Technical Report: Subsurface Injection of In Situ Remedial Reagents (ISRRs) Within the Los Angeles Regional Water Quality Control Board Jurisdiction

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List of Acronyms

BMPs	Best Management Practices
CPT	Cone Penetrometer Technology
DNAPL	dense non-aqueous phase liquid
DP	Direct Push
DPI	Direct Push Injection
DWR	Department of Water Resources
FT BGS	feet below ground surface
GPM	gallons per minute
ID	inside diameter
ISCO	In-Situ Chemical Oxidation
ISRR	In-Situ Remedial Reagent
ISRRs	In-Situ Remedial Reagents
ITRC	Interstate Technology Regulatory Cooperation
IW	Injection Well
LARWQCB	Los Angeles Regional Water Quality Control Board
LNAPL	light non-aqueous phase liquid
MSDS	Material Safety Data Sheet
OD	outside diameter
PPM	Parts per million
PSI	Pounds per square inch
PVC	Poly vinyl chloride
ROI	Radius of influence
ROWD	Report of Waste Discharge
VOC	Volatile organic compound
WDR	Waste Discharge Requirements

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Disclaimer

This document is a compilation of available information, knowledge, experience, and best practices regarding injection of in-situ remedial reagents for groundwater cleanup. This document does not contain regulatory requirements. In general, this document should be used as a reference. Differences may exist between the recommendations in this document and what is appropriate under site-specific conditions. The recommendations do not represent the positions or opinions of any companies or the government agencies involved. This document does not represent endorsement of practitioners or products mentioned in the technical report by the participating government agencies.

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1.0 Introduction

The In Situ Remediation Injection Working Group (Working Group) recognizes the effectiveness and efficiencies offered by advanced remediation technologies in treating certain contaminated groundwaters of the Los Angeles Region. In particular, the applications of In Situ Remediation Reagents (ISRRs) have demonstrated considerable success in cost effectively treating a range of subsurface contaminant types. However, the Working Group further recognizes that the safe and successful application of the reagents requires a proper understanding of site characteristics, delivery methods, application equipment, and monitoring methodology.

1.1 The ISRR Working Group

In August of 2008, the LARWQCB formed the ISRR working group to share information on techniques for applying ISRR technologies. The charter of the working group was to document best practices to be used when applying ISRR technologies so as to minimize any impact to the public from the use of these technologies. Specific attention was given to avoiding the visible surfacing of injected ISRR materials, minimizing impact to landscaping, and to ensuring no surface pathway for potential ISRR material run-off.

1.2 Purpose of Document

This technical report was developed by the ISRR working group with the objective of compiling general tools and best practices into a reference manual to be used during the planning, design, and field implementation phases of ISRR projects. The document was developed to guide practioners of ISRR in performing cost effective remediation projects while ensuring minimum impact to the public. Intended users of this technical report include regulators, consultants, and appliers of ISRR materials. This technical report places a strong emphasis on safety considerations and is intended to supplement similar guidance documents that have been published by the Interstate Technology & Regulatory Council for In Situ Chemical Oxidation (ITRC, 2005) and for direct push well technology (ITRC, 2006). The technical report also directs readers to references of the California Department of Water Resources Water Well Standards (see References).

2.0 Review of Fluid Injection Mechanics

Injection of a remedial reagent into the saturated zone results in the mixing and displacement of the aquifer water present. During this displacement, in a water-table aquifer (phreatic zone), the volume of fluid injected will temporarily cause a localized rise in the water level - a phenomenon referred to as mounding. The force imparted by the pull of gravity on the mounded groundwater and reagent fluid injected into the aquifer is referred to as the hydrostatic pressure. As the initial aquifer water is displaced the mounding dissipates relieving the temporary buildup in hydrostatic pressure. The rate at which the mounding dissipates is primarily dependent on the hydraulic conductivity (or permeability) of the soil in the aquifer. In this document the aquifer's ability to "accept" a given reagent volume applied at a given delivery rate is referred to as hydraulic conductivity. Figure 1 depicts groundwater mounding associated with ISRR injection as well as fracturing of the subsurface.

When injected with a given volume of remedial reagent, a high conductivity aquifer will respond by accepting the reagent at low application backpressure readings. Conversely, given the same volume and application rate in a low conductivity aquifer and/or in a shallow groundwater setting where the depth to groundwater is less than 10 feet below grade, this type of aquifer will respond with a higher backpressure, possibly rejecting some of the reagent volume and/or requiring a field modification of the application rate. If injection proceeds without field modification, the reagent fluid builds hydrostatic pressure in the subsurface. Because ISRR fluids are typically water-based and non-compressible, the continued buildup in hydrostatic pressure will be relieved when the fluid moves outward through "paths of least resistance". Such paths could include movement into subsurface utility conduits, into previously drilled boreholes or wells, or into fractures propagated by continued pumping under pressure. Often the paths taken by fluid moving under excessive hydrostatic pressure ultimately results in the fluid finding its way to the surface in an event referred to as "surfacing" or "daylighting". Figure 1 represents a conceptual set of circumstances in which subsurface fracturing leads to daylighting.

Excessive buildup of hydrostatic pressure can be avoided by proper design of the injection program and the proper selection of injection methods and tooling. Surfacing, if encountered in the field can be controlled through monitoring of backpressure and adjusting injection parameters such as injection pressure, flow rates and number of injection points to allow the aquifer time to equilibrate.

3.0 Pre-Design Considerations

3.1 Capacity of Subsurface to Accept Fluid Volume

In order to provide an adequate level of understanding of the target zone's ability to accept the designed ISRR volumes and application rates, the consultant should evaluate existing site data and/or acquire additional data as part of a Remedial Investigation Program. Capturing and analyzing this information will go a long way in determining the likelihood of application success.

The following data analysis and testing methods have been shown to be very useful in determining a soils hydraulic conductivity. NOTE: Interpretation of the various testing methods results is left to the individual reader. There are a number of soil testing methods that result in a transmissivity value which can be easily converted into hydraulic conductivity.

3.1.1 Blow Counts:

This is a low resolution method that consists of recording the number of blows required to advance a sampling tube a distance of 12 or 18 inches by a "hammer" of known weight. The number of blow counts is typically recorded on the boring log and are a very general measure of the soils relative density in that section of the boring. This measure is often meaningful to seasoned geoscientists and provides a general indication of the target zones "stiffness" and thereby assists in determining how fine grained or coarse grained the target zone might be.

3.1.2 Soil Conductivity:

Soil conductivity is a measure of the soils ability to conduct electrical current and can be collected using various techniques. The magnitude of this ability differs according to the material type, e.g. sands have a low conductivity compared to clays. If available, this measurement is often compared to soil boring logs to confirm the presence and location of fine grained units (high conductivity clayey soils) in relation to lower conductivity materials such as sands. It should be noted that the presence of hydrocarbons will reduce conductivity, possibly resulting in erroneous lithologic interpretations.

3.1.3 Well Recharge Rates:

This is a low resolution method that generally entails analysis of existing data. It is generally reliable because the rate of recharge is often measured consistently over time. The recharge rate of individual wells is generally collected during the site characterization program as part of the well installation process. The recharge data may also be available from on-going groundwater monitoring programs that still use the traditional removal of 3 casing volumes prior to sampling. The rate of recharge is a low resolution measure of transmissivity of the surrounding aquifer material.

3.1.4 Grain Size Analyses:

This method is a laboratory procedure that results in a very high resolution analysis of a specific vertical section of the aquifer. It relies on the collection of a "representative" target zone soil sample. This sample is passed through a series of sieves that sort the soil by grain size and the results are presented as a composition percentage of each soil sample. Grain size analyses can then be correlated with transmissivity (Carrier, 2003).

3.1.5 Slug Testing:

This is a moderate resolution field test that consists of an instantaneous removal or addition of water to a well and then measuring the resulting aquifer drawdown and stabilization. Upon stabilization of draw down the well's specific capacity and specific yield (Driscoll, 1986) can be determined. Mathematical methods are applied to the draw down section of the test and these data result in a slug test calculation. This method allows the seasoned user to calculate a rough hydraulic conductivity, transmissivity and storage coefficient for a given target zone aquifer.

3.1.6 Specific Capacity Test:

Specific capacity of a well is determined by dividing the well's discharge rate in gallons per minute (GPM) by the drawdown in feet (ft). This test is often performed when new wells are constructed by the driller and is typically recorded on the well completion log. The higher the specific capacity, the better is the conditioning of that well. Although injection is the reverse process of pumping, the specific capacity will give a rough indication of the potential for sustained injection and can be used to approximate the transmissivity of the surrounding aquifer (Heath, 1989). Comparison of specific original capacity results with future tests after multiple injection events will allow the evaluation of possible clogging in the filter pack or screen and/or the deterioration of the well screen.

3.1.7 Aquifer Pumping Test:

This is a high resolution field test that consists of a constant-rate pumping test (24 to 72 hour duration) and measurement of the associated drawdown in nearby observation wells. Periodic monitoring of water levels in the observation wells is recorded along with the recovery rate after the pumps are shut down. This data is plotted and mathematically analyzed to derive estimates of transmissivity and storage coefficients (Lohman, 1972 & Walton 1970).

3.1.8 Hydraulic Profiling Tool (HPT):

The direct push HPT can be used in both saturated and unsaturated conditions and provides a real time vertical profile of the soil hydraulic properties including hydraulic conductivity and electrical conductivity. The HPT can be pushed or hammered into the subsurface. While being advanced into the subsurface, the HPT is continuously injecting small amounts of water and measuring the pressure response with a downhole transducer, which then can be used to determine hydraulic conductivity.

In addition, the HPT can be used to select well screen intervals, evaluate locations to conduct slug tests, and measure static water conditions across a site. The HPT also provides a simultaneous log of electrical conductivity with an integrated Wenner array.

3.1.9 Cone Penetrometer Technology (CPT)

This technology emerged from the geotechnical/soil stability market place where it is typically employed for in-situ data collection. Typically, rod advancement is via hydraulic pressure or push.

A wide array of geotechnical soil and groundwater related properties can be collected using various sensors commonly employed with the CPT technology. These properties include geotechnical, geophysical as well as hydrogeologic elements.

3.2 Application Related Issues

It is critical that the Consultant take steps to identify any subsurface utilities and direct conduits to the surface that may be present at the site prior to injections of remedial substrates. The identification of these subsurface structures and conduits will lessen the likelihood of damaging a utility or “day lighting” remedial substrate.

3.2.1 Locate Subsurface Utilities:

It is a requirement that the Consultant or the application subcontractor contact *Dig Alert 2 Full Working Days* prior to field injection operations. The Consultant is encouraged to make a field inspection prior to injection operations to be sure that the injection application area is a sufficient distance from any underground utilities.

3.2.2 Locate Previous Boreholes:

Locate and, if possible, inspect any boreholes from previous rounds of assessment and remedial efforts. Previous abandoned bore holes may have improper or incompetent seals. The applications of ISRR via a pressurized application methodology may find these conduits to the surface and result in reagent surfacing.

If this occurs while applying remedial reagent, it may be appropriate to reseal the upper 3-5 feet with hydrated and compacted bentonite chips/pellets using a compacting tool or other field tools. Care should be taken to pack the bentonite chips in 1-2 foot "lifts" while hydrating thoroughly between lifts. This process should be repeated to the surface. If possible, the hydrated bentonite should be allowed to cure for approximately 24 hours before injection operations are performed in the area of the repaired borehole. If abandoned exploratory or well boreholes present on site result in short circuiting of ISRR to the surface it may be necessary to follow DWR Standards for abandoned borings and wells as discussed in Chapter 2, Water Well Standards.

3.2.3 Waste Discharge Permit Requirement

Prior to initiating an ISRR project, a Waste Discharge Requirement (WDR) must be filed with the LARWQCB. Based on the WDR, the Board will determine whether a site specific Waste Discharge Requirement (WDR) or a general WDR is required. Details regarding the WDR are available on the California Environmental Protection Agency – LA RWQCB website (http://www.waterboards.ca.gov/losangeles/publications_forms/forms/npdes-wdr_forms.shtml).

4.0 Injection Specific Design Using the Pre-Design Data

It is difficult to estimate site behavior during injection of ISRR materials based solely on estimation of site hydraulic characteristics. This is due to the tremendous amount of variability in the subsurface and the dynamic responses as injection proceeds. The applier will have to use an artful blend of estimated site hydraulics, previous experience on other similar sites, and an intuitive sense of the site's aquifer architecture. Since many of the ISRR's are applied in high-volume success generally hinges on the rate of vertical fluid acceptance.

Aquifer characteristics for most evaluations focus on the lateral components of aquifer flow; these include hydraulic conductivity and porosity either total or effective. In the previous section various standard tests for aquifers were briefly described. Most of these tests directly approximate an aquifer transmissivity and in some cases the storage coefficient. For practical purposes of aquifer evaluation the most useful values will be hydraulic conductivity and effective porosity.

Hydraulic conductivity (feet/day) is easily derived by dividing the estimated transmissivity ($feet^2$/day) by the aquifer's saturated thickness (feet). Some care must be taken to make adjustments in aquifer thickness parameters, particularly if the transmissivity estimates are derived from situations where the pumping well or observation wells used to make the estimate were partially penetrating or where they were screened in different intervals (Walton 1970). Most remediation efforts are performed in the upper sections of water-table aquifers. Storage values for these aquifers are equivalent to the specific yield and may be used for the effective porosity. The following sections briefly introduce direct calculations for injection limits, pre-injection testing, generalized application rates and volume guidance.

4.1 Vertical Acceptance Guidelines for Injection

The rate that an aquifer can accept fluids and the lateral migration of these fluids before reaching structural failure is significantly influenced by the vertical acceptance rate. Maximum injection pressure can be estimated by the density of the dry soil and saturated soil, the thickness of the vadose zone, and the height of the saturated zone above the injection point using the following equation:

$$P_{max} = [(\rho_{dry}\ g\ h_{dry} + \rho_{sat}\ g\ h_{sat}) - \rho_{water}\ g\ h_{sat}]\ \text{psi (or dynes/cm}^2\text{)}$$ (Equation 1)

Where:

P_{max} = Pressure maximum
ρ_{dry} = Density dry soil – vadose zone
ρsat = Density saturated soil
g = Gravitational acceleration
h_{dry} = Height dry or thickness of vadose zone above the injection point
h_{sat} = Height saturated of saturated zone above the injection point
ρ_{water} = Density water
psi = Pounds per Square Inch
cm^2 = Centimeters squared

It is recommended that for injection applications a 60 percent safety factor be applied to the maximum calculated pressure as part of the derivation of $P_{injection}$ (Payne, 2008). As fluids are injected into an aquifer the pressure applied to deliver these fluids is expressed upward against the effective hydraulic conductivity and the downward gravitational force of the water mound. Commonly the vertical hydraulic conductivity of many aquifers is approximately 10 percent of horizontal hydraulic conductivity and can be used as the effective hydraulic conductivity. The vertical acceptance is then determined by the relationship between pressure and the effective hydraulic conductivity as the vertical mounding expands. The following equation can be used to express this relationship between effective hydraulic conductivity and vertical mounding:

$$\frac{Q}{A} = K_{effective}\ (P_{injection} - \rho_{water}\ g\ h)/h$$ (Equation 2)

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Where:
Q/A = the flow rate applied over the area of the expanding mound. Vertical flow ceases as the mound height (h) reaches the pressure limit or the selected “not to exceed” injection pressure (Payne, 2008).

$K_{effective}$= Vertical Hydraulic conductivity
$P_{injection}$ = 60% of the allowable injection pressure
ρ_{water} = Density of water
g = Gravitational acceleration
h = mound height above water table

4.2 Application Rates and Fluid Application Volumes for Various Soil Types

The actual delivery rates for remedial reagents are always site specific and will vary both horizontally and vertically across a site.

Given unlimited time an aquifer can accept an unlimited amount of reagent. However, in order to achieve a relatively efficient injection rate while minimizing the potential for reagent surfacing there will be limits to the injection volumes and reagent application rates based on site specific factors. For injection of ISRRs, the following tables represent a very general set of guidelines that can be used in site remediation application planning.

Table 1 provides general “experience-based” application volumes for various soil types.

Table 1. Chemical Injection Recommended Injection Safety Standards

Task	Parameter	Range	Reactive Reagents	Non-Reactive Reagents	
				Liquid	***Non-Liquid***
Injection	Maximum % pore volume for Site(1)	GP-SP	< 33%	< 33%(2)	< 10%
		SP-SM	< 10%	< 33%	< 10%
		ML-CL	*< 5%*	< 10%	< 5%
	ROI	GP-SP	*< 30 feet*	< 30 feet	< 15 feet
		SP-SM	< 15 feet	< 15 feet	< 5 feet
		ML-CL	< 5 feet	< 5 feet	< 5 feet
	Flow Rate	GP-SP	1-5 ft bgs/<1 gpm (>5% peroxide solution not recommended)	1-5 ft bgs/gravity feed	1-5 ft bgs/<3 gpm
			5-10 ft bgs/<3 gpm	5-10 ft bgs/<5 gpm	5-10 ft bgs/<5 gpm
			10-30 ft bgs/<15 gpm	10-30 ft bgs/<15 gpm	10-25 ft bgs/<10 gpm
			>30 ft bgs/<25 gpm	>30 ft bgs/<25 gpm	>25 ft bgs/<15 gpm
		SP-SM	1-5 ft bgs/<1 gpm (>5% peroxide solution not recommended)	1-5 ft bgs/gravity feed	1-5 ft bgs/<3 gpm
			5-10 ft bgs/<3 gpm	5-10 ft bgs/<5 gpm	5-10 ft bgs/<3 gpm
			10-30 ft bgs/<15 gpm	10-30 ft bgs/<15 gpm	10-30 ft bgs/<10 gpm

Task	Parameter	Range	Reactive Reagents	Non-Reactive Reagents	
				Liquid	***Non-Liquid***
			>30 ft bgs/<25 gpm	>30 ft bgs/<15 gpm	>30 ft bgs/<10 gpm
		ML-CL	1-5 ft bgs/(prohibited in SILT or CLAY soils)	1-5 ft bgs/gravity feed	1-5 ft bgs/<3 gpm
			5-10 ft bgs/<3 gpm	5-10 ft bgs/<5 gpm	5-10 ft bgs/<3 gpm
			10-30 ft bgs/<3 gpm	10-30 ft bgs/<15 gpm	10-30 ft bgs/<10 gpm
			>30 ft bgs/<3 gpm	>30 ft bgs/<15 gpm	>30 ft bgs/<10 gpm

Table 1 (continued). Chemical Injection Recommended Injection Safety Standards

Task	Parameter	Recommendation
Injection Monitoring	Pressure (psi)	Pressure should be maintained and monitored to limit fracturing unless required to obtain flow due to reagent physical characteristics or tight soil conditions. Where higher pressure is required to induce fracturing a surfacing control mitigation plan shall be required.
	Temperature	Temperature should be limited to minimize vapor generation, unless a vapor control system is in place. Temperature should be limited to 150 degrees Fahrenheit (66 degrees Celsius) so as to avoid undesirable side effects.
	Flow Rate (gpm)	Monitor to ensure compliance with recommended flow rates provided above.
	Vapor concentrations (ppm)	When injection into high contaminant VOC zones, vapor should be monitored at all potential pathways to the surface
Other Items	Material Compatibility	Injection of oxidants shall require compatible materials from tank storage to pumps to injection tooling or wells. Generally, stainless steel or PVC is required for oxidants that are corrosive. Prior to injection of oxidants, applicators shall document compatibility of all equipment with the oxidant chosen.
	Injection Techniques/Strategies	See the In Situ Remedial Reagent technical guidance document for details regarding injection techniques and strategies for implementing a safe injection program and minimizing the likelihood of product surfacing.
	Injection Point Spacing	The distance between two adjacent injection points. In most cases ROI = ½ injection point spacing, but in some cases ROI is larger to account for a conservative overlapping of treatment areas.

Chemical Oxidants = hydrogen peroxide and catalyzed forms of hydrogen peroxide, sodium persulfate and activated forms of sodium persulfate, sodium and potassium permanganate,
percarbonate and activated forms of percarbonate
Bioremediation and Reducing Agents = magnesium peroxide, calcium oxyhydroxide, calcium peroxide, glycerol tripolylactate, lactic acid, glycerol, glycerol esters of polylactate and
fatty acids, zero valent iron, calcium polysulfide, emulsified oils, other electron donors, bioaugmentation

GP-SP = Poorly graded gravels to poorly graded sands
SP-SM = Poorly graded sands to silty sands
ML-CL = Silt to clay
Maximum % Pore Volume For Site - The percent volume of reagent injected of the effective porosity volume of the treatment zone.
ROI = Radius of Influence - The distance from the injection point where the reagents are expected to achieve their design contaminant destruction. ROI is a combination of the reagent
% pore volume injected and the additional distribution that occurs through diffusion, dispersion and advection.
ft bgs = feet below ground surface
GPM = gallons per minute
psi = pounds per square inch
ppm = part per million
(1) = per injection event
(2) = if application approach includes groundwater extraction then the maximum percent pore volume for the site can be equal to or less than 90%.
All chemicals are reactive under certain conditions and should be handled under the guidelines provided on their material safety data sheets (MSDS)

4.3 Pre-Injection Clean Water Testing and Infield Design Modifications

Once on-site, but prior to beginning an on-site injection, a pre-injection test should be conducted. The pre-injection test involves the injection of clean water into an area of the site, usually away from the main treatment area but in an area that appears consistent with the target zone. As a general rule the volume of the clean water test should be greater than the intended injection volume by 25 to 33 percent (multiply the planned reagent injection volume per well or point by a design factor of 1.25 or 1.33). This approach is not only conservative from a volume standpoint but will also compensate for additional difficulties that arise when using a reagent with a different density/viscosity than water and to account for potential reactivity and gas production. The application rate of the clean water injectate should be at a rate that is at least equal to the designed application rate of the ISRR.

It is very likely that during the pre-injection clean water testing it becomes evident that the ISRR injection volumes and/or injection rate originally designed for cannot be achieved. However, based on information gathered on aquifer response under various injection modifications tested during the clean water pre-test a number of alternatives or combinations of alternatives can be used to make the application both feasible and smoother. Often this will be an iterative process of trial and error to arrive at an optimal solution. Listed below are alternative application techniques that can be attempted for direct-push injections when design ISRR injection volumes cannot be achieved.

- Decrease the fluid volume attempted per point and add more injection locations;
- Move to a different injection location within the treatment area to find places where the aquifer accepts higher volumes;
- Isolate injection zones – inject at different volumes and rates to match condition in vertical zones of variable hydraulic conductivity to maximize volumes in the separate zones. This will require more points for the overall injection program;
- Decrease the application rate and increase the required time on-site;
- Experiment with different injection tips;
- Consider top-down versus bottom-up injection procedures.

5.0 Application Tooling Requirements/Methods

Due to site-specific complexities and ISRR variables it is not feasible to describe in detail all of the facets to be considered in carrying out a successful injection program. However, the following is a general description of application methods that are currently considered to be best practices which relate to most ISRR products currently in use. Prior to field implementation it is recommended that reagent users consult with the manufacturer of the reagent as well as the application contractor assigned to the project regarding product application volumes, injection rates and specific handling requirements.

There are several injection methods that are used in the application of ISRRs. These include direct-push injection (DPI) methods, injection well (IW) methods, hydraulic fracturing and injection methods, and pneumatic fracturing and injection methods. All methods can be used to inject reagents with a viscosity similar to water into the formation. Hydraulic fracturing and injection, pneumatic fracturing and injection, and DPI methods are more commonly used than IW methods to inject reagents that have a viscosity greater than water and/or contain solid material.

Virtually any injection method can result in displacement of overburden at some sites. Depending on site conditions, this may result in lifting or caving of the soil surface; particularly when the injection is being conducted at a shallow depth below ground surface, relatively high volumes of material are being injected, and/or relatively high pressures are employed. If such displacement is observed fracturing operations should be halted and the methodology should be reevaluated in view of the impact of the observed displacement on the site.

5.1 Direct Push Injection Technology

DPI methods rely on the hydraulic downward advancement of small diameter (1.25-3.25 inch) hollow steel rods into the target zone. Each DPI point consists of a series of threaded 3-5 foot long steel drive rods that are advanced via series of connected rod joints to the desired application depth prior to injection of the remedial reagent.

Direct push techniques generally rely on the displacement of soil around the diameter of rod tip. Soil displacement via the DPI rods does create localized areas of compaction immediately around the injection rods. The user and applier should be aware that these areas of compaction may alter the application of reagent into the desired target zone.

Most direct push (DP) hardware manufactures recommend use of rubber O-rings between each rod joint. Often grooves are placed in the steel rods specifically for this purpose. These O-rings are designed to maintain a water tight rod string. Appliers should consult their particular reagent manufacturer for appropriate O-rings to ensure compatibility with the ISRR product being applied. In some cases, use of Teflon® tape in place of the O-ring will be sufficient. Using drive rods with significantly worn threads or without O-rings is not recommended as without a water tight seal, the applier bleeds off remedial reagent in an uncontrolled and unmeasured manner. This potentially reduces the designed emplacement mass of the remedial reagent across the target zone. This bleed-off reduces the borehole seal and subsequently reduces the emplacement pressure exiting the downhole tooling and increasing the likelihood of surfacing around the DPI rod strings.

Although many variations of DPI tooling are in use today for ISRR application, two basic methods are widely practiced and are discussed below. For greater detail and additional information on direct push well installation techniques, please refer to the Interstate Technology and Regulatory Council (ITRC) website located at www.itrcweb.org (ITRC, 2006).

5.1.1 Expendable Tip Method

The DPI rod string is fitted with an expendable point. Upon achieving the desired depth the expendable tip is "dropped" or knocked out of the end of the lead rod Figure 2. A reagent is then injected via the open rod. This method is simple and is generally only appropriate for target zones that are reasonably homogenous. This method is potentially limiting because the remedial reagent must be applied in a "bottom up" fashion, meaning that the reagent is being pumped out the end of the lead rod at a known rate while slowly raising the rod set. This method provides a lower level of application flexibility (bottom up only) and may tend to focus the injected remedial substrate *downward* rather than outward. In most cases, this method provides limited ISRR distribution and is therefore not recommend.

This method should not be used to inject across strata where transmissivity increases with depth. In this case, use of bottom up injection could preferentially fill strata of higher permeability deeper in the hole while being withdrawn across strata of relatively lower permeability. To rectify this, the applicator may consider dedicating multiple injection points one to each discrete stratum thereby ensuring proper vertical placement. Alternatively the applicator could choose to use a horizontal injection tool and a top down approach (Figure 3).

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5.1.2 Horizontal Injection Method

Horizontal injection tooling is typically composed of a modified section of the lead rod. This section of the lead rod is typically equipped with a sleeve that covers a set of injection ports (Figure 3) or the lead rod may be pressure activated injection ports (Figure 4). Upon reaching the desired depth the operator begins injection of the remedial reagent through the injection ports in the rod (Figure 5). The horizontal injection method allows the operator to apply the reagent in a "top-down" as well as a "bottom up" operation. This method provides greater flexibility and enhances the outward injection of the reagent.

5.2 Other Injection Methods

5.2.1 Hydraulic Fracturing and Injection

The maximum injection pressure can be calculated by Equation 1. Hydraulic fracturing involves injecting a reagent into the subsurface at a pressure that initially exceeds the combined lithostatic pressure, hydrostatic pressure, cohesive strength of the formation, and other sources of resistance such as pressure loss through the injection tooling. The lithostatic and hydrostatic pressures are essentially equivalent to the weight of the soil and water columns, respectively, above the depth of injection. The cohesive strength is a measure of how well the soil particles are adhered to one another. Clays generally have significantly greater cohesive strength than sands. Other pressure losses, such as friction from the sidewalls of the injection rods, will create additional resistance that must be overcome. Once this pressure has been overcome and a fracture has been created, the pressure required to continue the injection will be lower.

Hydraulic fracturing and injection of reagents into the subsurface can be achieved using regular direct push equipment in combination with a high-flow/high pressure pump system. More advanced hydraulic fracturing methods involves placement of an injection nozzle at the depth the fracture is to be initiated. The injection nozzle can be advanced using any number of drilling techniques including direct push, hollow-stem auger and sonic drilling. Hydraulic fracturing can also be completed from open boreholes including bedrock borings. The reagent is pumped into the formation at a rate and pressure that exceeds the ability of the formation to accept the reagent via permeation. Fracturing occurs when there is a sudden and significant drop in the injection pressure while the flow rate remains constant or increases. After fracturing occurs, the injection flow rate of the reagent is maintained to propagate the fractures out from the injection borehole.

Typically, slurry is used to enable a solid reagent to be pumped. A common slurry used is a biodegradable slurry that is comprises a small amount of guar gum dissolved in water. Guar gum is a viscosifier that is commonly used in the food industry. The guar gum slurry can be cross-linked to create a very viscous gel that suspends solid reagents and helps maintain the fracture integrity as the fracture is propagated from the injection point.

Hydraulic fracturing is particularly suited to fracturing of consolidated soils, bedrock and media with low permeability but can be applied to all soil types. The potential benefit of employing a fracturing method is increased lateral distribution from a given injection location. Because the reagent is emplaced in a fracture that occupies a very small fraction of the subsurface, there is no longer a need to fill up the entire effective pore space to achieve a certain placement radius. The radius of influence will depend on several factors such as soil type, application method, injection rates, injection depth, and reagent viscosity, where more viscous reagent slurries enhance fracture propagation. However, safety concern should be considered for potential soil cave-in with a shallow groundwater site.

5.2.2 Pneumatic Fracturing and Injection

As the name suggests, pneumatic fracturing uses a gas to fracture the media and inject the reagent, with or without the use of packers to isolate the injection depth. The injection method is completed in two steps, pneumatic fracturing and pneumatic injection, which are completed sequentially. As with hydraulic fracturing, pneumatic fracturing is used to create and /or enhance subsurface fractures with controlled bursts of high-pressure gas at pressures exceeding the natural in situ geostatic pressures and at flow volumes exceeding the natural permeability of the subsurface. Fracturing allows greater volumes of reagents to be distributed in the subsurface and provides better access to hydraulically isolated zones in the plume.

The type of gas used depends on the reagent. For oxidative reagents, compressed air can be used. For reducing reagents, nitrogen gas is used to avoid injection of oxygen into the aquifer.

Pneumatic fracturing and injection has been applied in many types of geologic media including sands, silts, silty clays, and highly weathered fractured bedrock, and up to depths of 160 feet.

5.3 Injection Wells

Injection wells are typically used in a gravity feed mode, as excess pressure is not required to achieve adequate injection rates. Injection wells are typically screened in the uppermost portion of the water table, usually from 10 feet to 25 feet below the water table. Nested injection wells are designed for injections into aquifers of greater thickness and for injection into DNAPL zones located at the bottom of aquifers. Injection wells are commonly constructed of polyvinylchloride (PVC) or stainless steel pipe with the screen interval placed in the vertical section intended for treatment. Usually these wells are constructed with the intention of being temporary or semi-permanent. Occasionally more permanent type wells such as monitoring wells or pumping wells are used for injection purposes. Monitoring well should only be used for injection if they are not part of the compliance network, are screened in the right interval, and are tested to ensure their seals can contain the injection pressure.

The most significant difference between common monitoring wells and injection wells is that the injection wells are screened in a deliberate way to intersect only the selected zones identified for treatment. Unlike groundwater monitoring wells injection wells should not be screened across multiple zones or above the water table unless there is forethought and an intention to treat the capillary fringe area or vadose zone. Injection wells in conjunction with extraction wells can be used in a push-pull fashion that allows for greater dispersion of oxidants and greater radius of influence. Figure 6 is a general representation of an ISRR injection well.

Problems associated with daylighting of chemicals are not commonly observed using injection wells because excess pressure is not used during injection. The one exception to this is when hydrogen peroxide is injected. When peroxide is catalyzed (Fenton’s reaction) it gives off a large amount of oxygen gas which creates excessive backpressures in the subsurface. Further discussion of safety measures during peroxide injection is provided below in Section 8.0.

The proper design and construction of an injection well include filter pack, annular sealing and grouting features are equally critical for temporary injection wells as the more “permanent” monitoring and production wells. There are numerous methods for drilling boreholes for well construction including hollow-stem augers, direct-push technologies, mud rotary, air-rotary, and reverse rotary methods. A concise discussion of various drilling methods used in the industry can be found in Fetter 1993. For environmental clean-up and *in-situ* remediation the most common methods of drilling boreholes for well construction are direct-push technologies and hollow-stem augers; these two are discussed briefly below. Properly developed injections well are important to prevent clogging during injection and reduction of optimal injection rates. Please note that all well construction should be permitted by the appropriate local agencies and follow the

LARWQCB guidelines as found in the Department of Water Resources, Southern District (DWR) guidelines contained in DWR Bulletins 74-81 and 74-90 Combined.

5.3.1 Injection Well Specifications

The most common size range for newly constructed temporary injection wells is 1 to 2inches in diameter; however injection wells can be any size. The larger the diameter well screen, the greater the surface area open for slotted pipe (screen). Therefore, when possible it is advisable to use 2-inch or larger diameter wells. The larger diameter also affords greater access of tools and probes into the well if and/or when necessary.

If a small probe rod or auger diameter is used to set the wells then appropriately sized well casing diameters are used to allow for a proper thickness of well pack and seal in the limited annular space. The most important considerations when designing and installing oxidant injection wells are: 1) the quality of the bentonite seal and 2) the proper construction of a surface seal surrounding the well box. Fast acting bentonite pellets or chips should be used. Do not use time-released bentonite pellets or chips since they will cause excessive delay in establishing a good seal. A 2 to 3-foot thick bentonite seal is preferable above the sand pack. Use bentonite pellets if placed beneath the water table or medium chips if placed above the water table. Fully hydrate the pellets by addition of an equal amount of water. After 10 minutes, check the ability of the seal to hold and retain water. This can be done by adding a small quantity of water on top of the seal and immediately measuring the depth to water. Repeat the depth to water measurements every minute for up to 5 minutes or until the water level does not change. A good seal above the sand pack is critical to maintaining back pressure within the well and preventing failure of the seal. A faulty installed bentonite seal is often the primary cause for daylighting of oxidants.

The surface seal surrounding the well box is the other critical construction feature in a properly designed injection well. A minimum one-foot thick concrete seal across the bottom of the well box skirt and inside the manhole cover. It is recommended that a 12inch diameter well box is used with an 18-inch long skirt.

In cases with low hydraulic conductivity aquifer material and a smaller diameter injection well, continuous or 'wire-wound' screens should be considered. Continuous or wire-wound screens are more expensive and have a lower burst pressure than standard slotted screens. However, this type of screen may double the available opening space for a given treatment interval. Screen slot size should be equal to or greater than 0.020-inch even at the cost of some silting in of the well. In high sand and gravel content aquifers it is recommended that 0.030 and 0.040-inch screen slot size be used. This may increase injection production rates and help optimize application time. For temporary injection wells PVC pipe in Schedule 40 and 80 can be used. However, use of Schedule 80 is typically recommended due to its higher burst pressure and general durability for multiple injections. The applier should be aware of the burst pressures of all well materials and injection related equipment.

5.3.2 Methods of Injection Well Installation

5.3.2.1 Direct-Push Well Construction

Direct Push (DP) methods are rapidly becoming a popular and economical way of setting up an injection well system. DP methods allow for avoidance of drill cuttings from contaminated section being brought back to the surface. Current generation of DP rigs allow probe rods with wide diameters to be pushed to greater depths. Although a 2-inch diameter well can be installed via direct push, great care should be taken in setting a filter pack and sealing and/or grouting the well to surface since the annular space inside the rod around the well is very small. Good grouting procedures such as pressure grouting are best in these situations. A smaller well diameter (1 to 1.5-inches) is often much easier to properly construct and finish. The reader should follow LARWQCB and local agency guidelines as appropriate.

5.3.2.2 Hollow-Stem Auger Well Construction

Hollow-stem auger drilling is a widely available and relatively quick and economical method for advancing a borehole and constructing an injection well. Usually augers with outside diameters between 7 to 8 inches are used to set 2-inch injection wells. Larger diameters are available for constructing larger diameter wells if necessary. As the augers are advanced to create a borehole soil cutting will come to the surface that will need appropriate disposal on contaminated sites. The reader should follow LARWQCB and local agency guidelines as appropriate.

5.3.3 Injection Well Development

In order to maximize their usefulness, all newly constructed and existing wells used for ISRR injection need to be properly developed prior to the start of injection activities. Injection wells should be developed by surging and bailing to ensure removal of drilling water and all fine materials (silts and clays). Water quality parameters (turbidity, temperature, conductivity, pH, etc.) were taken at regular intervals during well development. Up to 5 well casings volumes (or more) may need to be removed. The well should be developed until the well produces clear (silt-free) water with stable water quality readings. Properly developed injections well are important to prevent clogging during injection and reduction of optimal injection rates.

6.0 Injection Sub-surface Monitoring

6.1 Measuring Aquifer Response

The measurement of the response within an aquifer to the injection of a remedial reagent is best monitored by use of traditional pressure transducers and/or water level instruments deployed within monitoring wells on-site. The proximity/configuration of these transducers and water level gauging equipment should be selected based on the target zone soil type and the type of injection program.

Direct water-level measurements are typically made using a water-level indicator/sounder attached to a measuring tape. This technology uses the completion of an electric circuit to determine when the probe is in contact with groundwater.

6.1.1 Pre-Application

Pre-application monitoring should consist of direct measurement of pertinent water levels in site wells near the intended injection area as well as a few background wells. These data are used to validate the water table elevation just prior to injection and establishes a baseline from which to judge changes in the aquifer from the subsequent injection events.

6.1.2 During Application

During application water-level measurements should be taken in select wells located an appropriate distance from the injection locations either during or immediately following injections. Not all wells in the vicinity of an injection will be available because some wells will be too close to the injection and capped or temporarily closed with tethered seal-caps or will be dedicated to pressure gauges for all or part of the work day. These measurements will then be compared with the pre-application measurements.

Groundwater mounding is identified when the groundwater table rises in response to the fluid injection. If measurable mounding is occurring, it is often a short lived phenomenon as many aquifers recover within minutes to hours. If multiple injection locations are in close proximity to the area being measure for mounding, recovery from mounding is usually delayed. Full recovery from a dense grid of injection points may take several hours (overnight). In the event water-level measurements indicate mounding of the water table approaching the surface, injection should be ceased to allow the mounding to decline and aquifer hydrostatic pressure to equilibrate.

6.2 Monitoring of Injection via Fracturing Using Tiltmeters

During fracturing by either pneumatic or hydraulic methods, there is a disturbance in the subsurface as fractures are propagated. The disturbance at the ground surface is on a micro scale. It is possible to measure this disturbance by using tiltmeters, which are highly sensitive instruments that can measure the minute ground surface deformations created during the fracturing process. The micro ground surface deformation is measured by several tiltmeters positioned radially around the injection borehole. Data from the series of tiltmeters can be interpreted to determine the shape, thickness, extent and orientation of fractures and amendment distribution in the subsurface. Computer software is used to interpret and present a graphic depiction of the fractures. Tiltmeters can also be used to monitor the potential movement of adjacent of structures.

7.0 Measuring Application Related Parameters

7.1 Instrumentation

The injection pressure and flow rate of remedial reagents is best monitored by use of traditional pressure gauges and flow meters. The positioning/configuration of the gauges as well as the individual gage pressure range should be selected based on the target zones soil type, the injection program type (wells vs. DPI) etc. All equipment including pressure gauges and flow meters need to be constructed of materials compatible with reagents.

The following sections provide information on relative positioning of the various basic injection components, e.g., reagent and water tanks, pumps, gauges and downhole injection point configurations.

7.2 Direct Push Injection Monitoring

7.2.1 Single Boring

For the purposes of this discussion it is assumed that injection of remedial reagents via direct push utilizes a direct push rod assembly with a minimum outside diameter (OD) of 1.25 inches and a nominal inside diameter (ID) of 0.625 inch. The simplest injection configuration is a one rod-one pump configuration, this configuration consists of a single injection pump connected directly to the top of a set of direct push rods. Upon reaching the desired depth, the operator either drops the expendable tip (Figure 2) or opens the injection tool (Figures 3 and 4) and begins injection of the remedial reagent. In this configuration the injection backpressure is best monitored at the top or very near the top of the rod string. As discussed earlier in section 5.1.1, due to limitations associated with the expendable tip method, in most cases this method is not recommended.

7.2.2 Manifold Systems

On larger projects it is often desirable to use more than one direct push rig. In this instance one or more DPI rigs advances rods to the injection depth and the rods are withdrawn or advance systematically in order to obtain the desired mass/volume per vertical unit of aquifer. In this multi-point application configuration the injection of a remedial reagent is often best accomplished using a manifold system and multiple pumps. This system allows the injection of remedial reagent via a single appropriately sized pump. Figure 9 is a photograph of a generic manifold system. The manifold splits a single remedial reagent stream into multiple streams of similar pressures. Each reagent stream has a minimum of one pressure gauge and one flow meter, allowing the applier to monitor and inject remedial reagent into multiple points simultaneously or into a single point. This method requires the applier to monitor closely the backpressure, flow rate and total gallons applied in each well. This system allows the applier to manage (by varying the flow rate) the application rate and the subsequent aquifer response in each point/well based on the injection backpressure.

Depending on the remedial reagent selected, the influent stream is generally monitored by use of traditional pressure gauges and flow meters. Pressure gauges and flow meters need to be constructed of materials compatible with reagents. The positioning/configuration and the number of the gauges as well as the individual gage pressure range should be selected based on the type of injection program. The relative position and size of pumps, gauges and injection point are discussed below and a general configuration diagram (Figure 10).

The positioning of gate valves, pressure and flow meters are critical to monitoring each of the manifold points/wells independently. Typically, each delivery line has a flow meter and pressure gauge along with 2 gate valves (Figure 11). This configuration will enable the applier to modify the delivery rate of reagent to an individual point/well based on the backpressure and delivery GPM.

7.3 Backpressure

Measuring fluid injection backpressure is a critical component of any application program. At a minimum the applier should be monitoring the starting pressure, the injection pressure and the post-injection pressure of each application point. The purpose of these measurements is to document site specific injection-related fluid acceptance capacities. Depending on the actual delivery rate the backpressure will behave inversely to the target zones transmissivity. For example, in a given aquifer, if an applier injects the remedial reagent at 10 gpm and the aquifer transmissivity (due to vertical heterogeneity) varies from 10^{-2} to 10^{-4} centimeters per second (cm/sec), the back pressure measured at the top of the injection string (rod or injection well) will increase with a decrease in the target zones transmissivity (its capacity to accept the remedial reagent).

Application backpressure, when measured over time, can provide insight into the target zone's localized transmissivity and ultimately its "capacity to accept" the estimated reagent volumes requirements needed for the site. A series of general curves are presented below to illustrate the relationship between pressure versus (vs.) time under various aquifer response scenarios to remedial agent injection. The curves depicted in the following sections are not meant to represent a specific remedial reagent or soil type and assume response to a single remedial reagent injection event. Below is a list of assumptions used for the development of these generalized curves:

- applied remedial reagent has a viscosity similar to water
- the application target zone is in an unconsolidated aquifer matrix
- application of the remedial reagent is at a constant rate (gallons per minute [gpm])
- until a predetermined not to exceed pressure is reached at which time the injection is stopped and the point/well is "shut in" under pressure
- resulting in the propagation of a fracture or a case where another break in the pressure is obtained
- the application tooling, pumps and monitoring instrumentation is appropriately sized for the remedial reagent volumes and anticipated backpressures

7.3.1 Backpressure for Water Like Reagents

7.3.1.1 Pressure: Rapid Spike → Slow to Moderate Decline → Stabilization

Figure 7A represents the pressure signature of the injection of remedial reagent into low to moderate conductivity soils when direct push is the primary injection method or the injection is taking place into undeveloped wells. When a direct push injection point is pushed into place, it does not remove any soil thus it has to displace that soil producing a denser or more compacted soil condition around the injection string which is more commonly known as the “smear zone.” This is also seen in well applications when the well is placed with an auger rig. The spinning of the auger has a tendency to take fines from the soil and compacts them against the sidewall of the bore hole producing a denser or more compacted soil condition on the outer edge of the borehole. In well applications; the well is then often times developed to break down the more dense or compacted area. However, if the well is not developed or developed poorly, you can see similar conditions to those of direct push applications.

In this scenario, section A represents a rapid increase in pressure caused by the low hydraulic conductivity smear zone around the tool string until the pressure exceeds the low hydraulic conductivity of the smear zone fracturing through this zone, and (section B) then drops slowly until it reaches stabilization (section C) with the surrounding formation.

7.3.1.2 Pressure: Rapid Spike → Rapid or Slow to Moderate Decline

Figure 7B represents the pressure signature of the injection of remedial reagent into a low hydraulic conductivity soil. In this scenario the section A of the curve represents a rapid rise in backpressure and followed by a rapid fall in pressure as shown in section B or a slow to moderate decline in pressure as shown in section C.

If a rapid decline in pressure is observed (often time all the way to 0 psi) as in section B it usually means that the pressures have exceeded the natural hydraulic conductivity of the formation resulting in failure of the point/well’s seal or fractures have connected with old borings or utilities that will eventually result in surfacing. The applicator must immediately cease the application at this location and move to another location.

If, however, the pressure drops at a slow to moderate rate as in section C the applier may assume that fracturing has taken place and continue to inject with extreme caution at a lower flow rate making sure that surfacing does not take place , or may choose to end the injection at this point and move to another location.

7.3.1.3 Pressure: Slow Increase → Spike → Rapid Decline→ Stabilization

Figure 7C represents the different pressure signatures associated with the injection of a remedial reagent into a soil with medium hydraulic conductivity soil. In the early phase of the injection as represented by section A the curves are very similar and represent an aquifer matrix that initially accepts the remedial reagent volume application and then slowly becomes unable to accept the reagent at the same delivery rate. In this case the applier must decide whether or not to field modify (reduce) the application rate. If the applier elects to continue to apply the reagent at a steady rate, as represented in sections B, the injection pressure will soon exceed the natural hydraulic conductivity of the soil resulting in fracturing as represented in sections C and D of this curve. If the applier elects to lower the application rate as shown in section E this allows the aquifer adjust to and more readily accept the application of the design volume at the new "Field Adjusted" Application Rate.

7.3.1.4 Pressure: Slow Increase →Moderate Decline→ Stabilization

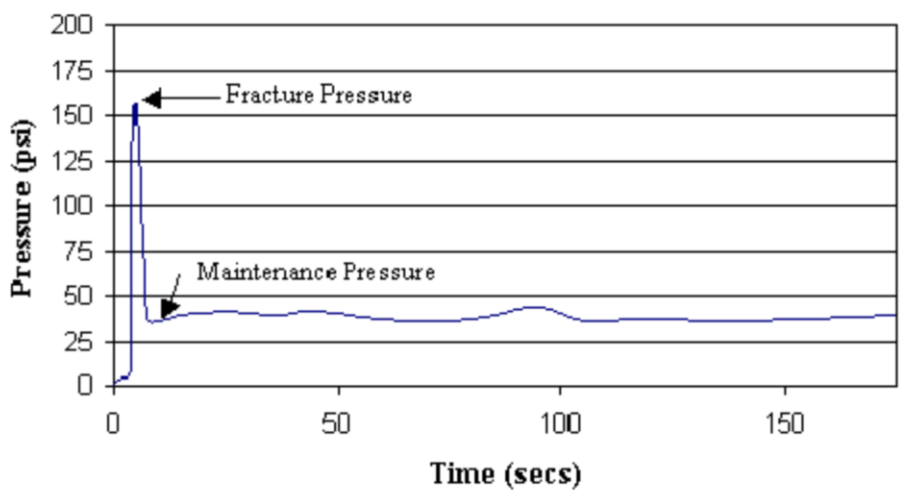
Figure 7D represents injection of a remediation fluid into a more transmissive aquifer soil. Under this scenario the pressure versus time curve indicates a relatively slow response from the aquifer and a corresponding gradual increase in the application pressure under a steady pumping rate. Section A of the curve represents an aquifer matrix that initially accepts the remedial reagent volume application and then slowly becomes unable to accept the reagent at the same delivery rate. Once pumping ceases the aquifer quickly recovers as depicted in Section B of the curve. Since the aquifer is able to accept the reagent fluid at a reasonable rate and recovers quickly the applier must decide whether to reduce the delivery rate and thereby avoid excessively high application pressures as well as continue to distribute the reagent over a wider area of the aquifer. Or continue to apply the reagent at an unmodified and steady application rate as represented in Section A, in this scenario the injection pressure will eventually exceed the natural hydraulic conductivity of the soil and result in fracturing and/or day lighting. However, if the applier elects to field adjust the application rate (lower) the pressure will decline and the reagent application volume will increase. Section C of this curve represents a new "field adjusted" optimal application rate and illustrates the potential for a higher volume injection.

7.3.2 Backpressure for Viscous and/or Solid Reagents

During injection of viscous and/or solid reagents via DP Injection, there will be an increase in pressure until a fracture is initiated. This is the point where the injection would be stopped if the reagent had a viscosity similar to water and the intent was injection via permeation. To inject viscous and/or solid reagents, the formation must be fractured to enable the reagent to be injected. Fracturing of the formation may also be necessary for reagents with a viscosity similar to water where the formation has a low permeability.

Once a fracture is created, pumping of the reagent is continued to propagate the fracture. This is defined as the maintenance pressure as shown in Figure 8. Pumping continues until the specified mass or volume of reagent is injected.

Figure 8. Injection Pressure vs. Time



7.3.3 Addressing Potential Daylighting when Injecting Viscous and/or Solid Reagents

Several steps can be taken to minimize the potential for daylighting. These include the following:

- Obtain a thorough understanding of the geology in which the injections are being made, including the depth of the injection zone, the nature and thickness of geologic units above and below.
- If available, review information on injections performed by others in the same area.
- Avoid injection near sub-surface utilities and sub-surface construction features of buildings and facilities, which can act as preferential pathways or prevent injection.
- Have adequate equipment on hand to decrease the potential for daylighting, such as sufficient injection rods to dissipate injection pressures over larger areas.
- Limit the injection volume and/or mass of reagent injected per injection point/fracture. The mass accepted per vertical foot of an injection point will vary depending on the injection depth and the formation. These factors should therefore be considered when deciding on lateral spacing between injection points. Recommendations vary for different reagents and application methods and it is therefore advisable to consult the reagent manufacturer and injection contractor for specific guidelines.
- When injections are performed at shallow depths, the material has a greater probability of finding a preferential pathway to reach the surface if injected at a high

flow rate. One strategy to avoid daylighting in this scenario is to pump the material at the lowest rate that allows the fracture to remain open and thus accept the viscous and/or solid reagent.

- Implement the injections in a pattern that maximizes the distance between sequential injections to allow the pressures within the subsurface to equilibrate between injections. In addition, it is recommended to seal the borehole immediately after completion of injections to potentially avoid material seeping out of the completed injection points.

- Use tooling to improve vertical distribution that allows for top-down injections, which in turn allows for placement of the reagent into multiple smaller fractures uniformly distributed across the targeted depth interval.

- Utilize injection tips and above-ground connections with check valves to prevent back-flow and allow for controlled pressure relief if needed.

- Use slurries that contain a higher percentage of solids in the case of solid ISRRs to decrease the volume required for injection and thus the risk of daylighting.

If daylighting occurs, the following actions may be beneficial in minimizing the impact of the event:

- If daylighting does occur at a particular boring or interval, contractors should take actions to cause the daylighting to cease, such as discontinuing injection at that interval.

- Contain/control any releases in accordance with manufacturer directions. As an example, reactive compounds (such as strong oxidizers) may require neutralization.

- If daylighting occurs, modify the injection plan in accordance with the above recommendations to limit the possibility of daylighting occurring again. For most applications, increasing the distribution of the injections spatially and over time, and decreasing the injection volume per injection point will reduce the risk of daylighting.

If daylighting occurs, it may be an indication of a larger network of preferential pathways in the vicinity of the injection point. In most cases, this injection point will have to be abandoned and other injections in the immediate vicinity should be avoided if possible. A visual survey of the land for previous probe or drill points may help in identifying potential preferential pathways that may be able to be sealed.

8.0 Injection - Health and Safety

Proper handling, storage, and application of chemical reagents used for *in situ* remediation are essential to complete a safe and successful project. The following sections provide best management practices that should be implemented as part of an ISRR application project.

8.1 Safety Considerations Specific to Application of Hydrogen Peroxide

Catalyzation of hydrogen peroxide (Fenton's Reaction) is accomplished by the addition of an iron solution (200-500 ppm) at a pH range from 3.5 to 5.0. During field injection, optimization of the Fenton's reaction can be achieved through the continuous monitoring of several reaction parameters and then controlling the injection rate of hydrogen peroxide to maintain the reaction temperature within an optimal range. Continuous monitoring of temperature is performed by placing thermocouples within the annular space adjacent to the screened interval of the injection wells. The optimum temperature range of the Fenton's reaction has been found to be between 110 to 150 degrees Fahrenheit. At this temperature range, the catalyzed hydrogen peroxide generates hydroxyl radicals and superoxide radicals without excessive decomposition of the hydrogen peroxide.

Temperatures over 150 degrees F increase the possibility of daylighting of peroxide and possible ground surface damage due to excessive oxygen release from the subsurface. The Fenton's reaction is short-lived (4-10 hours) and may be expended before the dissolved phase contaminants are destroyed.

Catalyzed hydrogen peroxide (a Fenton's-like reaction) differs from other ISCO technologies in that it generates excessive heat (exothermic reaction) which is effective in stripping the absorbed contaminants from the soil and converting it to a dissolved phase. The desorption of the contaminant mass becomes effective when temperatures are increased to approximately 115 to 120 degrees Fahrenheit. The Fenton's-like reaction creates hydroxyl radicals and superoxides, which are highly effective oxidizing agents but have a very short life span of minutes and hours. Often times, the catalyzed peroxide is quickly expended before all the dissolved phase contaminants are contacted and destroyed.

A maximum hydrogen peroxide concentration of up to 10-12% is recommended for a safe injection that will minimize the potential for daylighting of peroxide and damage to the asphalt or concrete paving.

Experience has shown that use of hydrogen peroxide concentrations of 17% can cause daylighting from depths as deep as 80 feet below ground surface. The maximum temperatures that are created using 17% peroxide are much higher (up to 200 degrees F) compared to 10% peroxide (maximum of about 150 degrees F). Bulging asphalt and displaced concrete can often result when using 17% peroxide. Use of peroxide at concentrations of 10% to 12% will still allow for desorption of contaminants and the generation of hydroxyl radicals (which are desirable), and yet minimize the potential for the undesirable side effects.

Monitoring of in-situ temperatures is performed by placement of thermocouples (temperature probes) in the application wells during installation. The thermocouples are placed within the annular space adjacent to the screened interval so that the temperature of the catalyzed peroxide reaction can be measured in-situ. The thermocouples are connected to a continuous temperature recorder where the data may be plotted for interpretation and optimization while in the field. The data are also downloaded for computer storage and reporting purposes. A temperature graph illustrating the temperature variation at a site in Los Angeles County, CA is shown in Figure 11 below.

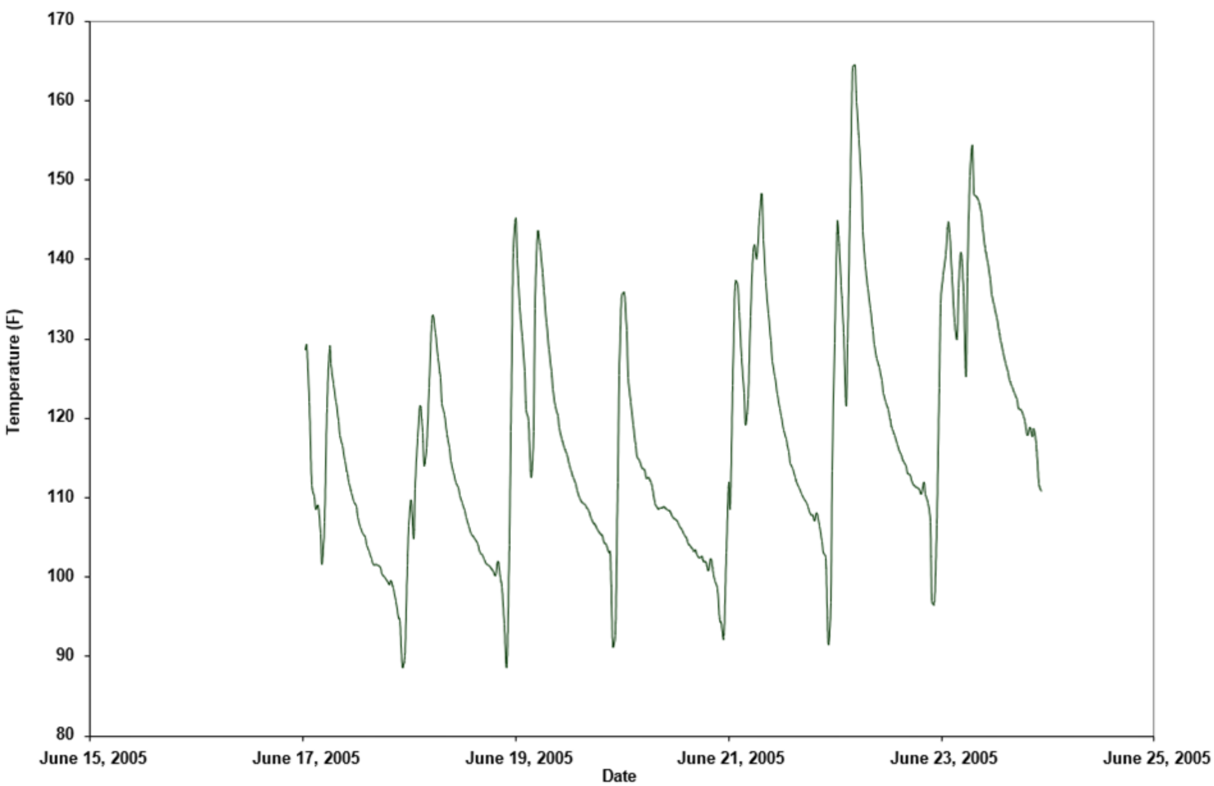


Figure 11. Daily Temperature Variation During Application of Catalyzed Hydrogen Peroxide

This graph of daily temperature fluctuations illustrates the immediate effect that peroxide injection rate has on the in-situ temperature surrounding the well screen. Temperatures rise rapidly to a daily maximum of 130 to 160 degrees F while actively injecting peroxide. Temperatures decline rapidly each day when the peroxide injection rate is shut down during operations, during lunch breaks each day, and at the end of each days work (8 to 10 hour injection duration). A gradual increase in the base temperature of the groundwater (noted as the low point each day) occurs each day of injection, increasing from below 90 degrees to 100 degrees by the end of day 8.

8.2 Material Safety Data Sheets

Prior to mobilizing to the field the applier should obtain copies of material safety data sheets (MSDS) for all reagents that are being utilized at the site. In addition, site personnel should be familiar with the safe handling requirements for these chemicals as well as the proper disposal and emergency response procedures as outlined in the MSDS. Application instructions should be obtained from the company providing the reagent and the applier should follow these instructions throughout the application process.

8.3 Site Specific Health and Safety Plan

Prior to any on-site activities all personnel should be briefed on the site specific health and safety plan developed by the group responsible for overseeing site operations. This plan must meet all state, and federal requirements of Occupational Safety and Health Association.

8.4 Special Considerations – Treatment of NAPL

Treatment of LNAPL, especially flammable substances such as gasoline and jet fuel, pose a significant safety risk because of the heat and the oxygen given off by chemical oxidation technologies such as the Fenton's reaction. Conversely, treatment of DNAPL is usually not a safety risk because chlorinated compounds are not flammable. The conversion of NAPL to dissolved phase occurs at a temperature above approximately 140 degrees Fahrenheit. Increased decomposition of the hydrogen peroxide also begins to occur above this temperature.

NAPL has to be converted to dissolved phase in order to be treated by chemical oxidation. This is an energy intensive reaction and generally consumes a large amount of ISCO reagent in the process. Thus, removal of NAPL using ISCO reagents is usually not cost effective. It is always more efficient to remove substantial amounts of NAPL using conventional means, such as product skimming or pumping. However, the presence of a small amount of NAPL at a site is often not known when ISCO treatment is undertaken.

Explosions can occur if LNAPL treatment is not performed with safety precautions in place. Only experienced ISCO practitioners should be allowed to design and implement LNAPL removal projects. A suitable bench scale treatability test should be performed to confirm that LNAPL can be safely removed in a laboratory setting before this type of project will be approved or permitted.

8.5 Special Considerations – ISCO at Active Gas Stations

Special consideration need to be taken when evaluating the use of certain ISCO reagents at active gas stations.

There are potential safety issues at active gas stations related to:

- The generation of excessive heat and combustible vapors,
- Potential exposure of oxidants or vapors to station customers, and

- Potential damage to underground structures due to the corrosive and exothermic nature of some of the oxidants.

Prior to injection of oxidants at an active gas station, the site specific health and safety plan should include a characterization of the chemical properties of the specific oxidants to be used, compatibility of the oxidants with subsurface structures (e.g., USTs and conveyance piping materials) and utilities, proximity of the treatment zone to fuel and underground equipment, the identification of liquid and vapor migration pathways, and monitoring and vapor control mitigations as needed.

9.0 Best Management Practices (BMPs)

9.1 Exclusion Zone

During an ISRR application, simple common sense practices should be employed to minimize the potential for spills, leaks, and any other form of unwanted discharge of the reagent to the ground surface. It is important to plan accordingly when defining your work area and exclusion zone.

At a minimum it is recommended that the exclusion zone be 20% larger than your work area. For this document the work area is defined as the area where injection points are designated and the exclusion zone is the area where site access is limited to properly trained personnel associated with the remediation project.

9.2 Spillage Prevention

While every effort should be taken to minimize spills and leaks, precautionary measures should be taken to minimize and contain any injected reagents that reach the ground surface. Prior to mixing reagents at the site, secondary containment systems or spill type berms of materials which are compatible to the specific reagents that are being used should be placed around mixing equipment, transfer hoses, and injection points. Additional containment/berming materials should be available onsite in the case that injected reagents reach the ground surface. In this case, containment/berming materials should be placed around the affected area until all reagents have been properly removed. All liquids associated with the reagent injection should be kept onsite and within the exclusion zone. Placement of containment/berming materials within drainage channels and upstream of storm drains is required. Every effort should be made to minimize the potential for discharged fluids from leaving the site via surface runoff.

9.3 Secondary Containment

The mixing tanks used for mixing ISRRs should be placed within a lined secondary containment berm for control of spills or leaks. The hose, fittings, valves, and manifold leading from the mixing tank to the injection wells should be leak tested with tap water before injection of the chemicals. A safety shower and an eye wash station should be available next to the mixing tank. In the event of a spill or leak outside of the secondary containment area, safety valves should be immediately shut off and sand bags and a shop vacuum should be used to contain the spilled material. Nearby storm drains should be blocked with spill booms or sand bags to prevent off-site release of chemical reagents. Emergency response personnel should be called immediately in situations where potential off-site release of chemicals may occur.

Absorbent materials should not be used for soaking up certain spilled ISCO reagents, since after the water evaporates the remaining oxidants (persulfate and permanganate) can auto-ignite paper products and other organic materials and cause a fire.

10.0 Summary

In this document we have attempted to consolidate ideas and approaches as well as to provide technical information on the injection of ISRRs at sites within the LARWQCB jurisdiction.

The purpose of this document is to provide technical information for the safest and best practices currently in use within the Region. It is believed that application of the best practices outlined in this document will not only increase the efficiency of ISRR application but will help to avoid common problems such as reagent surfacing.

It should be understood that site specific heterogeneity and groundwater conditions govern the application of ISRRs. This technical report cannot address specific issues on a given site rather; it is designed to assist the user and applier of ISSRs in pre-injection evaluation and subsequent successful application. It is always prudent to consult with product and equipment manufacturers and regulators on a site-specific basis.

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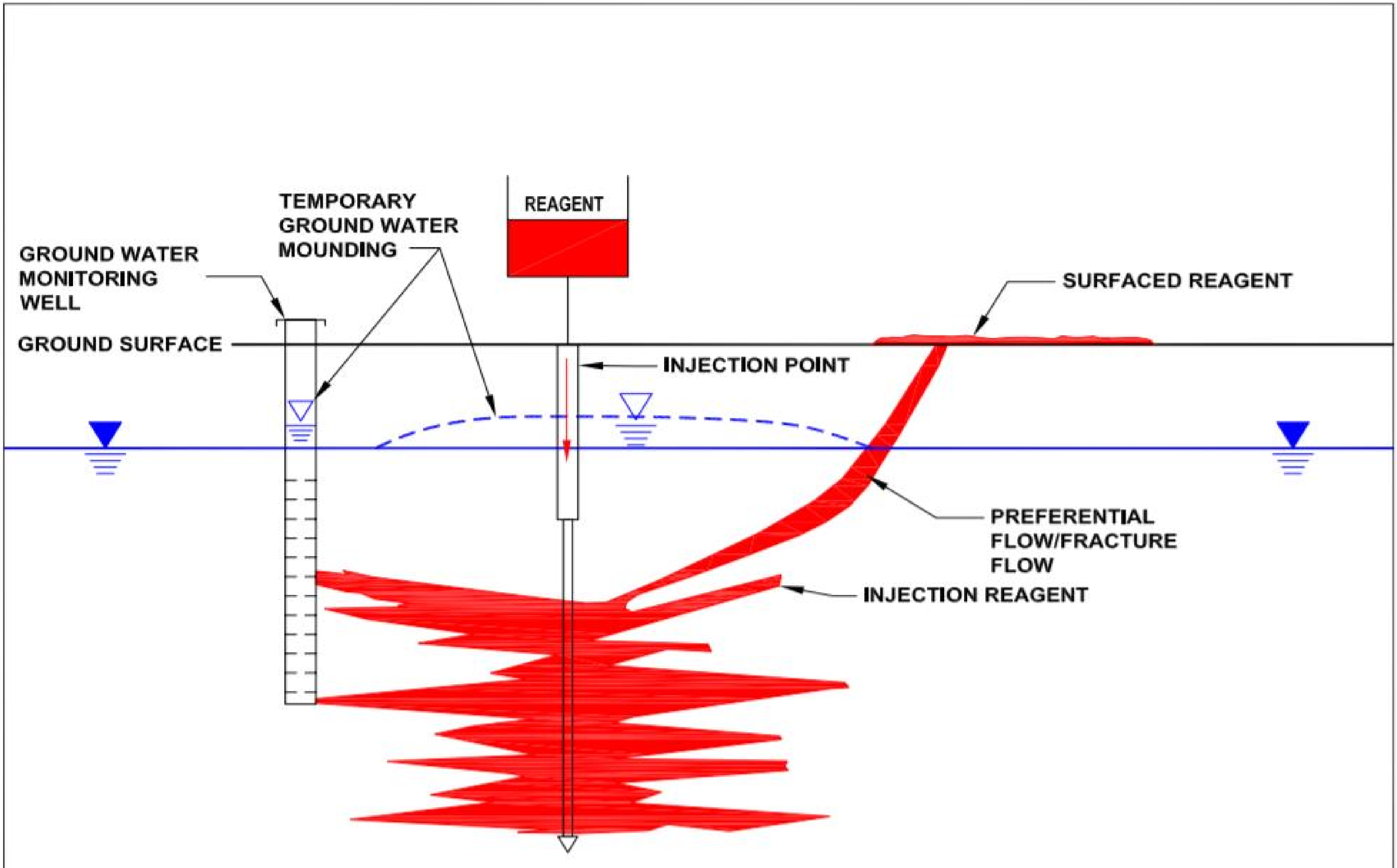
FIGURES

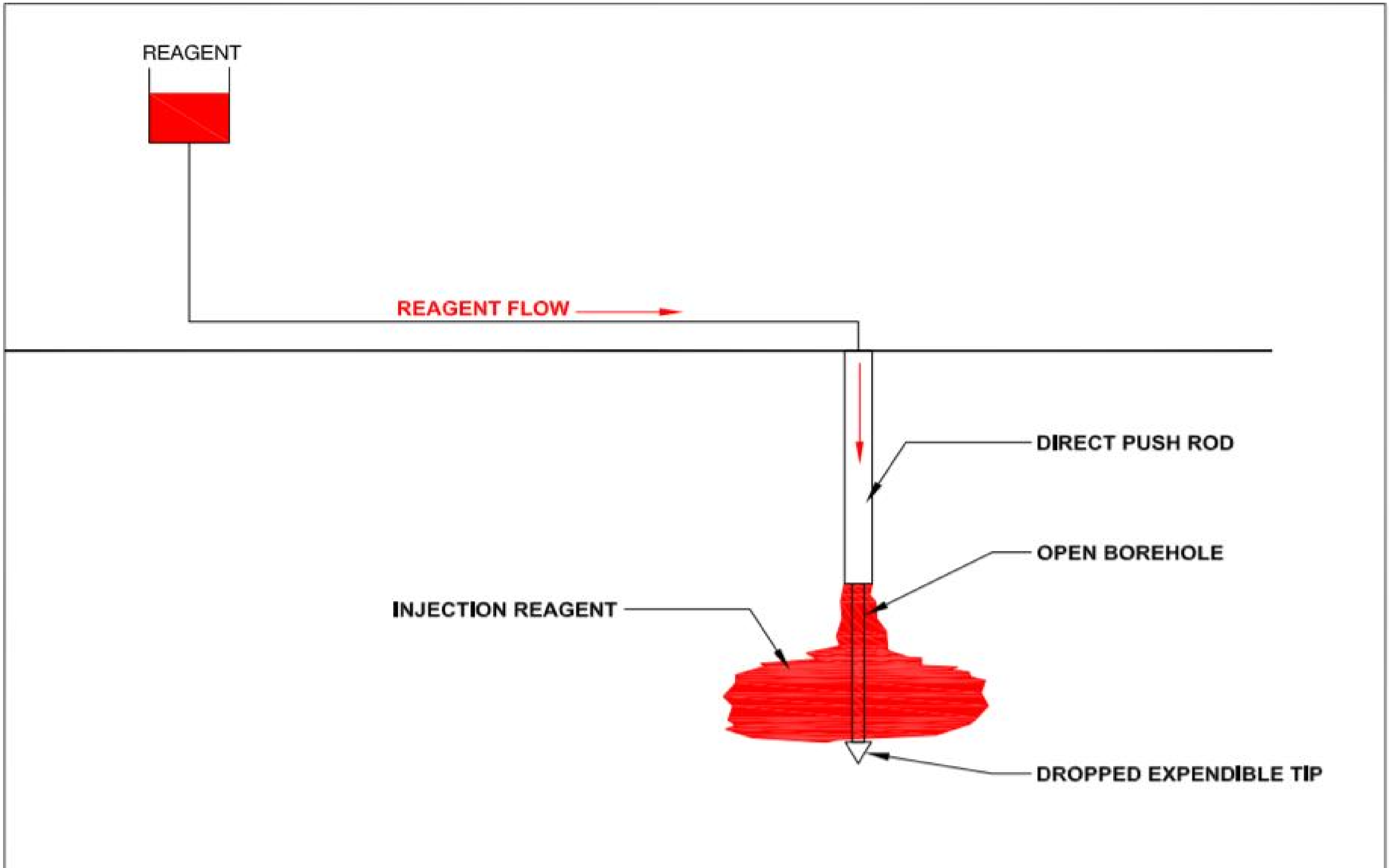


INSITU REMEDIAL REAGENTS WORKING GROUP

CONCEPTUAL INJECTION SHOWING SURFACING

FIGURE 1

SCALE: N.T.S

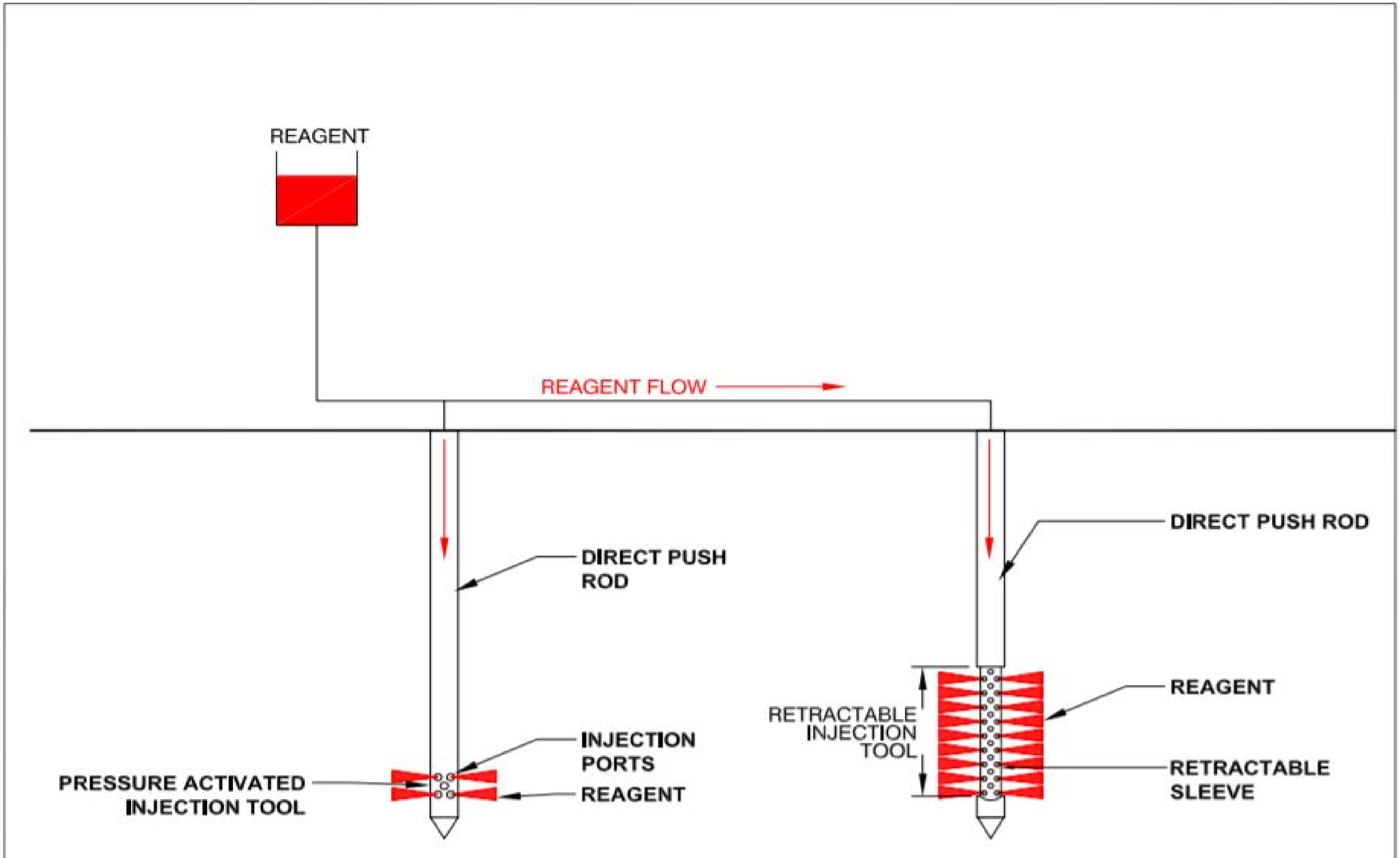


INSITU REMEDIAL REAGENTS WORKING GROUP

CONCEPTUAL INJECTION SHOWING EXPENDABLE TIP METHOD

FIGURE 2

SCALE: N.T.S



INSITU REMEDIAL REAGENTS WORKING GROUP

CONCEPTUAL INJECTION SHOWING HORIZONTAL INJECTION METHODS

FIGURE 3

SCALE: N.T.S

RETRACTABLE SLEEVE INJECTION TOOL DIAGRAM - OPEN

RETRACTABLE SLEEVE INJECTION TOOL DIAGRAM

RETRACTABLE SLEEVE INJECTION TOOL DIAGRAM - CLOSED

INSITU REMEDIAL REAGENTS WORKING GROUP

HORIZONTAL INJECTION: RETRACTABLE SLEEVE INJECTION TOOL

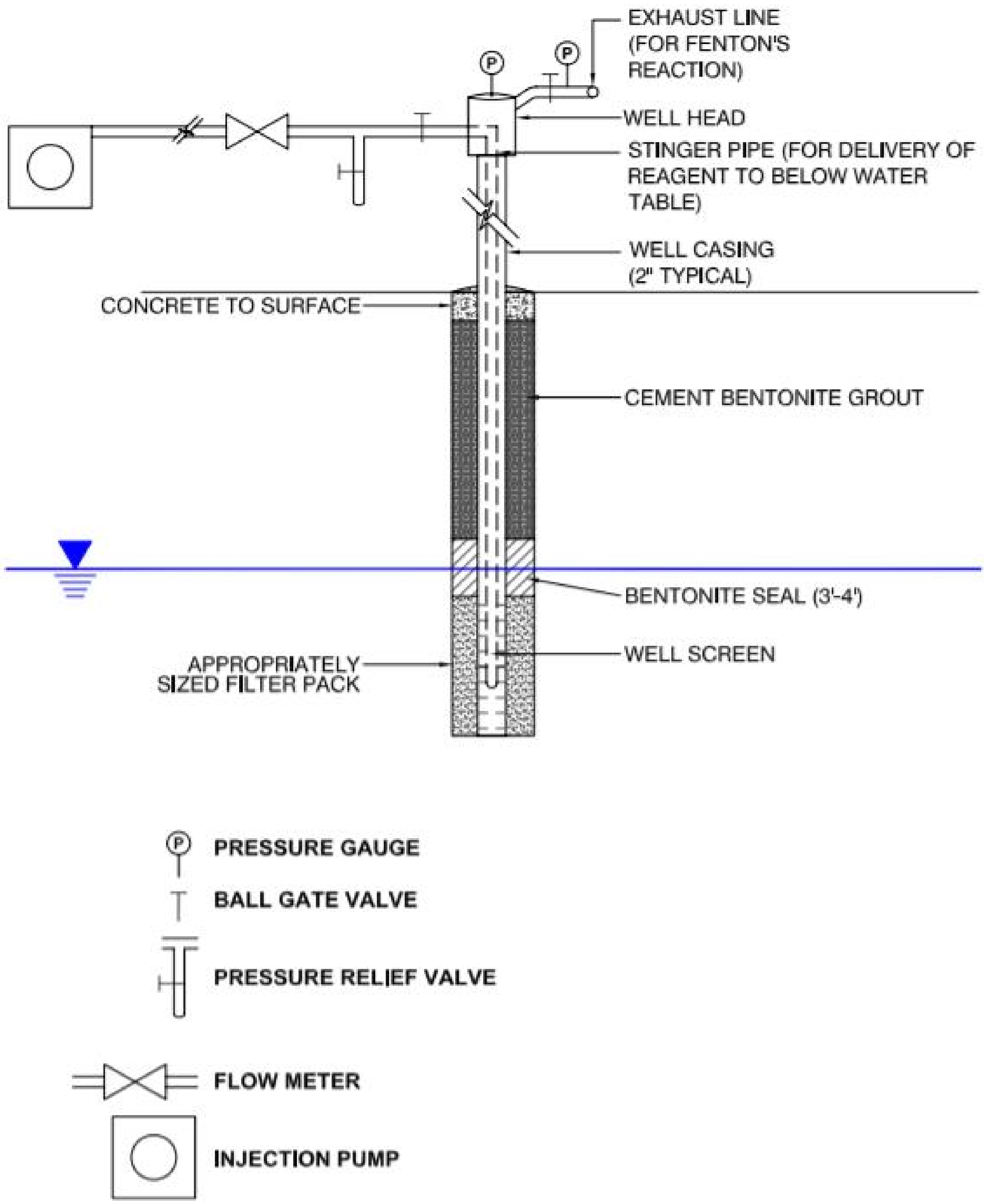
FIGURE 4

SCALE: N.T.S

PRESSURE ACTIVATED INJECTION TOOL PROBE

PRESSURE ACTIVATED INJECTION TOOL PROBE
SHOWING FLUID INJECTION PATTERN/ORIENTATION

INSITU REMEDIAL REAGENTS WORKING GROUP	HORIZONTAL INJECTION: PRESSURE ACTIVATED INJECTION TOOL
	FIGURE 5 — SCALE: N.T.S

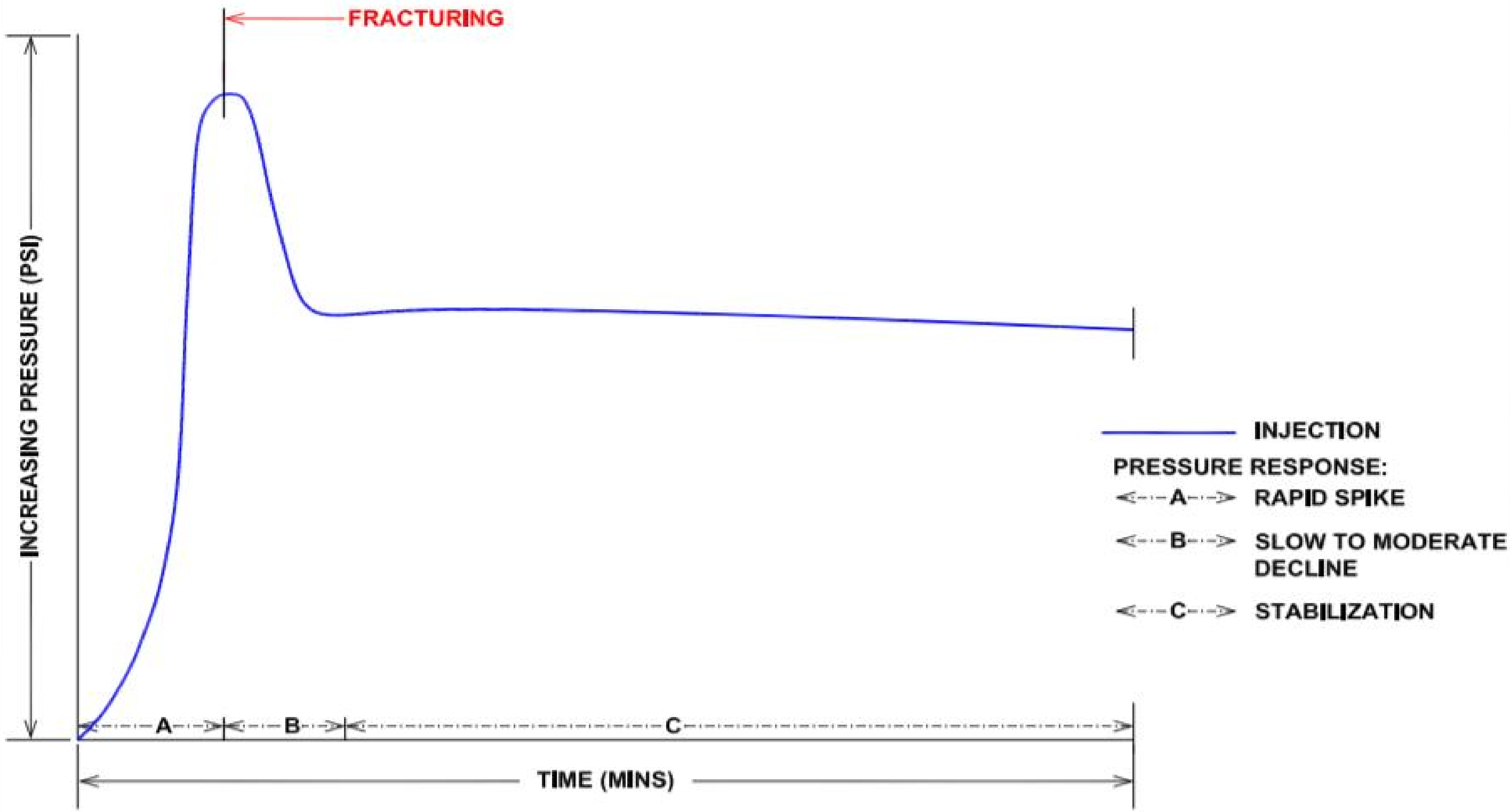


INSITU REMEDIAL REAGENTS WORKING GROUP

GENERAL INJECTION WELL DIAGRAM

FIGURE 6

SCALE: N.T.S.



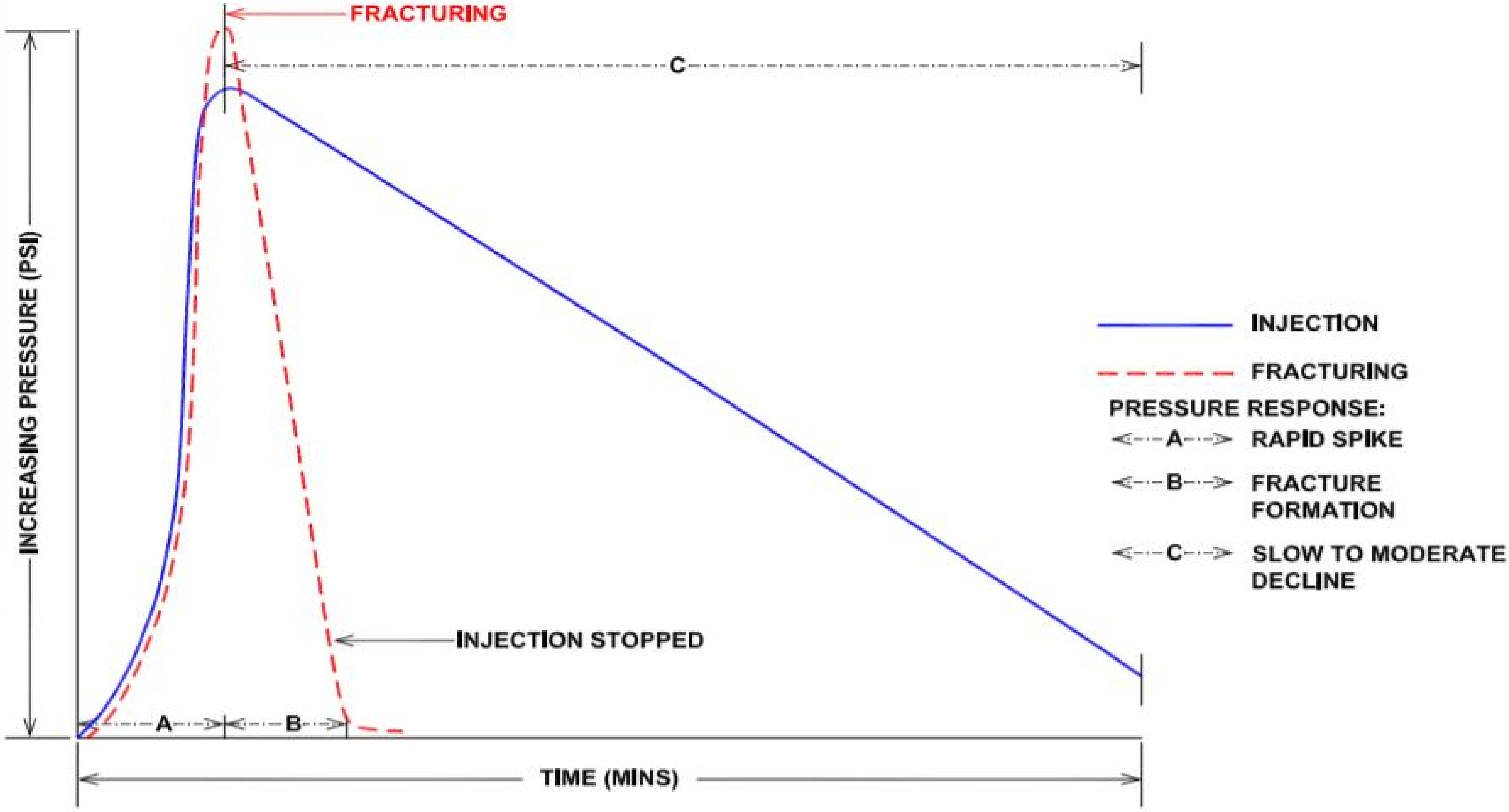
NOTE:
APPLIES TO DIRECT PUSH AND UNDERDEVELOPED WELLS

INSITU REMEDIAL REAGENTS WORKING GROUP

PRESSURE:
RAPID SPIKE → SLOW TO MODERATE DECLINE → STABILIZATION

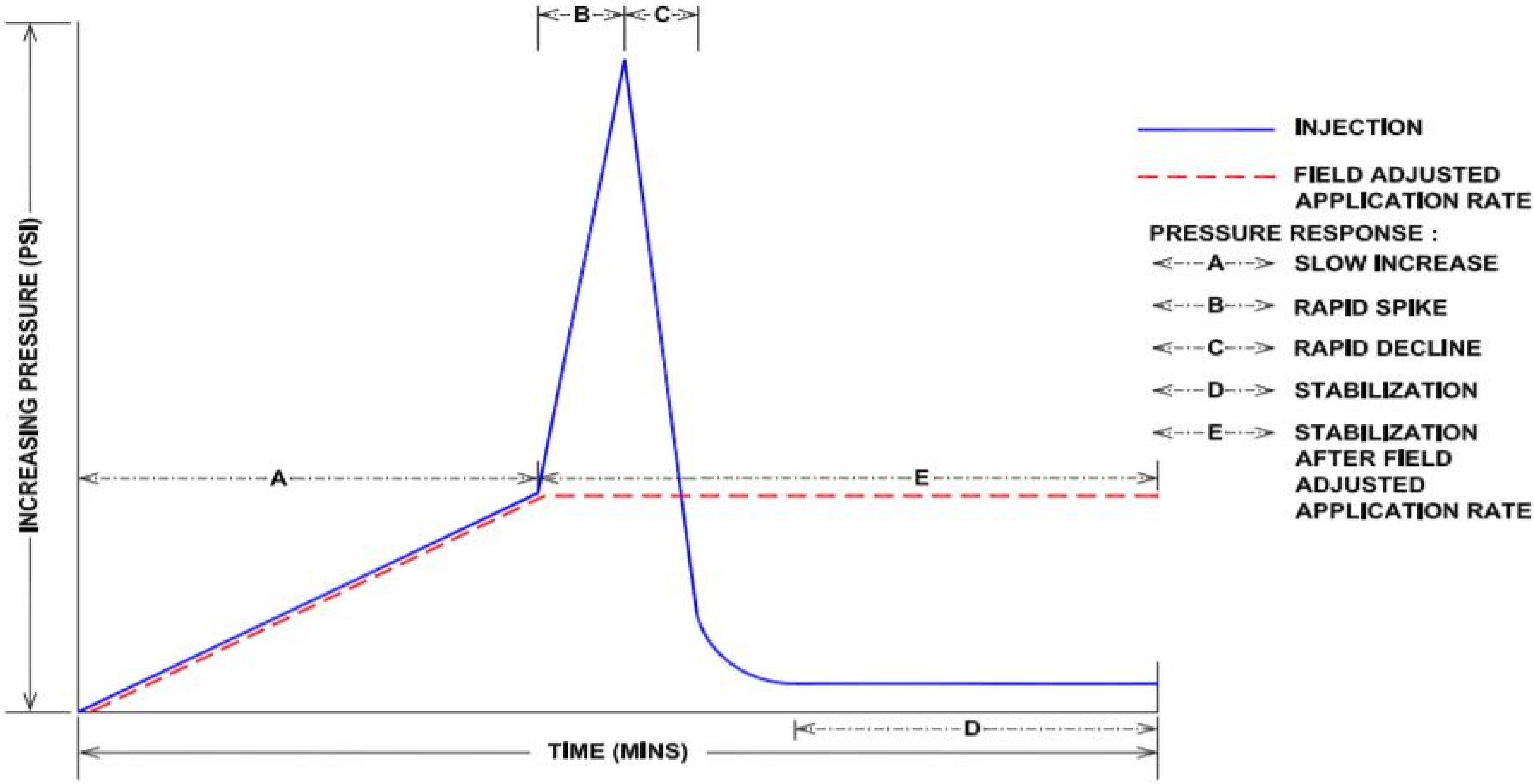
FIGURE 7A

SCALE: N.T.S



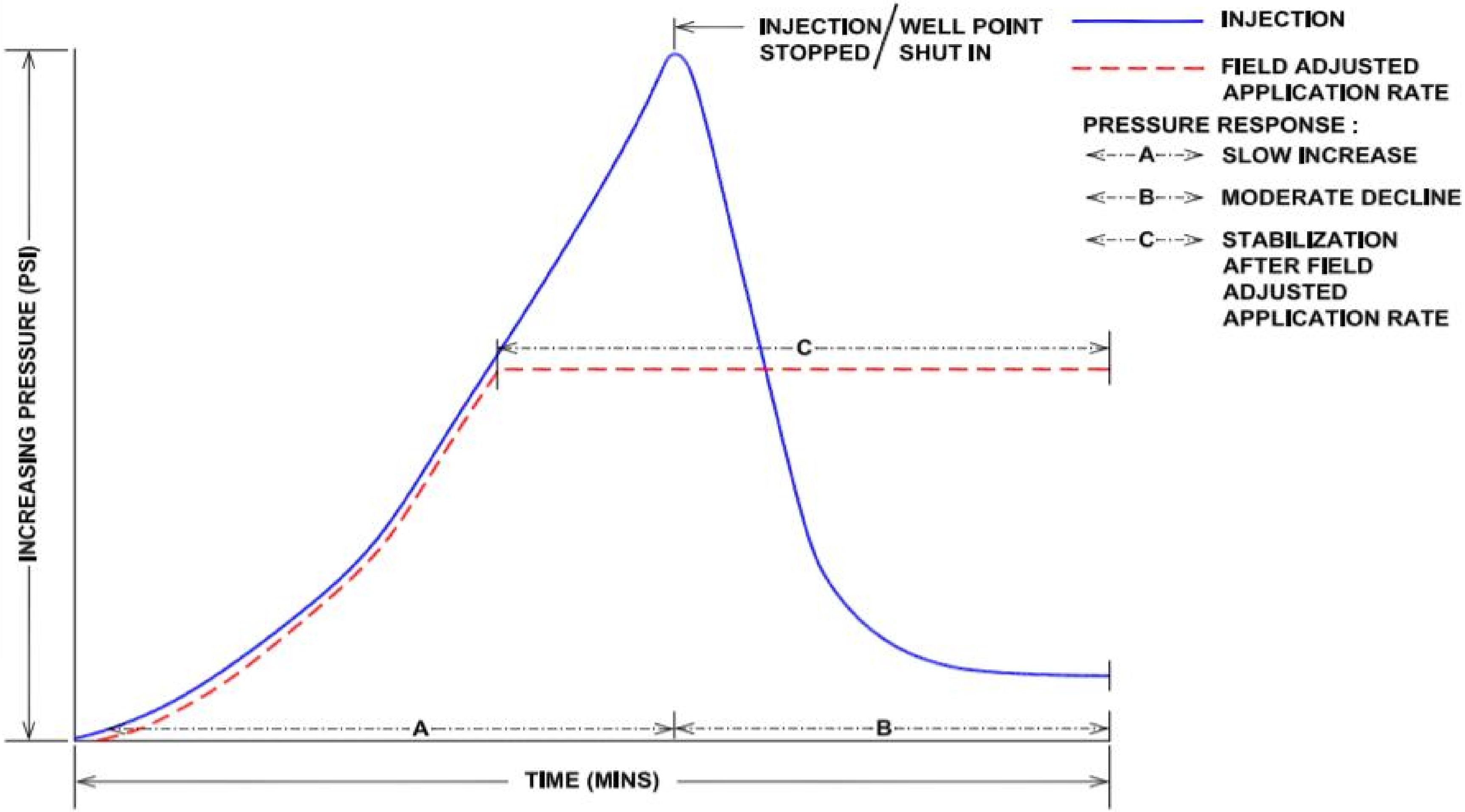
NOTE: APPLIES TO DIRECT PUSH AND UNDERDEVELOPED WELLS

INSITU REMEDIAL REAGENTS WORKING GROUP	PRESSURE: RAPID SPIKE → SLOW TO MODERATE DECLINE
	FIGURE 7B — SCALE: N.T.S



NOTE: APPLIES TO DIRECT PUSH AND UNDERDEVELOPED WELLS

INSITU REMEDIAL REAGENTS WORKING GROUP	**PRESSURE:** **SLOW INCREASE → RAPID SPIKE → RAPID DECLINE → STABILIZATION**
	FIGURE 7C — SCALE: N.T.S



NOTE: APPLIES TO DIRECT PUSH AND UNDERDEVELOPED WELLS

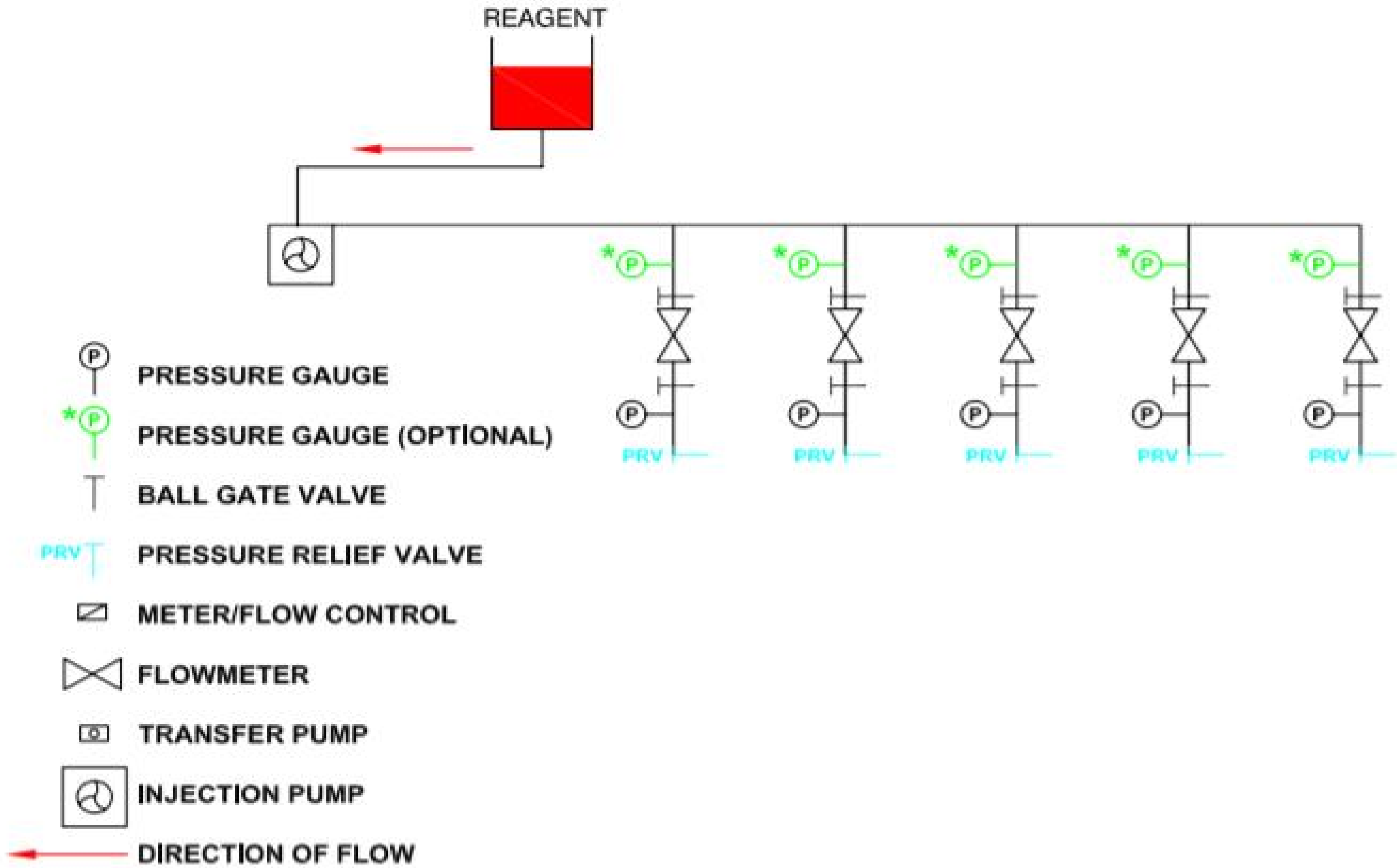
INSITU REMEDIAL REAGENTS WORKING GROUP	PRESSURE: SLOW INCREASE → MODERATE DECLINE → STABILIZATION
	FIGURE 7D — SCALE: N.T.S

INSITU REMEDIAL REAGENTS WORKING GROUP

PHOTO OF GENERIC INJECTION MANIFOLD SYSTEM

FIGURE 9

SCALE: N.T.S



INSITU REMEDIAL REAGENTS WORKING GROUP

INJECTION MANIFOLD SYSTEM BASIC CONFIGURATION

FIGURE 10

SCALE: N.T.S