, PhD, PE, CDM Smith

July 14, 2016



**CDM
Smith®**

Presentation Outline

- Hydraulic fracturing (i.e., permeability enhancement technology):
 - Oil and gas vs. remediation comparison
- Monitoring/validation tools
- ESTCP ER-201430 project
- Objectives of the technology demonstration at MCB-CP
- Benefits, risk, and mitigation measures

Hydraulic Fracturing in the Oil & Gas Industry

- High-pressure injections of water, sand, and chemicals for extraction of oil and gas
- Revolutionized the energy industry in the US and Canada
- Environmental concerns:
 - Intensive resource and energy requirements
 - Possible groundwater contamination
 - Unwanted seismic activity

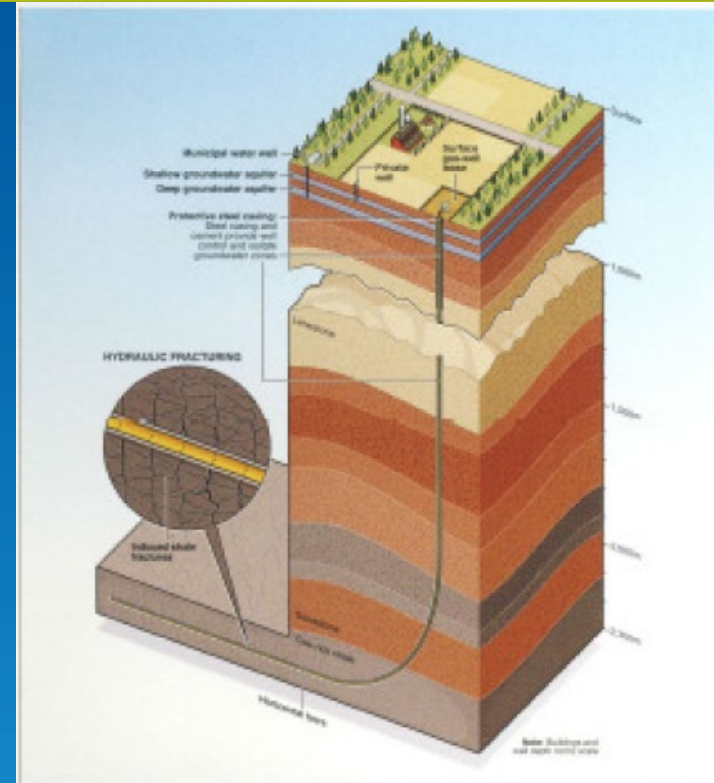


Image courtesy of the Canadian Society for Unconventional Gas

Hydraulic Fracturing in the Oil & Gas Industry

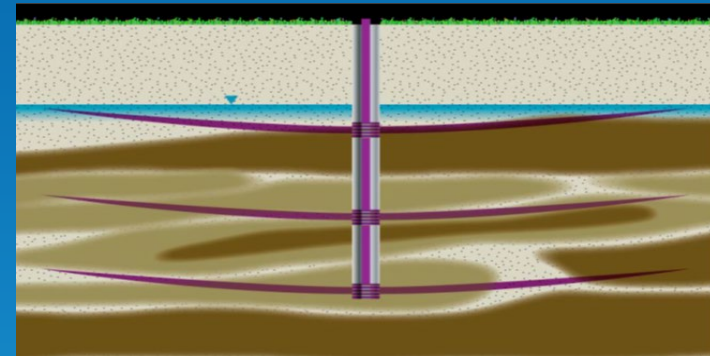


Image courtesy of Wikimedia



Hydraulic Fracturing in the Remediation Industry (a.k.a. Permeability Enhancement)

- Modified from oil & gas hydraulic fracturing to aid remediation of soil and groundwater in the late 1980s
- Introduction of a low- to high-viscosity fluid into a borehole at a rate and pressure high enough to overcome the confining stress and material strength of a geologic formation → formation of a fracture
- Goals:
 - Increased bulk hydraulic conductivity
 - Increased amendment delivery radius of influence
 - Enhanced contaminant/amendment contact



Depth-discrete and primarily horizontal fractures minimize the risk of vertical contaminant migration

Permeability Enhancement Equipment



Equipped with mobile mixing tank and pumps, fluid delivery system, and real-time pressure and flow data acquisition

Not a Permeation Injection

- Permeation injection moves through the pore structure, displacing fluid
- Permeability enhancement technology creates a “parting” of the soil/rock like an axe splitting wood; injected amendments fill the newly created space



Delivery System

Water-based, pH-buffered,
food-grade base gel



Low-density guar/Chitin
enhancement fluid



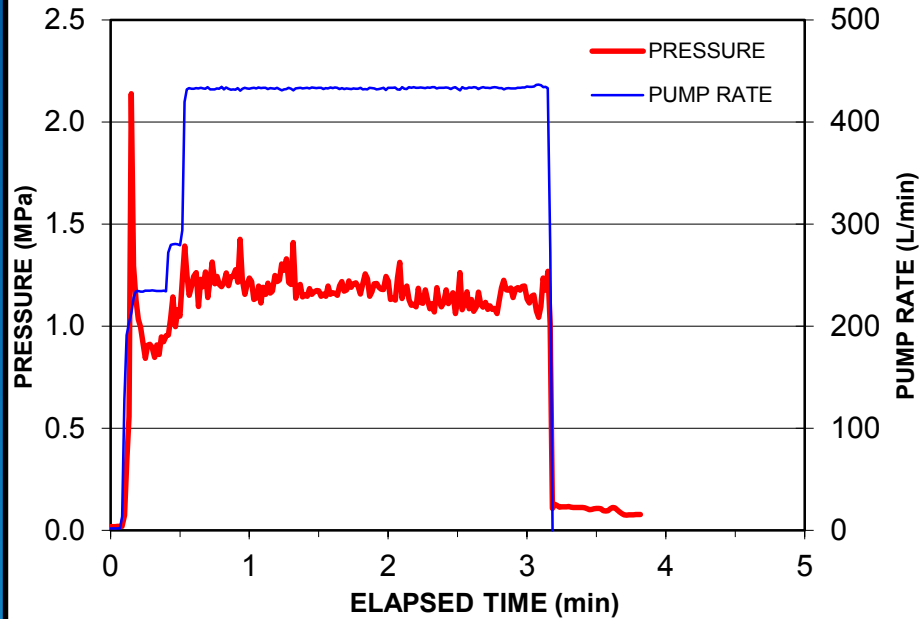
High-density guar/ZVI
enhancement fluid



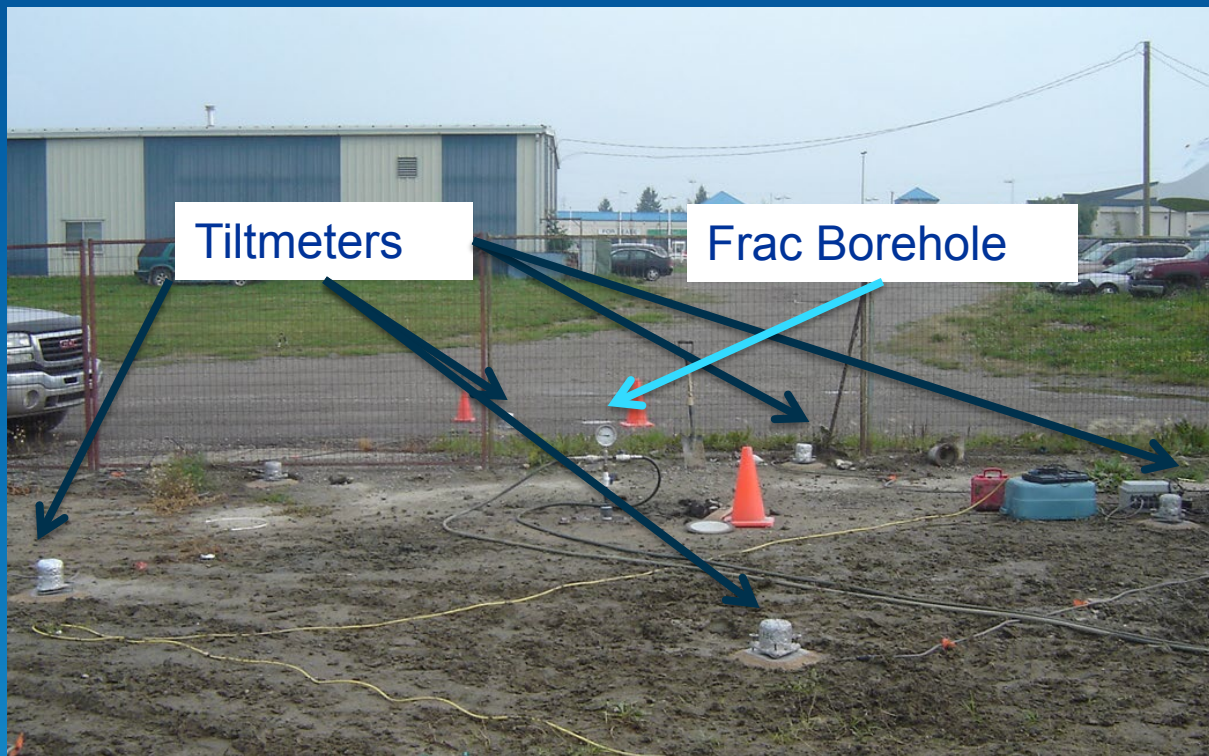
40/50 sand and guar will be emplaced at MCB-CP

Flow Rate & Pressure Monitoring

FRACTURE EMPLACEMENT
PRESSURE & PUMP RATE VS ELAPSED TIME



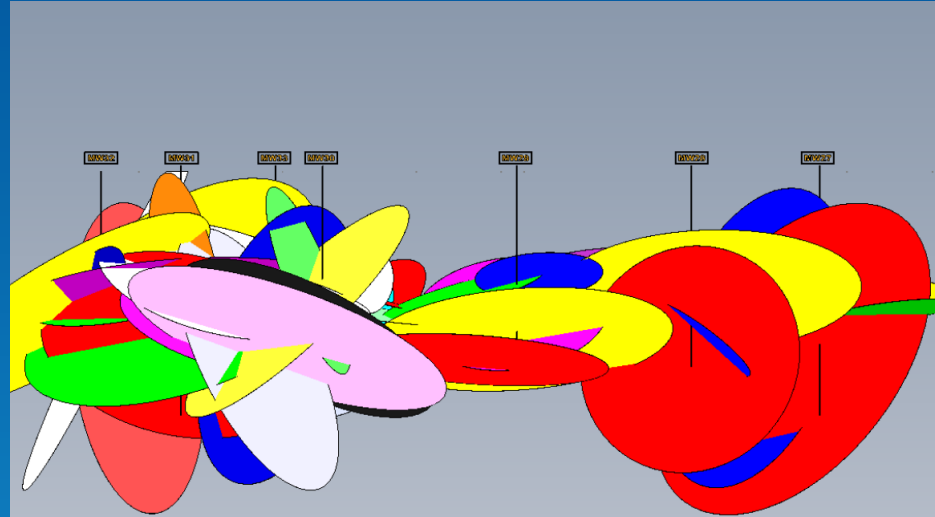
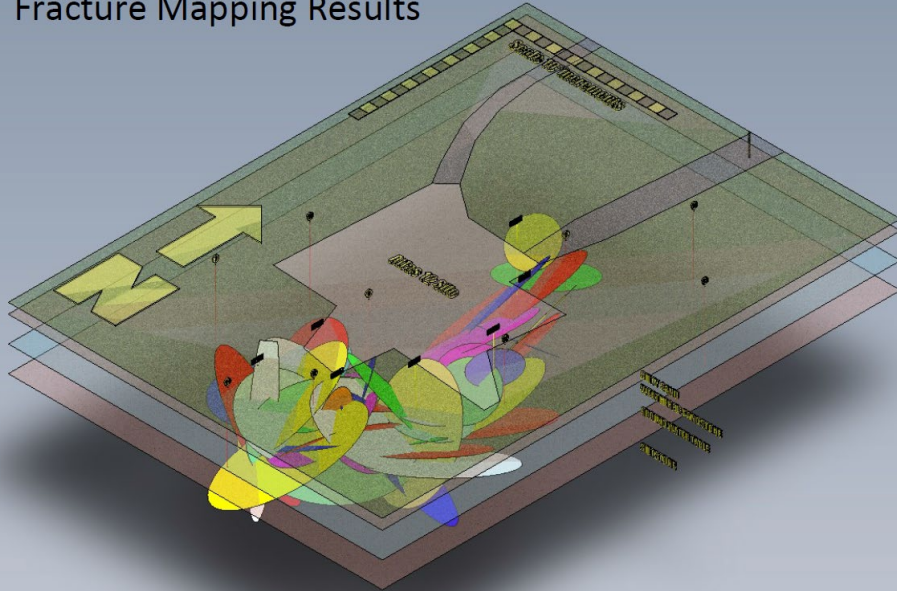
Tilt-Meter Monitoring



Tiltmeter setup in the field

Tilt-Meter Monitoring

Fracture Mapping Results



Fracture Mapping Results

Soil Confirmation Sampling



Fractures Placed in Clay Till



Induced Sand Fractures

Tilt-meter data will be used to guide the soil confirmation sampling locations

Fracturing: Oil & Gas versus Remediation

Oil & Gas		Remediation
Overall objective	Extraction of natural resources	Soil and groundwater remediation
Fracturing orientation	Vertical	Horizontal
Fracturing volume	Hundreds of thousands of gallons	Hundreds to thousands of gallons
Fracturing depth	> 1,000 feet bgs	< 100 feet bgs
Fracture-initiating pressure	1,000 – 10,000 psi	100-1,000 psi
Chemicals used	Potentially toxic	Non-toxic, food-grade

ESTCP ER-201430 Project Background

- Low-permeability sites represent a significant challenge in remediation
- Conventional injection approaches are rarely successful at low-permeability sites
- Permeability enhancement technology can address these issues
- ESTCP ER-201430 project will provide comparison and validation data at 3 DoD sites with different geologies

Previous Technology Demonstrations

Site	Project lead	Technology/ reagent	Lithology	Contaminants	Highlights
Xerox Site, Oak Brook, IL	Univ. of Cincinnati	Hydraulic/none	Silty clay	Chlorinated solvents, BTEX	Increased SVE's flow rates by more than an order of magnitude
Atlas Missile Site 12, Windsor, CO	USACE/Air Force	Hydraulic/EHC-G	Weathered bedrock	TCE	94% TCE mass reduction in source area
Savannah River Site Upland Unit, Savannah, GA	DoD	Hydraulic/none	Clay	Chlorinated solvents	Increased SVE's flow rates by at least an order of magnitude
Distler Brickyard Site, West Point, KY	EPA	Hydraulic/chitin	Silty clay	Chlorinated solvents, metals	Complete contaminant removal

Hydraulic permeability enhancement has been implemented at many sites with similar or more complicated lithology with great success!



Objectives at the MCB-CP Site 1115

- Demonstrate permeability enhancement technology in the low K sandstone/siltstone lithology
- Collect multiple lines of evidence to:
 - Demonstrate enhanced amendment delivery
 - Validate advanced mapping techniques
 - Aid performance monitoring
 - Ensure no vertical migration of contaminants
- Treat contaminants present in the injection area
- Transfer lessons learned to areas of similar lithology at the site



Benefits to MCB-CP

- Innovative, combined treatment technology for benzene:
 - Chemical oxidation by alkaline-activated persulfate
 - Effective distribution by permeability enhancement injections
 - Potential for biodegradation under sulfate-reducing conditions following chemical oxidation
- Emplacement of sand and installation of permanent wells allow for groundwater monitoring and follow-up injections, if needed
- The demonstrated technology can be applied to other areas of concern at MCB-CP

Risk and Mitigation

- Surfacing:
 - Packer-assisted, depth-discrete permeability enhancement minimizes surfacing
 - Injection pressure will be continuously measured and adjusted as necessary
 - Visual inspection will be performed to identify surfacing
- Nearby well damages:
 - Very rare; existing wells at edge of expected injection radius
 - Injection pressure will be kept at a minimum to decrease risk
 - New monitoring wells will be completed appropriately to reduce risk
- Vertical contaminant migration:
 - Minimized by the discrete-depth, packer-isolated enhancement methodology

Logistics

Pre-
enhancement
drilling &
monitoring

Site
mobilization

Drilling
enhancement
borehole &
other
monitoring
activities

Permeability
enhancement
and
monitoring

Installation of
a permanent
injection well
at the
enhancement
location

In-well
injection of
alkaline-
activated
persulfate

Post-
enhancement
monitoring &
sampling

All onsite activities will be completed within ~2 weeks

MCB-CP Demonstration Area

- Deep Groundwater Monitoring Well - Upper Zone
- Deep Groundwater Monitoring Well - Lower Zone
- Shallow Groundwater Monitoring Well (Not Used in Contouring)
- * Lower Zone Analytical Results Not Used in Contouring

289.00 Groundwater Elevation Contour Using Entire Data Set - March 17, 2015
(Feet Above Mean Sea Level)

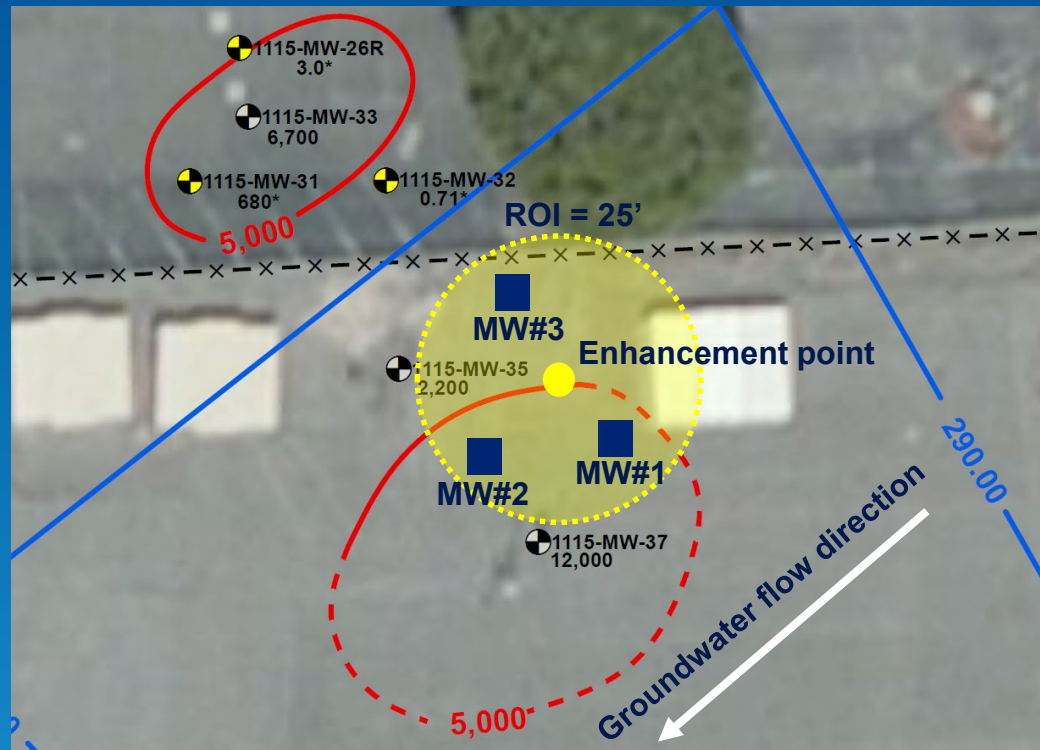
Groundwater Flow Direction

2,200 Benzene Isoconcentration Contour (Micrograms per Liter)

2,200 Benzene Analytical Result (Micrograms per Liter)

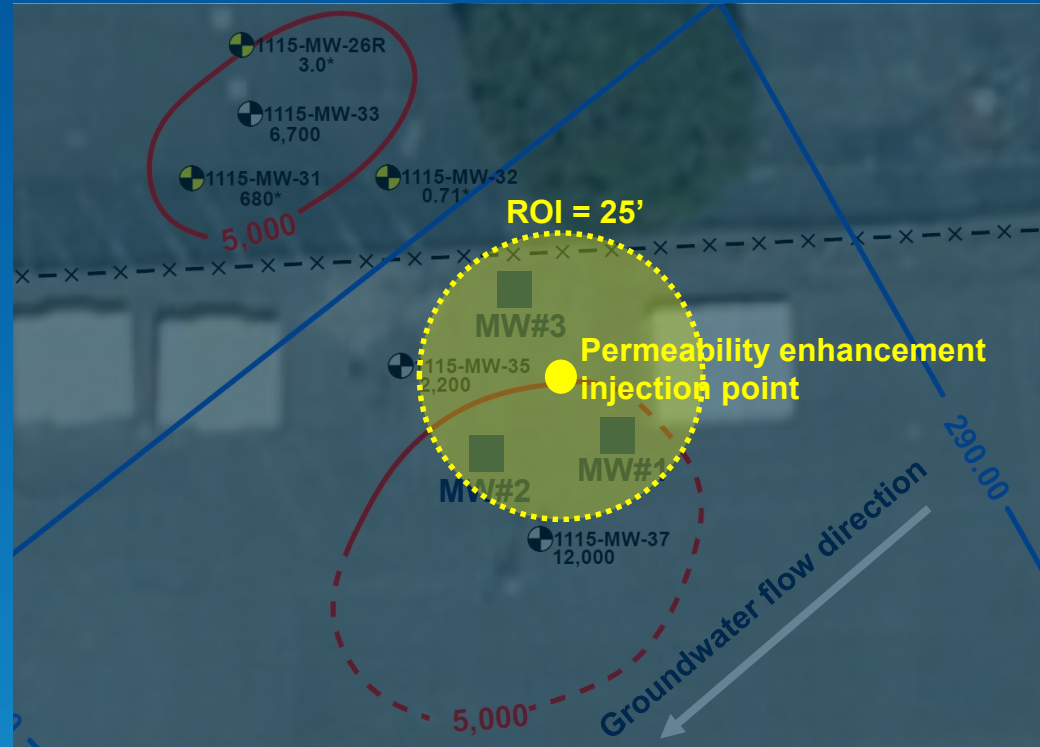


0 12.5 25 50 Feet



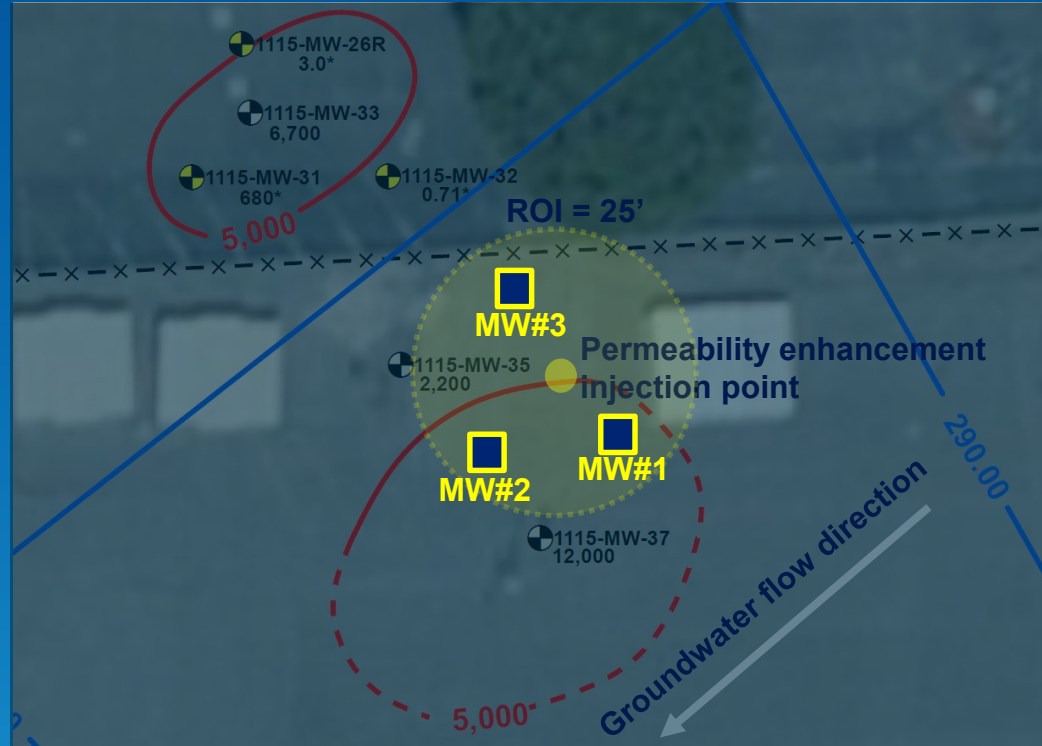
Permeability Enhancement Injection Point

- 1 injection point
- 5 enhancement intervals between 20 and 40 feet bgs
- Packer-assisted, bottom-up methodology
- Approximately 600 gallons of sand/guar per interval
- Injection well conversion following permeability enhancement



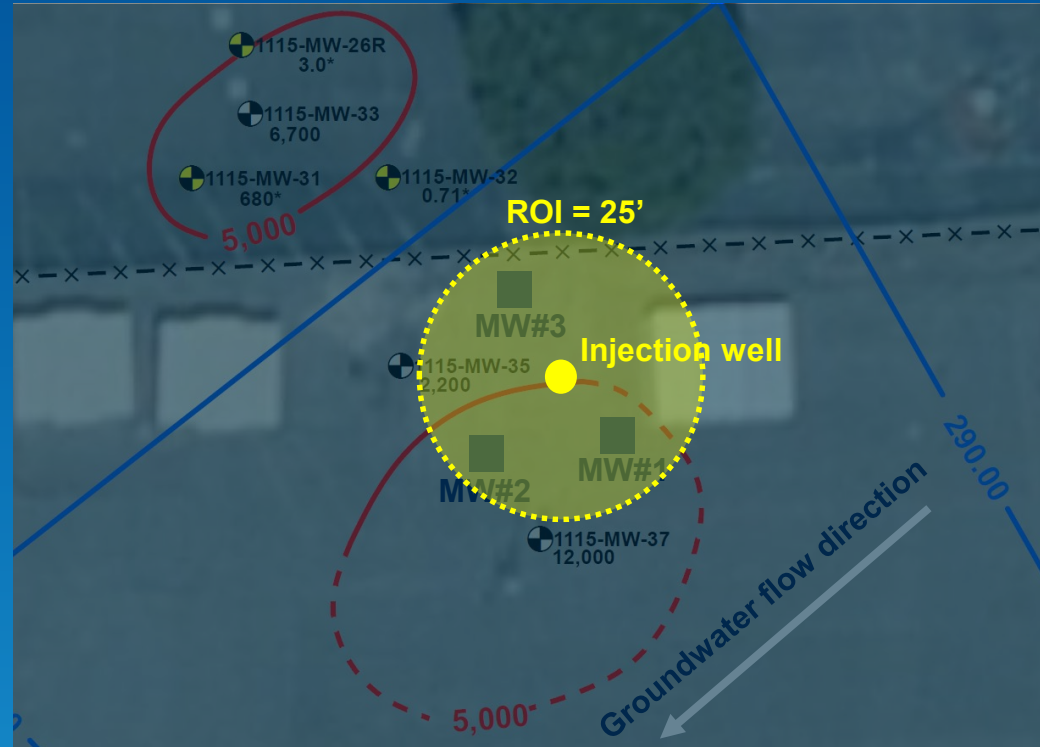
Monitoring Points

- 3 new monitoring wells at different distances from the injection point
- Well seals: Type II Portland Cement with 5% bentonite
- 2" ID, Schedule 40 PVC with 10-slot PVC screen
- Screened in the same intervals as existing monitoring wells



Post-enhancement Injection

- Installation of a permanent injection well
- 2" ID, Schedule 40 PVC with 20-slot PVC screen
- Screened in the same enhancement interval
- Removal of guar during development
- Injection of ~ 3,000 gallons of alkaline activated persulfate (~5% by vol)



Monitoring and Validation Tools

- Continuous and real-time injection rate and pressure data
- Tilt-meter monitoring
- Groundwater monitoring (0, 1, and 6 months)
- Lithologic characterization & soil confirmation sampling
- Pumping test

Summary

- MCB-CP is a key part of ESTCP ER-201430 project:
 - Only sandstone/siltstone site
 - Amendment distribution in similar sites is a significant challenge for DoD
 - Success/lessons learned from the demonstration can be applied to many other DoD sites, including at MCB-CP
- Many previous applications of the technology for environmental benefit
- Project POP end date = March 2017
- Final reports and guidance documents will be available to the public

A Rigorous Demonstration of Permeability-Enhancement Technology for *In Situ* Remediation in Low Permeability Media at LCAAP Area 17D



Prepared for:

Lake City Army Ammunition Plant

Prepared By:

Zoom Nguyen, CDM Smith

Nathan Smith, CDM Smith

Kent Sorenson, PhD, CDM Smith

August 17, 2015



**CDM
Smith®**

Background

- Low-permeability sites represent a significant challenge in remediation
- Many issues are encountered when using conventional injection approaches at low-permeability sites → optimization is needed
- Permeability enhancement technology can address these issues
- ESTCP ER-201430 project provides the comparison and validation data at 3 DoD sites with different geologies

Previous Technology Demonstrations

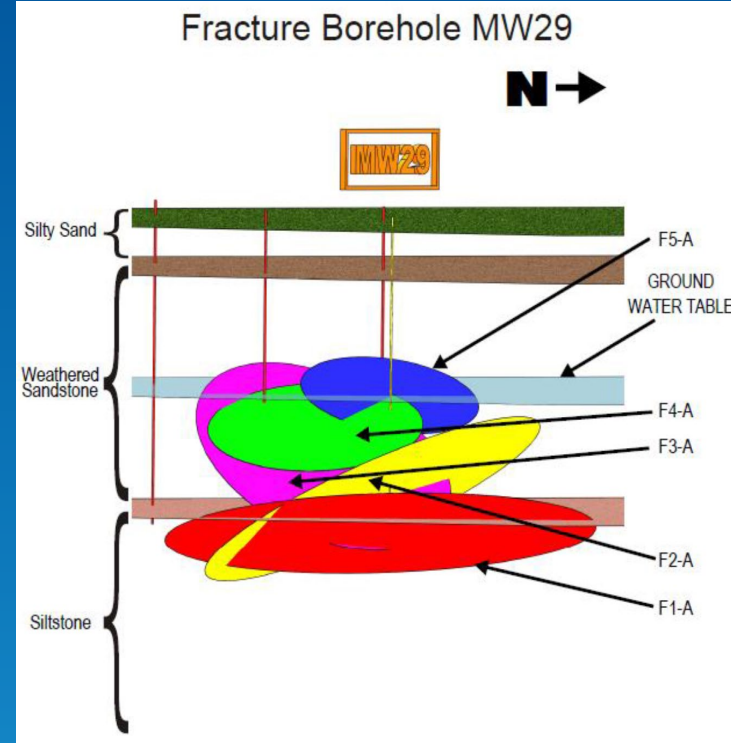
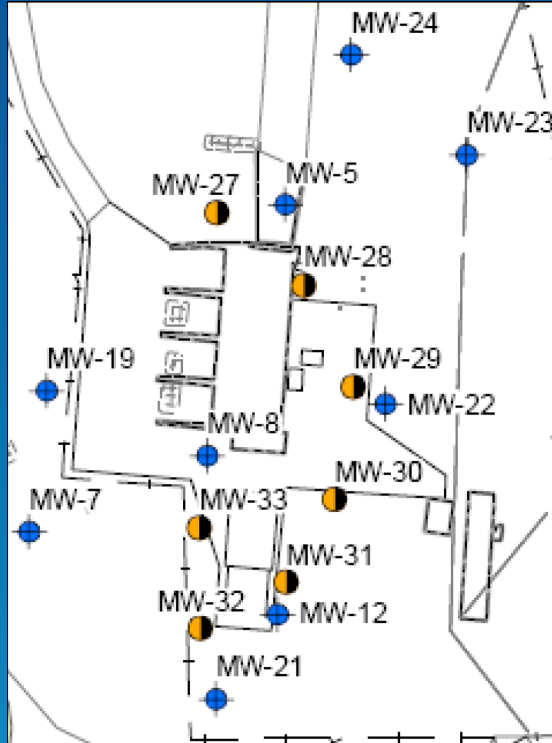
Site	Project lead	Technology/ reagent	Contaminants	Highlights
Hunters Point Naval Shipyard, San Francisco, CA	EPA, NAVFAC	Pneumatic/ZVI	Fuels, pesticides, chlorinated solvents	Solvent concentrations decreased between 87 to 99% after 12 weeks
Atlas Missile Site 12, Windsor, CO	USACE/Air Force	Hydraulic/EHC-G	TCE	94% TCE mass reduction in source area
Savannah River Site Upland Unit, Savannah, GA	DoD	Hydraulic/none	Chlorinated solvents	Increased SVE's flow rates by at least an order of magnitude
Distler Brickyard Site, West Point, KY	EPA	Hydraulic/chitin	Chlorinated solvents, metals	Complete contaminant removal

No comparison study has ever been done!

Objectives at LCAAP Area 17D

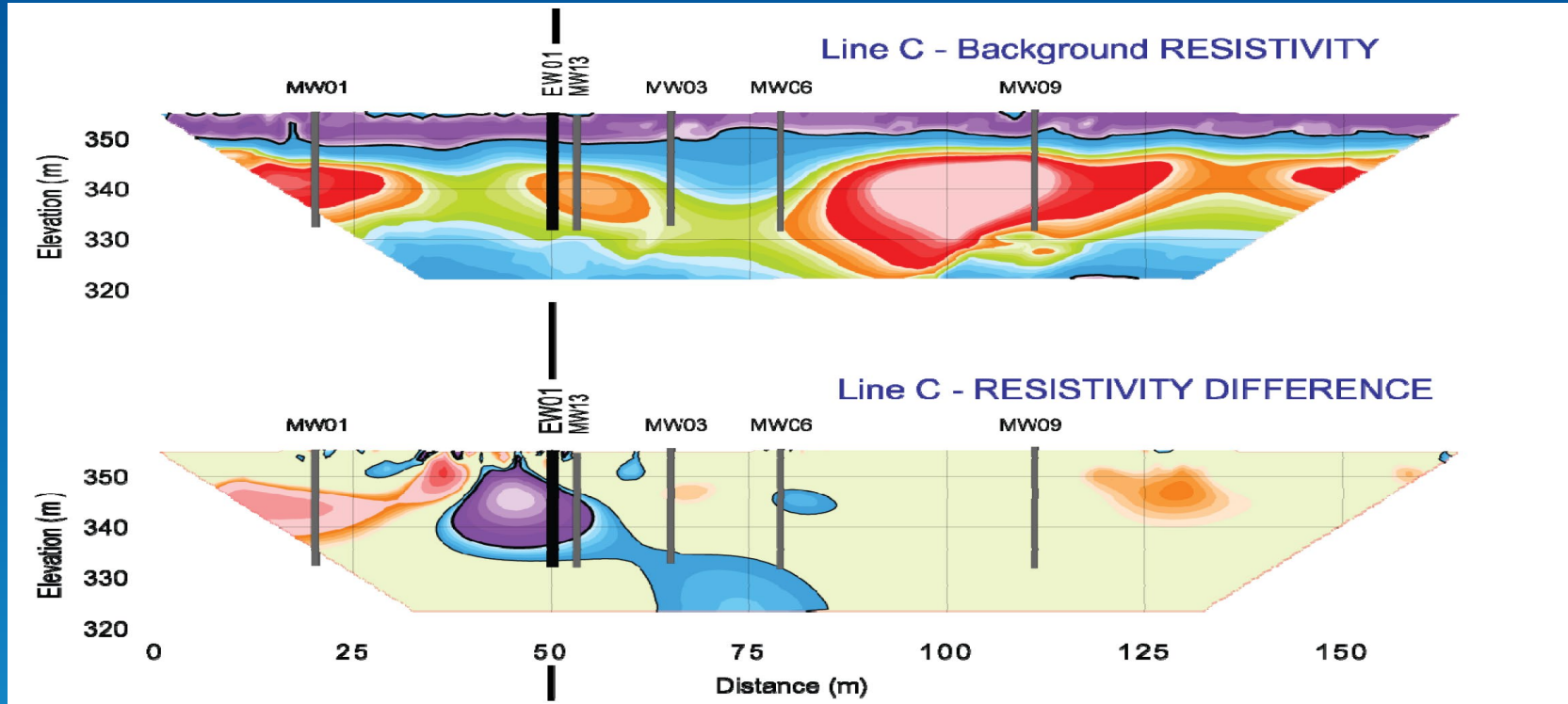
- Low-K lithology ideal for pilot demonstration & direct comparison between hydraulic and pneumatic permeability-enhancing technologies
- Multiple lines of evidence will be collected to:
 - Demonstrate enhanced amendment delivery
 - Validate advanced mapping techniques
 - Aid performance monitoring
 - Ensure no vertical migration of contaminants
- Success/lessons learned will be transferred to other areas of similar lithology at the site

Tilt-Meter Implementation



Use of tilt-meter to monitor hydraulic permeability enhancement with ZVI

Electrical Resistivity Tomography



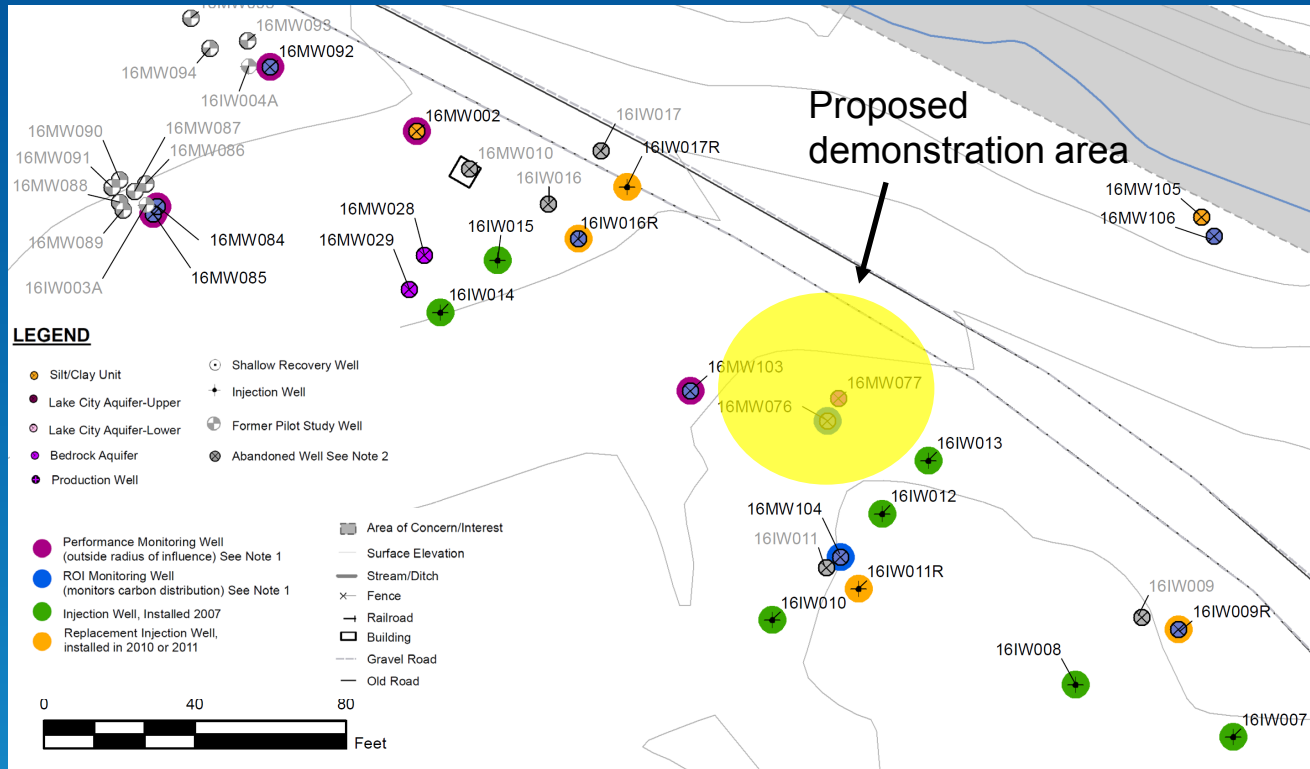
Use of ERT to monitor hydraulic permeability enhancement with permanganate in ESTCP ER-0635

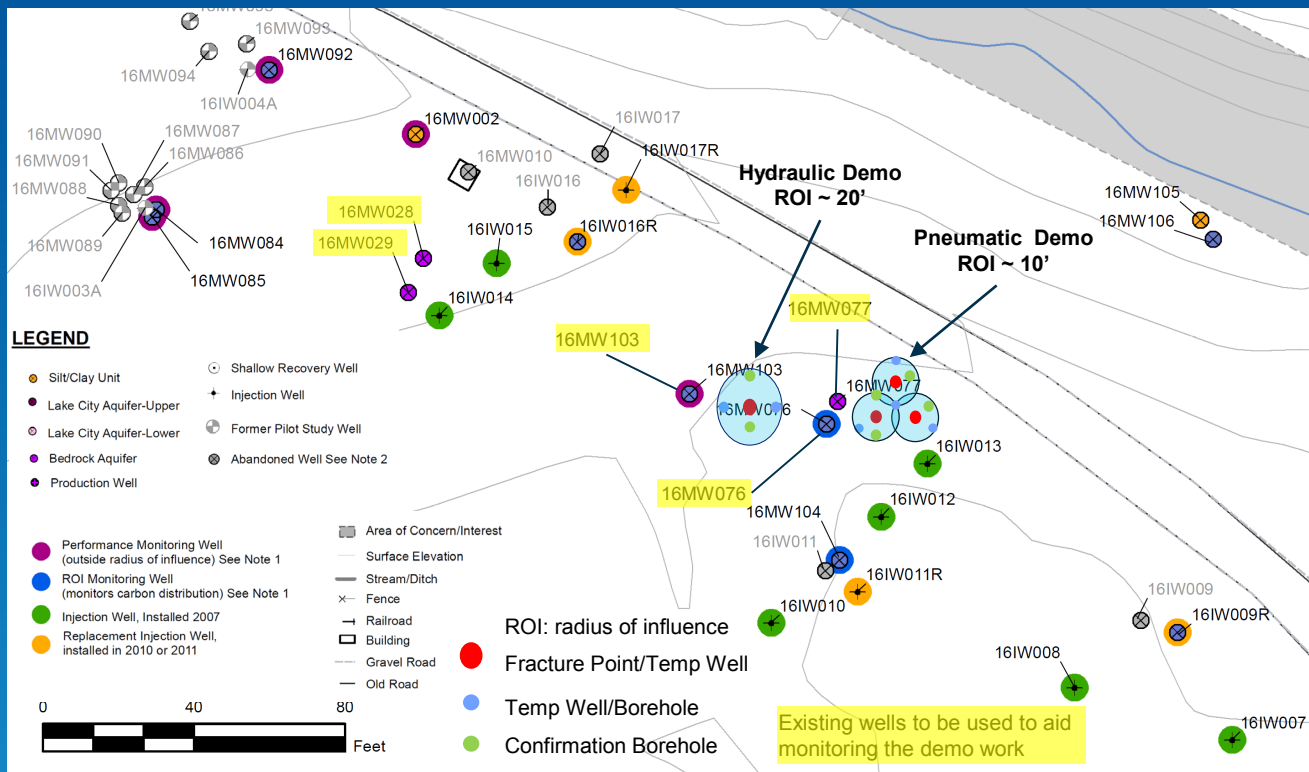
Other Monitoring Tools

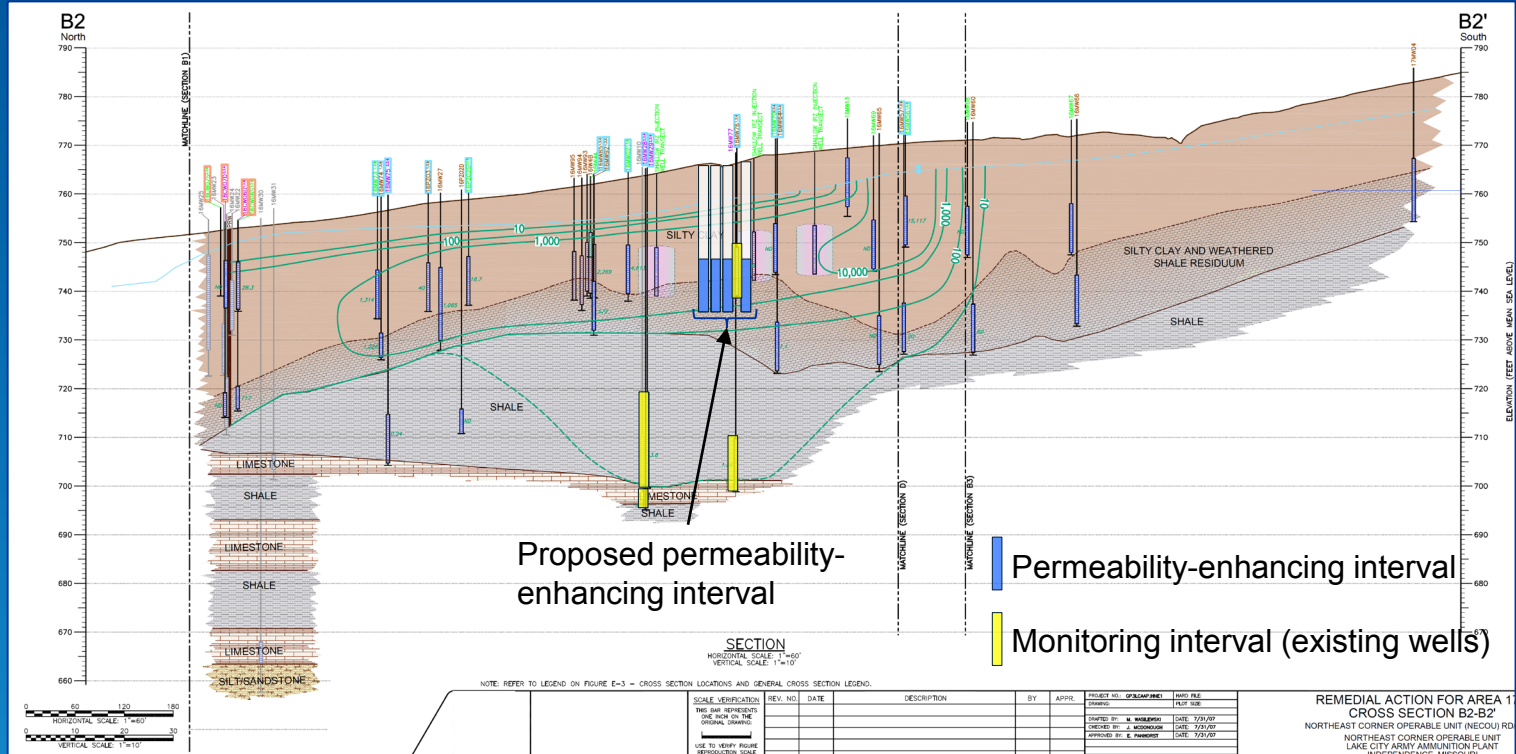
- Lithologic characterization
- Soil confirmation sampling
 - TOC
- Groundwater sampling
(completed in targeted unit and below):
 - VOCs
 - TOC
 - MEEA
- Pumping tests



Proposed Demonstration Area

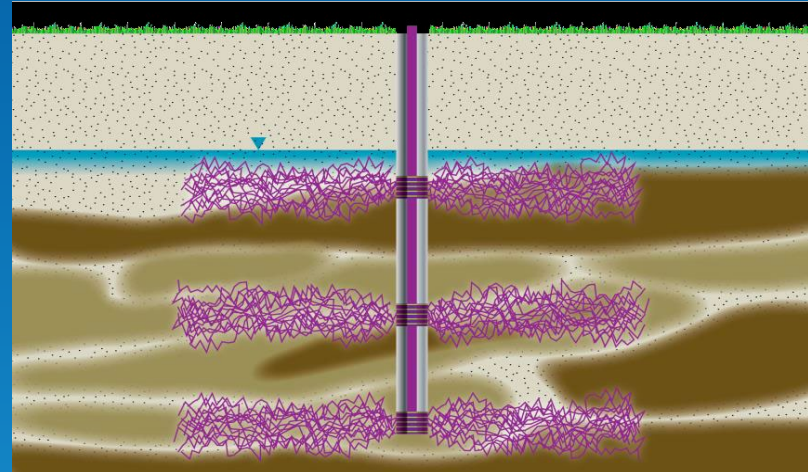






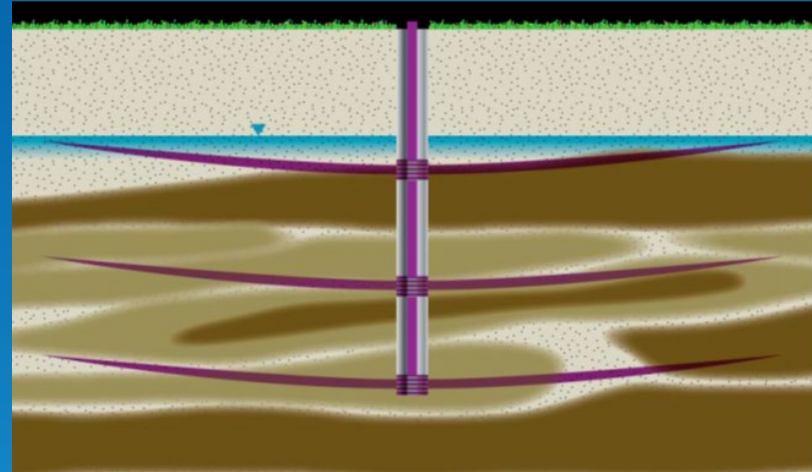
Test Design Details - Pneumatic

- Pneumatic permeability enhancement technology:
 - Emulsified Vegetable Oil (EVO) alone
 - 3 points
 - 5 enhancement intervals between 15-35 feet below ground surface
 - Desired ROI ~ 10 feet
- Monitoring/validation testing:
 - Lithologic & soil confirmation sampling
 - Pumping test
 - Tilt-metering
 - ERT
 - Groundwater sampling



Test Design Details - Hydraulic

- Hydraulic permeability enhancement technology :
 - Sand & guar followed by EVO injection
 - 1 point
 - 5 enhancement intervals between 15-35' bgs
 - Desired ROI ~ 20 ft
- Monitoring/validation testing:
 - Lithologic & soil confirmation sampling
 - Pumping test
 - Tilt-metering
 - ERT
 - Groundwater sampling



Tentative Schedule

ID	Task Name	Start	Finish	September				November			January		
				M	B	E	M	B	E	M	B	E	M
1	Mobilization 1	Mon 10/5/15	Thu 10/29/15										
2	Mobilization 1a	Mon 10/5/15	Wed 10/14/15										
3	Lithologic characterization	Mon 10/5/15	Tue 10/6/15										
4	Drilling of permeability enhancement boreholes	Tue 10/6/15	Wed 10/7/15										
5	Pre-enhancement soil sampling	Wed 10/7/15	Thu 10/8/15										
6	Monitoring well installation & development	Fri 10/9/15	Fri 10/9/15										
7	GW sampling at new monitoring wells	Mon 10/12/15	Mon 10/12/15										
8	Pre-enhancement ERT	Tue 10/13/15	Tue 10/13/15										
9	Pre-enhancement pumping tests	Wed 10/14/15	Wed 10/14/15										
10	Mobilization 1b	Mon 10/19/15	Thu 10/29/15										
11	Pneumatic permeability enhancement & tilt-meter monitoring	Mon 10/19/15	Wed 10/21/15										
12	Post-enhancement soil confirmation sampling for pneumatic	Thu 10/22/15	Fri 10/23/15										
13	Hydraulic permeability enhancement & tilt-meter monitoring	Fri 10/23/15	Fri 10/23/15										
14	Post-enhancement soil confirmation sampling for hydraulic	Sat 10/24/15	Sat 10/24/15										
15	Post-enhancement ERT for pneumatic	Sun 10/25/15	Sun 10/25/15										
16	Post-enhancement ERT for hydraulic	Mon 10/26/15	Mon 10/26/15										
17	Post-enhancement pumping tests for pneumatic	Tue 10/27/15	Tue 10/27/15										
18	Borehole abandonment	Wed 10/28/15	Wed 10/28/15										
19	Post-enhancement pumping tests for hydraulic	Thu 10/29/15	Thu 10/29/15										
20	Mobilization 2	Mon 11/23/15	Tue 11/24/15										
21	Post-enhancement GW sampling round 1	Mon 11/23/15	Tue 11/24/15										
22	Mobilization 3	Mon 2/22/16	Thu 2/25/16										
23	Post-enhancement GW sampling round 2	Mon 2/22/16	Mon 2/22/16										
24	Well abandonment	Tue 2/23/16	Thu 2/25/16										