Appendix D. Injection Fact Sheets

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D1 Direct Push Delivery Methods

Direct push injection (DPI) methods provide a flexible and cost-effective platform for the injection of remediation amendments into unconsolidated soils. DPI methods use specialized drill rigs to advance hollow steel rods to a targeted injection depth and inject amendments through specialized tooling or open hollow rods. Similar injection methods can be applied using other drilling technologies (for example, cone penetrometer and rotary sonic) that use hollow tooling flush with the side of the borehole.

DPI methods can be used to inject both low and high viscosity amendments. The minimum treatment depth for DPI methods is typically dictated by the depth at which daylighting of amendment to the ground surface cannot be controlled during injection. The maximum treatment depth is typically dictated by the refusal depth during tooling advancement, and this maximum depth is a function of geology in the TTZ, DPI rig size/rated down pressure, tooling diameter, and tooling strength.

D1.1 Types of Equipment

The typical DPI method involves equipping the lead rod with an injection tool (as described below) and advancing the injection tool to the targeted treatment depth. DPI can be performed using either a top-down or bottom-up injection sequence. DPI rigs have a hydraulic power plant that produces a downward force coupled with percussive hammering action to advance rods to depth. Recent advances in DPI equipment (for example, rig and tooling improvements) have allowed DPI methods to achieve successively greater depths.

The direct push drilling provider will typically recommend an appropriately sized DPI rig based on previous site investigations or regional knowledge of the geology. Tracked rigs tend to be more efficient, especially with tight grid spacings and manifolding to multiple locations. The size (height and width) of the rig needs to match the site conditions, and access restrictions should be considered. Depending on the magnitude of the injection program, multiple rigs may be used during implementation to reduce implementation time and limit costs.

Types of injection tooling vary from commercially available products to custom tooling manufactured by DPI drilling providers. Variations in DPI injection tooling can include the diameter of the tooling, the size of holes or slots, and the density of holes or slots in the tooling.

The mechanism of action of DPI tooling can vary. Several typical examples are described below:

- Low pressure ported (slotted) injection tools with inner stainless steel screens can be provided with or without retractable sleeves that protect the screen as the injection tool advances in the subsurface.
- High-pressure ported injection tools are typically more robust in tight formations. The tooling is manufactured with different injection port orientations; for example, some are oriented at 90 degrees, with a port every 6 inches. These tools can also be custom manufactured depending on distribution objectives.
- Pressure-activated injection tools are ported injection tools with a spring-loaded pressure-activated opening device that moves a metal slider to expose the injection ports. They are advantageous in flowing sand conditions and in tight formations.
- Open rods equipped with a tip holder and expendable tip provide a low-cost method of injecting amendments. Upon reaching the targeted treatment depth the expendable tip is dropped or knocked out of the tip holder, and amendment is injected through the open rods as the rod string is raised. This method can be used only for bottom-up injections.

A water-tight seal must be maintained between threaded rod sections, because amendment injections using DPI methods are typically performed under pressure. Most DPI equipment manufacturers recommend use of rubber O-rings between rod sections to form a seal.

Aboveground injection components may include storage tanks, mixing tanks or inline mixers, pumps, injection piping, and injection manifolds equipped with pressure gauges, flow meters, and flow control valves. For simultaneous injections at multiple locations, injection manifolds are typically used to route the flow from the injection pump to several injection rods. Separate flow meters, pressure gauges, and flow control valves on each individual injection line can be beneficial to document injection performance at each location. The specific aboveground injection equipment used at a given site depends upon the site hydrogeologic conditions, the amendment being injected, and the overall targeted treatment footprint.

D1.2 Types of Delivery

DPI methods can be used to deliver both high and low viscosity amendments. Examples of high viscosity amendments include solids, such as ZVI, powdered or activated carbon, calcium peroxide, potassium persulfate, potassium permanganate, gypsum, and lime. The solids can be mixed with other in situ remediation products (for example, ZVI and emulsified oils, and powdered carbon and gypsum) to facilitate packaged remedies. ZVI (micro-scale and larger) must be suspended in a guar gum solution or added by continuous mechanical mixing with water.

High viscosity amendments are typically installed at discrete intervals due to the high pressures needed to force the solids out into the TTZ. If sufficient flow and pressure are not achieved, distribution will be limited and solids can filter out in the formation near the injection tooling.

Low viscosity amendments can also be applied using DPI methods. Typically, these amendments are formulated by diluting a concentrated liquid or solid with water followed by mechanical mixing.

A pump is typically used to deliver amendments to the injection tooling, unless gravity feed injection is feasible. When selecting a pump for DPI, the following criteria should be considered: viscosity/abrasiveness of the amendment, chemical compatibility of the pump internals (that is, wetted components) with the amendment, and estimated injection pressures and flow rates. Pumps typically used for DPI include the following:

- Centrifugal pumps transport low viscosity amendments by the conversion of rotational energy to fluid flow. Centrifugal pumps provide a constant flow rate and work well for high flow rates and low pressures. They are ideal for low viscosity fluids.
- Positive displacement pumps move low and high viscosity amendments by trapping a fixed amount of fluid and forcing that trapped volume into the discharge pipe. Positive displacement pumps are necessary for high viscosity amendments, such as grouts and slurries, but can also be used for injection of liquids. Two common types of positive displacement pumps used for amendment injections are piston pumps and diaphragm pumps. Piston pumps are well-suited for injecting abrasive amendments, and diaphragm pumps can be selected with chemical-resistant wetted components capable of handling highly corrosive amendments.
- Progressive cavity pumps are a special category of positive displacement pump that transfer fluids through a series of small, fixed cavities with the use of a rotor or screw. These pumps can be used to inject both low and high viscosity fluids and are well-suited for injecting abrasive amendments and viscous amendments that are sensitive to shear.

D1.3 Advantages

- Injection points are temporary and the spacing can be adjusted in the field if necessary. Injection point locations, targeted injection depths, and injection rates and volumes can be modified over time to optimize delivery as the TTZ changes size and shape.
- Upon reapplication of bioremediation amendments, there is no concern for biofouling as with repeated injections into permanent injection wells.
- Temporary DPI locations do not require injection well permits for installation or expensive abandonment procedures following injection.
- Injection rates and volumes can be designed to maximize distribution and speed.
- Use of manifolds allows multiple application points to be injected simultaneously, thus improving injection performance and lowering costs, especially where flow rates and/or injection pressures must be limited.
- Low viscosity amendments require less energy to apply and can be more readily distributed in the subsurface.
- High viscosity amendments can be successful on sites with both fine-grained and coarse-grained lithologies.

D1.4 Limitations

- Reapplication requires a DPI operator and injection equipment to mobilize for each event.
- Flow rates into DPI points may be less than those into an injection well.
- Depth and lithology can be limiting for DPI.
- Injections in low permeability zones generally require a higher pressure pump than injections targeting highly permeable zones.
- High viscosity amendments are injected using high flow and high pressure, which can result in daylighting to the ground surface, especially when injections are performed at shallow depths. In some cases, daylighting can be limited by using a smaller lateral spacing (that is, injection grid) between injection points and smaller injection volumes or lower injection pressures.
- High viscosity amendments are not compatible with screened injection tools because of the velocity and pressure needed to force the solids through the screen.
- Injection of high viscosity amendments requires more expertise than low viscosity delivery and verification of amendment distribution can be difficult.

D2 Injection Through Wells & Boreholes

This injection method uses screened wells or open boreholes to distribute liquids within a TTZ or a given water-bearing stratum. This method can either rely on groundwater head difference between an aboveground injection system and the targeted injection interval (that is, gravity injection) or can be performed under pressure using a pump.

Permanent wells for injection applications are constructed with materials appropriate for the geological formation, groundwater chemistry, contaminants present, and selected amendment/amendments. Injection wells are installed and screened within a horizon to directly access the intended interval for injection. When hydraulic conductivities vary by multiple orders of magnitude, shorter screened intervals may improve amendment distribution and contaminant contact. Ultimately the most permeable intervals in contact with a well screen will receive a majority of the injected amendment, so matching the well screen intervals to the targeted injection depths is a critical design parameter.

Although they require a significant up-front investment, permanent injection wells can be more economical for injection-based remedies that span multiple years and multiple injection events, if the treatment zone remains the same and the well spacing does not require adjustments. Although the short-term costs of well drilling and construction are higher than temporary delivery methods (for example, DPI), the reuse of wells during later injection events offsets these costs and the payback period is typically realized after the second or third injection event. Injection wells provide routine access to the TTZ and allow for modification of amendment, dose, and volume to optimize injection programs based on observed performance.

D2.1 Types of Equipment

Injection wells in unconsolidated media are commonly constructed with slotted polyvinyl chloride (PVC) casing and screen, because this material is less costly and more readily available than other materials such as stainless steel. Stainless steel wire-wrapped or vee-wire screens provide greater open area than slotted PVC screens and are designed to minimize biofouling and scaling of the screen, thus requiring less maintenance. Some amendments may react with well materials or may generate elevated temperatures within the well, and these factors should be considered when selecting well construction materials. The presence of a NAPL phase (which may soften PVC) and other contaminant considerations may affect construction material selection. Options for bedrock injection wells include open boreholes providing access to one or more fracture(s) or fracture intervals, or screened wells intercepting fractures to be targeted for treatment. For open borehole designs, the competency of the bedrock should also be considered to ensure that blockages or borehole collapse do not isolate portions of the vertical interval or trap downhole equipment. Although vertical injection wells and bedrock boreholes are most common, injection wells can be constructed in unconsolidated media or bedrock using horizontal drilling methods.

Injections through wells and boreholes use permanent vertical wells, horizontal wells, or open boreholes coupled with aboveground injection equipment. Aboveground injection components may include storage tanks, mixing tanks or inline mixers, pumps, injection piping, and injection manifolds equipped with pressure gauges, flow meters, and flow control valves. Injection piping should be connected to wellhead fittings designed to withstand expected injection pressures. The specific aboveground injection equipment used at a given site depends upon the site hydrogeologic conditions, the amendment being injected, and the overall target treatment footprint.

D2.2 Types of Delivery

This delivery method is often used when multiple injections are anticipated over time, or when targeted treatment depths exceed the capability of direct push drill rigs. When targeting multiple water-bearing zones or thick targeted treatment depth intervals, multiple wells with shorter well screens or nested wells may be required. Injection wells are almost exclusively used when continuous recirculation of amendments is planned.

Amendment injections into wells and boreholes under gravity can be successful in TTZs with moderate to high hydraulic conductivity; however, injection flow rates can be increased by applying direct pressure to the wellhead. Most injection well annular seals are constructed using hydrated bentonite or neat cement, which are essential to sealing off the well screen and filter pack and preventing daylighting around the well annulus to ground surface. If excess wellhead pressure is applied, well seals can become compromised, resulting in permanent damage to the well.

Inflatable packers can also be used to isolate a target injection zone. This method is commonly used in open bedrock boreholes to target injections into specific fracture intervals. Packer use in screened wells should be implemented with caution due to the potential to damage the well. Following treatment, properly installed injection wells may be used for monitoring for parameters other than contaminants. However, in some cases regulatory agencies allow injection wells to be used as long-term monitoring wells if the groundwater geochemical parameters have returned to baseline conditions (that is, preinjection) and the injected amendments have been fully used.

D2.3 Advantages

- A system of wells can be used for pilot testing, single full-scale injections, and multiyear injection programs without the need for additional infrastructure costs, with the exception of any additional wells or boreholes needed for future amendment distribution.
- Injection wells and boreholes can help maintain control of the treatment area using either a recirculation scheme or a push-pull scheme, which can enhance amendment distribution, increasing the ROI, and also limit displacement of contaminants beyond the treatment area during injection.
- Multiple injections events can be performed without the need for additional drilling unless remaining contamination can't be contacted by existing well locations.
- Wells and boreholes can be used to provide real-time feedback during injections, including amendment distribution (ROI), dose within the treatment area, and water level response, all of which allow effective field adjustment of mix ratio, injection pressure, etc. Amendment concentrations can also be monitored over time to assess amendment longevity in the subsurface.

D2.4 Limitations

- Injection through wells and boreholes creates a larger and semipermanent treatment footprint compared to more agile and mobile DPI. The decision to add injection points requires the time, permitting, and funding associated with well installation.
- The effectiveness of treatment with this delivery method may be limited in lower permeability formations (for example, silts and clays) due to challenges with distribution.
- Although depth is not limited, well installation cost can be prohibitive and the need for eventual well or borehole abandonment should be considered.
- In the case of wells, the types of amendments are limited to those that are soluble or contain relatively small solids that are smaller than the well screen slot size and formation pore throat size.
- Fouling of the well screen may occur during or after injection, reducing the flow rates and increasing pressures (in the case of pressurized injection) during future injection activities. One method to minimize fouling is to include chase or flush water following amendment injection to push the injected amendment beyond the sand pack and into the formation.
- Injection pressures are limited to those that can be safely withstood by the well seal. Excessive injection pressure can damage the well seal and lead to daylighting of amendment. Injection pressure limitations due to well seal concerns may result in reduced injection flow rates and/or poor amendment distribution.
- Targeting vertically thick or heterogeneous TTZs with nested injection wells may result in high costs.
- Once a well is used for injection, it is generally not acceptable for use as a monitoring well for compliance purposes, but may be used for other purposes such as measuring reagent persistence.

D3 Electrokinetics Delivery Methods

Electrokinetics uses electric currents to facilitate transport of remediation amendments and/or contaminants within the saturated zone. Electromigration is the movement of charged (ionic) molecules through the aquifer formation between electrodes. It is induced by an electrical current applied to the electrodes. Positively charged ions (for example, many metals and certain organic compounds) migrate toward the cathode, while negatively charged ions (for example, anions such as nitrate, permanganate, and certain metal complexes and organic compounds) migrate toward the anode. Transport of nonionic species (such as many chlorinated solvents) is enhanced by electroosmotic processes, which induce pore fluid migration between electrodes. The combination of electromigration and electroosmotic processes makes electrokinetics a potentially effective method for both amendment and contaminant transport in some low-permeability formations.

D3.1 Types of Equipment

The fundamental types of equipment required for all applications are electrodes (anodes and cathodes) and a low voltage, direct current power supply. Additional equipment required depends upon the specific design of the remedy. For example, an extraction system may be required to extract groundwater containing mobilized contaminants, whereas a liquid injection system may be required to prepare and supply an amendment such as a bioremediation nutrient, chemical oxidant, or surfactant.

D3.2 Types of Delivery/Electrodes

Electrokinetic methods require placing positively charged (anode) and negatively charged (cathode) electrodes in the subsurface. There are many ways to deploy electrodes, and the construction method and soil type impact the orientation of the electrodes. Methods for electrode installation include wells, vertical trenches, sheet piling, injected solids, and directly installed probes, as described below:

- Well installations: Electrodes are placed directly in wells. In addition to housing electrodes, the same wells can be used for injection of electrolytic solutions and other amendments and/or extraction of contaminated fluids.
- Vertical trenches and sheet piling: Steel sheet piling directly driven into the ground can serve as electrodes. Electrodes can also be placed into permeable barrier zones that intersect the water table and are filled with sand or other reactive or nonreactive solids. Fluids can also be injected and/or extracted from the trenches.
- Injected solids: Hydraulic slurry injection can be used to create horizontal or vertical lenses of conductive material at depths greater than those that can be trenched; the lenses are then converted to electrodes by drilling wells to intercept the lenses and installing electrodes in contact with the conductive material.
- Directly installed probes: Rods can be pushed directly into the ground to serve as electrodes.

D3.3 Advantages

- Electrokinetic methods can be particularly effective for enhancing amendment and/or contaminant migration through low-permeability soils.
- A wide range of possible construction orientations exists.
- The electrode can be switched from anode to cathode.
- A wide range of amendments and contaminants can be targeted—for instance, organics (dissolved and/or NAPL), metals (for example, uranium, chromium, etc.), anions (for example, ammonia, sulfate, etc.), and oxidants (permanganate, persulfate, etc.).

D3.4 Limitations

- Amendments and/or contaminants migrate in the dissolved state; sorbed-phase contamination can be addressed only by desorption or by direct reaction with injected amendments.
- Migration rates of amendments and/or contaminants are slow as a function of the tight formation and low hydraulic conductivity, which is mitigated by designing the installation with close spacing.
- Electrolysis reactions on the electrodes create acidic conditions at the electrode site (anodes), which may migrate with groundwater and may also degrade the electrodes (this could also be an advantage in some circumstances, for example, to induce mobilization of certain metals).
- Some metals may precipitate due to pH shifts or oxidation reactions at the electrodes.
- Electrokinetics may affect other soil or aquifer properties in addition to pH, including soil moisture and microbial biomass.
- Buried metallic structures or other conductive materials may affect voltage gradients and corresponding amendment and/or contaminant migration rates or pathways. In addition, any affected soil or aquifer property (for example, pH) could potentially cause damage to subsurface structures.
- Although electrokinetic processes can be used in higher permeability soils, these processes are likely less efficient and more costly than traditional amendment injection and/or recirculation methods.
- Fluid injection and recovery may be required even if remediation processes occur strictly in situ.

D4 Solid Injection Principles

D4.1 Fracture-Based Delivery

Soil and bedrock fracturing offers the ability to create new permeability structures within a targeted formation to enhance contaminant removal or their in situ destruction. Among the fracture design specifications that can be manipulated (and thus optimized) are fracture content (amendment for in situ reactions or material to enhance permeability), location, depth, extent, aperture, and orientation. Some fracture design elements can be controlled (for example, fracture content, injection location, initial depth), but the extent of fracture propagation and its aperture or orientation from the injection point is less certain and can vary based on delivery techniques. The primary methods for creating fractures are hydraulic and pneumatic. For hydraulic fracturing the carrier media (used to produce the fractures) is a liquid, while for pneumatic fracturing the carrier is nitrogen gas. Although the carrier media is the primary difference between these two methods, the injection tooling for each fracturing method is also typically different. Furthermore, a wide range of hydraulic fracturing tooling is used. The different tooling provides varying degrees of fracture control and orientation, resulting in more or less control of the delivered materials.

D4.2 Governing Principles

Both hydraulic and pneumatic fracturing techniques apply pressure sufficient to overcome the natural matrix cohesion (including overburden pressure) and cause the matrix to fail and fracture. Fractures can be propagated using multiple techniques, including through temporary injection borings or DPI rods. When temporary borings are used, the fracture tooling is advanced downward through the boring to the desired depth. A high pressure is applied to notch the casing and subsequently advance the injection media into the surrounding formation. When direct push rods are used with injection tooling advanced at the end, once the tooling is at the desired injection depth, the pressure is increased to a magnitude sufficient to overcome the stress and elasticity of the surrounding formation with either water or liquid amendments. The net injection pressure is modulated at the surface via injection pump controls.

The ability to develop sufficent pressure to initiate and propagate a fracture implies that the fluid is delivered to the formation at a rate greater than the accompanying Darcy flow into the formation. The advancing fracture results in dilation with an overall size that depends on the elastic modulus of the deformed formation. The deformation surrounds the fracture in three dimensions and the extent of deformation is affected by injection depth, injection volume, and geology, and may range from no measurable deflection to several millimeters.

Once the fracture is established, amendments or a propagation material migrate through the newly created void space outward into the formation. Fracture extension away from the injection point is controlled by the energy losses along its length. The stress intensity at the leading edge of the fracture is responsible for overcoming the native matrix strength, which consumes energy. Even in nonconsolidated strata where the cohesion is negligible (for example, sand and gravel), the extention of the fracture tip does require rearrangement of the grains, which also consumes energy.

As it advances, the fracture may intersect natural flow paths that deflect the fracture direction and can result in leak off from the original intended fracture interval. This mechanism can have unintended consequences, such as the transport of injected materials to land surface (daylighting) or to unintended vertical intervals. The degree of leakage is controlled by relative permeability effects distributed along and near the fracture faces.

Fracture orientation will follow the path of least resistance, which could be through more permeable soil materials than the intended fracture depth, or to shallower intervals (or even land surface) with low overburden pressure. The fracture emplacement processes described above can influence fracture propagation independent of the subsurface matrix structure or geology. As an example, postfracture excavations have shown induced fractures to cut across multiple geological units while maintaining a mildly dipping trajectory. In other cases, induced fractures will follow a unit boundary that they encounter.

Fracturing does not change the pore structure of the surrounding matrix; permeability of the existing formation does not change. Conversely, establishing new flow paths is what allows for overall transmission of fluid and is ultimately what supports contaminant remediation. These flow paths will convey contaminants and water at different rates than the native surrounding material, thus serving to focus flow through intervals in which amendments have been emplaced. Diffusion and dispersion enhance amendment distribution or geochemical changes from the fractures into more of the contaminated subsurface.

D4.3 Differences Between Hydraulic and Pneumatic Fracturing

Pneumatic fracturing and hydraulic fracturing differ principally in the viscosity, compressibility, and density of the fluid used to apply the pressure. Nitrogen, which is used for most pneumatic fracturing, has viscosity of 0.018 cp while the high viscosity non-Newtonian amendments used to create many hydraulic fractures can have effective viscosity on the order of 200 cp. Gases are compressible, and water/aqueous slurry is incompressible. Over the range of typical fracturing pressures encountered in environmental work, the compressibility of gases varies from approximately 5×10^{-7} Pa^{-1} to 2×10^{-8} Pa^{-1} while compressability of typical solutions injected is roughly the same (5×10^{-10} Pa^{-1}) as that of water. Although the density of nitrogen used to create fractures is on the order of 1 kg/m^3, the density of water is a thousand times greater. The multiple order of magnitude contrast between the properties of nitrogen and water explains differences in the functions and capabilites of the two methods.

The most significant consequence of the viscosity difference is that leak off is much greater with pneumatic fracturing. It can be sufficiently great to arrest propagation of the parent fracture, leading to non-uniform or partial fracturing around the well and limited overall fracture extension. Since leak off is greater during pneumatic fracturing than during hydraulic fracturing, fluid needs to be delivered to the formation at a greater rate to maintain the pressure necessary to dilate and extend the fracture. In most cases, the fracture is then filled with the selected amendment, which is often a liquid or solid slurry, and often a proppant such as sand. The advantage of this phenomenon is delivering treatment material throughout the targeted formation and potentially reducing the transport between the fracture and the groundwater, as well as affected soils that could otherwise contribute to back-diffusion.

The greater viscosity of hydraulic fracturing fluids not only suppresses leak off but also, in conjunction with its greater density that counters bouyancy effects, enables the transport of large amounts of solid amendments such as ZVI in a hydrated guar gum solution. Active amendment from these materials then migrates with the surrounding groundwater and can intersect contaminants. If the solid is slightly soluble in groundwater, the fracture can act as a long-term in situ passive source of amendment. Distribution mechanisms of amendment away from the fracture can involve advection as well as diffusion and dispersion transport processes. Even if the solid has limited solubility, it may serve well in low-permeability media. If the permeability contrast between the injected treatment material creating the fractures and the surrounding formation exceeds two orders of magnitude, the fracture will act as a preferential flow path and groundwater flowing through it can be remediated much as in the case of a permeable reactive barrier (PRB).

Descriptions of the tooling and methods used for hydraulic and pneumatic fracture are included in Sections D5 and D6. The applicability of these methods to specific site conditions is discussed in the following section.

D5 Hydraulic Fracturing-Based Delivery Methods

Fracturing occurs when a fluid is injected into a soil or rock formation at a rate faster than can be accepted by the formation via Darcy flow. If a principally liquid fracturing fluid is injected at such a rate, hydraulic fracturing occurs. The mechanisms of hydraulic fracture formation, which follow from fundamental characteristics and properties of solid materials, dictate that fracturing creates planar features that extend away from the point of injection. When granular solids such as sand or iron grains are included in the fracturing fluid, the fracture can persist as a new structure of desired size and location in the subsurface. Further, the predictability of fracture forms can be improved by creating a void (commonly called a notch or kerf) at the point of injection, prior to injecting the fracturing fluid, with a geometry intended to direct the initial fracture formation (that is, nucleation). Common terms applied to these methods in the environmental remediation industry include hydraulic fracturing, emplacement, controlled fracturing, jet injection, jet-assisted fracturing, jet fracturing, and slurry emplacement.

Hydrology governs the interaction of contaminants with the injected material, and optimal remediation is accomplished by balancing the treatment characteristics of injected amendments with the design of a hydraulic fracturing program. Considerations for the design of a hydraulic fracturing program may include manipulating the fracture form (that is, lateral extent, thickness, orientation, amendment loading) and varying the fracture layout (that is, X-Y location, overlap between adjacent fractures, fracture spacing with depth). For horizontal fractures consider a design with lateral fracture extents of 5–30 m. The smaller the lateral extent, the more controlled the fracture dimensions, and the larger the extent, the higher the uncertainty of the fracture location. In addition to the horizontal fracture extent, the horizontal fracture design should consider the fracture thicknesses. Thin fractures (for example, from 1 to 10 mm thick) can penetrate low-permeability layers better, but may limit the volume of amendment that can be delivered to the subsurface. Thicker fractures (for example, 10–30 mm thick) enable a higher volume of amendment to be delivered to the subsurface; however, ground surface uplift should be considered. Both horizontal and vertical fractures can be created using different fracturing methods, while working within the confines of the formation characteristics.

D5.1 Types of Equipment

Fracturing methods can be applied directly to a shallow formation with standard direct push equipment. Creating deeper hydraulic fractures requires more robust direct push equipment or sonic tooling. Alternatively, dedicated wells of solid PVC (or steel) casing can first be installed using sonic, auger, mud rotary, or air rotary drilling methods. The solid casing is then cut at selected elevations to allow one or more fractures to be created. In very competent formations, such as crystalline bedrock, fractures can be created in open boreholes. A key feature of robust fracturing methods is the ability to focus fluid pressure on a small portion of the target formation. Thus, best practices for direct push use a short section of borehole, whereas straddle packers are used in wells and open-hole settings.

Hydraulic fracturing requires a pump that can develop both a sufficient pressure to overcome the strength of the target formation and an adequate injection rate. Typically, positive displacement pumps are used, and when granular solids are included, the pump must be mechanically compatible. Preparing and handling fracturing fluid may require specialized mixing equipment as well as bulk solids handling equipment. Mixing equipment and pumps are typically provided by a dedicated service contractor. Creating a notch prior to injecting the fracturing fluid can be completed using physical methods (that is, cutting) or high-pressure water jetting.

D5.2 Types of Delivery

As described above, a variety of drilling methods can be used to apply hydraulic fracturing. These methods include direct push, sonic, auger, mud rotary, or air rotary. Injection manifolds can be useful for large numbers of injection points already fractured, wells completed, and high volumes of liquid amendments. The manifold routes the flow from the injection pump to several injection rods simultaneously. A separate flow meter and pressure gage on the main line and each injection line can be beneficial to document injection performance at each location.

D5.3 Advantages

- Hydraulic fracturing provides the opportunity to deliver very large amounts of solid material into the target formation in a relatively short amount of time. Such a large dose may be designed to address significant contaminant mass, passively extend the duration of remediation (after emplacing large amounts of amendment in fractures), or both.
- Hydraulic fracturing techniques can be applied in almost any geologic formation, including bedrock.
- Hydraulic fracturing can be used to deliver remediation amendments, to enhance permeability by injecting sand or other granular materials, or to achieve both.
- Although noncohesive materials (for example, coarse sands and gravels) do not strictly fracture, the application of fracturing methods often results in similar distributions of injected material, thus supporting in situ remediation processes.
- The planned or deliberate application of hydraulic fracturing methods ensures that material (amendments or proppants) will be delivered in a controlled manner to the target zones. Unplanned or inadvertent fracturing, often occurring during DPI of liquids, can result in poor distribution of remediation amendments and amendment surfacing.
- The direction and magnitude of micro ground surface deformations or “tilt” can be qualitatively measured by tiltmeters, elevation surveying on the ground surface, and downhole pressure readings at monitoring well locations. A network of tiltmeters determines the dip angle, orientation, and extent of fractures in the subsurface. This information can be input into an interactive 3-D model to visualize the fracture network in the treatment zone.

D5.4 Limitations

- Optimal practice of hydraulic fracturing requires specialized mixing equipment, pumps, and injection tooling in combination with the experience of a dedicated service contractor.
- Hydraulic fracturing generally cannot be deployed in existing wells, although open boreholes in competent bedrock can be used.
- Hydraulic fracturing may not be viable in very shallow settings, especially if the overburden is loose or otherwise cannot contain the fracture in the subsurface.
- Surface deformation can occur during hydraulic fracturing, so the injection program must consider the potential for impacts to shallow and aboveground infrastructure (for example, buried utilities, buildings, railroad tracks, etc.).

D6 Pneumatic Fracturing-Based Delivery Methods

Fracturing opens new space within geologic formations that can be exploited to enable or enhance in situ remediation in two ways. First, permeability can be enhanced to the extent that the new permeable space provides flow pathways and improves well performance (either extraction or delivery). Second, filling the newly created space with reactive material can establish in situ remediation that proceeds passively without further operations at the surface. This second feature also allows use of reactive granular solids that can not penetrate the pore space of the formation or otherwise contact the contaminants.

Pneumatic fracturing uses nitrogen gas as the fracturing medium. In contrast, hydraulic fracturing relies on aqueous-based fluids, which have viscosity, density, and compressibility orders of magnitude different from gases. Pneumatic fractures can be used to enhance well performance, although solid particles, such as ZVI sand, are commonly entrained in the flow to create in situ reactive treatment zones.

D6.1 Types of Equipment

Surface equipment for pneumatic fracturing can include reservoirs for compressed gas (typically tube trailers or similar compressed gas transport vehicles), manifolds to manage the gas supply and incorporate any admixing material whether liquid or granular solid, bulk storage vessels (tanks, bins, or hoppers) and handling equipment, pumps and hoses, and instrumentation. Surface equipment usually can be provided as a package by the injection contractor.

Drilling equipment is needed to advance the tooling downhole. Downhole tooling is developed around an injection nozzle assembly positioned between straddle packers. The packers are used to isolate target intervals, and an initiation notch is cut with high gas flow and/or pressure to facilitate fracture nucleation. Vertical separation between target intervals depends on the remediation amendment used, the volume and dose of amendment to be delivered to the subsurface, and the lithology. New techniques for combining sonic drilling with delivery can enhance application efficiency by potentially reducing the time at sites where well casings were required to keep the borehole open.

D6.2 Types of Delivery

Pneumatic fractures usually are created from open or cased boreholes. Consider using pneumatic fracturing in boreholes with a minimim of 4-inch diameter to house the straddle packers. Usually, a bottom-up approach is followed. Stiffer formations that offer stable open borehores can be addressed with conventional fracturing practices. Formations that slough or exhibit charactersitics of flowing sands require more complicated integration of the drilling technique with the fracturing process. There also have been applications where pneumatic fractures are created through DPI tooling.

D6.3 Advantages

- The volume and flow rates used in pneumatic fracturing can create a haze of newly opened fractures that contribute to fluid flow. This enhanced fracture density can reduce the time frame for diffusive transport between fractures and thus the time frame for remediation.
- The open apertures created by pneumatic fracturing offer unimpeded flow paths that can persist after the fracturing process because irregularities along the fracture surface and shifting of the geologic medium prevent closure.
- Pneumatic fracturing does not introduce additional water into the formation, which may prove critical where water might block pores or otherwise interfere with flow of free product or air in the contaminated porous media.
- The direction and magnitude of micro ground surface deformations or “tilt” can be qualitatively measured by tiltmeters, elevation surveying on the ground surface, and downhole pressure readings at monitoring well locations. A network of tiltmeters determines the dip angle, orientation, and extent of fractures in the subsurface. This information can be input into an interactive 3-D model to visualize the fracture network in the treatment zone.

D6.4 Limitations

- Although pneumatic fracturing can be performed in almost any geologic matrix, its application in bedrock is limited by pressure and compressibility to only the most weathered portions, where the primary function of the fracturing events is to dilate and clear loose debris from existing natural fractures.
- Fracture growth may be arrested before the desired extent is achieved in the process known as leak off,

accomplishing only partial fracturing.
- Borehole collapse onto the fracturing setup and sealing issues can be problematic. Soil collapse would require retrieval of the packer assembly and reaming out after collapse or overdrilling if the annular seal is lost.
- High pressures present health and safety challenges. The requisite volume and pressure of gas (nitrogen) usually results in deployment of one or more compressed gas tube trailers. Packers and hoses need to be sufficiently robust to contain injection pressure.
- Pneumatic delivery, due to a unique injection nozzle, typically is not applied through direct push tooling and primarily is used in open bore holes.

D7 Permeable Reactive Barrier Construction

PRBs are a type of subsurface reactive treatment zone created by placing permeable reactive material in the subsurface to passively intercept and treat affected groundwater (ITRC 2011). As contaminated groundwater flows through the PRB under native or induced hydraulic gradients, the contaminants are sequestered or transformed to meet remedial action objectives. PRBs are constructed across the plume perpendicular to the groundwater flow direction. They can be placed near source areas for isolation, as well as downgradient to control plume expansion. To be effective, the barrier must be designed and placed to prevent short-circuiting and groundwater mounding or diversion, and to account for hydrogeologic and geochemical conditions. The latter barrier is used so that the appropriate type and amount of amendment, generally measured by barrier thickness and residence time, is emplaced. A thorough understanding of site hydraulics is critical to successful PRB application.

While PRBs can be constructed using multiple, closely spaced amendment injections, this section focuses primarily on methods other than vertical injection points for emplacing the PRB.

D7.1 Types of Equipment

PRBs that are not injected/fractured generally require large machinery and extensive site access to install. The type of equipment depends upon the depth required, geologic materials encountered, and volume of amendment to be placed. Excavators, pile drivers, trenchless PRB installation technology (for example, continuous pass trenchers), and injection/fracture placement technology have been used to install reactive media and create PRBs.

D7.2 Types of Delivery

The most common noninjected/fractured PRBs are shallow (less than 35 ft below grade) and are installed using an excavator to open a trench and allow placement of granular treatment media. Excavation support (for example, biopolymer slurry or shoring) is generally required to maintain the open trench pending backfill. Excavation becomes more challenging and expensive with depth. If site conditions allow, a trenchless technology combines excavation and backfill into a single step, eliminating the need for supplemental excavation support. Depending on the method used for trenching and the reactive media, horizontal delivery piping can be added to the PRB backfill to rejuvenate it with additional amendments over time. Large-diameter augers have also been used to place amendments in vertical columns in close proximity to create a continuous PRB.

Injection or fracturing techniques are also used to construct subsurface PRBs. Although these placement techniques allow for greater depth and less short-term site disruption, they require a smaller size amendment (micro, nano, or liquid), typically resulting in more frequent replacement, unless long-lasting amendments are injected (for example, ZVI, emulsified vegetable oils). Permanent or temporary injection points are used to place reactive materials into the subsurface under pressure. The injection points are spaced to provide overlapping radii of influence between them, forming a treatment zone. Injection wells can be placed either vertically or horizontally, with the latter providing options for delivery beneath buildings.

Groundwater flow through PRBs can be induced by constructing them to have a higher hydraulic conductivity (K) than the surrounding aquifer material. Groundwater flow through PRBs can be accomplished using impermeable wings (slurry walls or sheet piles) on either side of the PRB to direct groundwater to flow through the reactive materials. These configurations are referred to as funnel and gate. The sequence in which the reactive and impermeable media are placed should be considered within the larger PRB design. Site hydraulics and anticipated treatment media replacement should be considered when evaluating continuous treatment zones versus funnel and gate configurations.

D7.3 Advantages

- Well designed and properly constructed PRBs are effective at cutting off plumes and protecting receptors.
- They require little to no long-term operation and maintenance requirements, except where biofouling occurs.
- Even when the source cannot be effectively addressed, a PRB can provide long-term risk mitigation and receptor protection.
- A PRB can be a critical component of a monitored natural attenuation strategy for groundwater by cutting off the source, leading to shrinking of the plume.
- A PRB can be designed to passively treat many different contaminants.
- Often PRBs are constructed with low-cost materials such as mulch.
- Many PRB designs incorporate a screen or slotted pipe that can be used to replenish a substrate.
- Decommissioning a PRB is typically low cost unless the reactive or impermeable media need to be removed.

D7.4 Limitations

- PRBs do not treat the source of contamination and therefore need to be maintained until the source is depleted or concentrations in the contaminant plume fall below cleanup criteria.
- Although PRBs may require minimal long-term operation and maintenance, the capital cost may be higher than other remedial technologies. Amendment longevity and replacement techniques are critical to understanding life cycle costs.
- Short-circuiting (flow around) the PRB is a common challenge. Detailed understanding of geology and hydrogeology is required. Keying the PRB into a confining layer can prevent underflow.
- Robust construction quality assurance is required to achieve the proper installation. Because site heterogeneity is often encountered during installation, an adaptive management plan (design modifications based on observed field conditions) is recommended.
- To engineer around uncertainty, PRBs may be designed conservatively, generally in terms of thickness. Thickness, depth, and longevity are key cost components for a PRB.
- Changes in groundwater characteristics and impacts to secondary water quality immediately downgradient of PRBs may limit use. Also, PRBs may clog over time, exacerbating short-circuiting and limiting treatment capacity.

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