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Removal Action Design Plan (RADP) with Effectiveness Monitoring Plan (EMP) for the P-Area Groundwater (PAGW) Operable Unit (OU)

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DISCLAIMER

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LIST OF ABBREVIATIONS AND ACRONYMS

~	approximately
AM	Action Memorandum
AOC	Area of Contamination
bgs	below ground surface
CAS	Chemical Abstracts Service
cis-DCE	cis-1,2-dichloroethylene
cm	centimeter
CPT	cone penetrometer technology
cVOC	chlorinated volatile organic compound
EMP	Effectiveness Monitoring Plan
ft	foot/feet
ft^2	square feet/foot
HPG	hydroxypropylguar
HPIT	hydraulic pulse interference testing
Hz	Hertz
IDW	Investigative-Derived Waste
in.	inch
km	kilometer
LAZ	Lower Aquifer Zone
LF	linear feet/foot
LM	linear meter
m	meter
m^2	square meter
MCL	maximum contaminant level
mi	mile
NTC	non-time critical
OU	Operable Unit
PAOU	P-Area Operable Unit
PAGW	P-Area Groundwater
PCE	tetrachloroethylene
PDI	Pre-Design Investigation
ppb	parts per billion
PRB	permeable reactive barrier
P-RBC	P-Area Reactor Building Complex
PSA	Potential Source Area
PVC	polyvinyl chloride
QAPP	Quality Assurance Project Plan
RADP	Removal Action Design Plan
RAR	Removal Action Report
ROD	Record of Decision
RSER/EE/CA	Removal Site Evaluation Report/Engineering Evaluation/Cost Analysis

LIST OF ABBREVIATIONS AND ACRONYMS *(Continued/End)*

SC	Steel Creek
SCDHEC	South Carolina Department of Health and Environmental Control
SEMS	Superfund Enterprise Management System
SRNS	Savannah River Nuclear Solutions
SRS	Savannah River Site
TCE	trichloroethylene
UAZ	Upper Aquifer Zone
μg/L	microgram per liter
UIC	Underground Injection Control
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
USFS	United States Department of Agriculture Forest Service
WMP	Waste Management Plan
ZVI	zero-valent iron

1.0 GENERAL DESCRIPTION

1.1 Purpose and Scope

The purpose of this Removal Action Design Plan (RADP) with Effectiveness Monitoring Plan (EMP) is to provide the design information for the implementation of the non-time critical (NTC) removal action at the P-Area Groundwater (PAGW) Operable Unit (OU) and the post-construction plan for monitoring. The scope of this removal action is to reduce the mass and downgradient transport of the PAGW OU trichloroethylene (TCE) groundwater plume(s) (USDOE 2018). The focus of this removal action is in the neck area of the TCE groundwater plume(s) at P Area.

This RADP report presents a description of the unit, details of the removal action design, permitting requirements, description of the construction strategy, and post-construction plans. The Applicable or Relevant and Appropriate Requirements for the selected removal are presented in the Action Memorandum (AM), Revision 0 (USDOE 2018) as well as the Removal Site Evaluation Report/Engineering Evaluation/Cost Analysis (RSER/EE/CA) (SRNS 2018a) for the PAGW OU.

1.2 General Description and History of the PAGW OU

P Area is located in the central portion of the Savannah River Site (SRS) approximately (~) 4.0 kilometers (km) (2.5-miles [mi]) east-southeast of the geographical center of the SRS and about 6.4-km (4-mi) west of the nearest site boundary (Figure 1). P Area consists of a closed nuclear reactor building complex and several surface OUs and structures that were previously characterized and identified as sources to soil and groundwater contamination (WSRC 2006).

The P Area surface units identified as posing a risk to human health, the environment, and contributing to groundwater contamination were remediated as part of the P-Area Operable Unit (PAOU), including the P-Area Reactor Building Complex (P-RBC) (105-P) (SRNS 2008). Remedial actions associated with surface units included in the PAOU have been completed and are documented in the PAOU Post Construction Report (SRNS 2012b). In particular, one surface unit, Potential Source Area (PSA)-3A, was determined to be the source of TCE plumes discharging to Steel Creek (SC) and the focus of this removal action (Figure 1). PSA-3A was remediated in 2011 and the remedial goals were met using soil vapor extraction enhanced with soil fracturing and In-Situ Chemical Oxidation injection.

The PAGW OU encompasses the groundwater beneath P Area, northwest to SC, northeast toward PAR Pond and SRS Road F, and southeast to Meyers Branch and is established for the purposes of groundwater modeling. Groundwater over portions of the PAGW OU areal extent has been impacted by reactor and facility operations between 1954 and 1991. Groundwater plumes are present in the PAGW OU Upper Aquifer Zone (UAZ) and Lower Aquifer Zone (LAZ) of the Upper Three Runs Aquifer.

The nature and extent of contamination was investigated for the PAGW OU using groundwater monitoring wells, direct-push technology, and surface water samples (SRNS 2013). Groundwater contamination associated with chlorinated volatile organic compounds (cVOCs) is primarily exhibited in a narrow band north of the P-RBC and extends to the west to SC, where impact is known, and east towards an unnamed tributary to PAR Pond. The cVOC groundwater plumes can be described in three parts: 1) source area, 2) neck area, and 3) distal area (Figures 2 and 3). Maximum contaminant level (MCL) exceedances in groundwater occur over an area of ~17/21 acres for TCE in the UAZ/LAZ. Tetrachloroethylene (PCE) and cis-1,2-dichloroethylene (cis-DCE) plumes present in the UAZ and LAZ are contained within the TCE plume area as described and shown in the Sampling and Analysis Plan Addendum (SRNS 2018b). The source area represents most of the groundwater contamination and is centered north of the P-RBC within the P-Area facility area. The neck area represents the area where the cVOC groundwater plumes are controlled by a buried geologic feature thus creating a narrowing of the groundwater plumes and is located to the west just outside of the P-Area facility area. The distal area represents the area where the plumes are closest to SC. Table 1 lists the maximum reported concentrations for TCE, PCE, and cis-DCE in the UAZ and LAZ at the three areas during the fourth quarter sampling event in 2016 (SRNS 2018a). Surface water in SC is impacted by discharges of TCE contaminated groundwater above the MCL of 5-micrograms per liter (µg/L). The area of impact is localized to the upper section of the creek. Maximum TCE concentrations were observed at 28.3-µg/L in 2013. Recent (2018) measured TCE concentrations are 14.9-µg/L.

1.3 Regulatory Documentation

The United States Department of Energy (USDOE), US Environmental Protection Agency (USEPA), and South Carolina Department of Health and Environmental Control (SCDHEC) have agreed to conduct a NTC removal action at the PAGW OU to reduce potential risk to human health and the environment. The RSER/EE/CA for the PAGW OU documents the evaluation of removal alternatives for the TCE plumes and recommends the preferred NTC removal action to address the potential risk from TCE plumes in groundwater of the PAGW OU (SRNS 2018a). The removal action chosen in the AM includes the installation of a zero-valent iron (ZVI) permeable reactive barrier (PRB) in the neck area of the TCE plumes to intercept and dechlorinate contaminated groundwater (USDOE 2018).

2.0 REMOVAL ACTION DESIGN

The NTC removal action objective documented in the PAGW OU AM (USDOE 2018) is to protect human health and the environment by reducing the mass and downgradient transport of the PAGW OU TCE groundwater plume(s). The selected removal action is to install a ZVI-PRB within the neck area of the TCE groundwater plume(s) perpendicular to groundwater flow.

2.1 Design Summary

The large cVOC mass in the source area of the PAGW OU, which is projected to flow with groundwater through the neck area on its way to SC, warrants a NTC removal action to reduce the cVOC mass. Installation of a ZVI-PRB to intersect TCE plume(s) in the neck area was chosen as the preferred method in the *Removal Site Evaluation Report/Engineering Evaluation/Cost Analysis for Trichloroethylene Plumes Discharging to Steel Creek in P-Area Groundwater Operable Unit (NBN) (U)* (SRNS 2018a). The selected removal action was presented to the public in the *Action Memorandum and Responsiveness Summary for the Non-Time Critical Removal Action for the P-Area Groundwater Operable Unit (U)* (USDOE 2018) for 30 days.

Along with a review of historical data from the neck area, a Pre-Design Investigation (PDI) was performed in the neck area of the TCE plumes to confirm site lithology, hydrogeologic, geochemical characteristics, and confirm extent of cVOC contamination as it relates to design, construction, and performance of the ZVI-PRB (See Section 2.3 and 2.5). During the RSER/EE/CA process, the assumption was that both the UAZ and LAZ TCE plumes would be targeted with the ZVI-PRB. Data from the PDI indicated that TCE concentrations in the LAZ were much lower than in the UAZ and that the groundwater flow direction of the LAZ was much more northerly than what was expected (SRNS 2019a). Considering that the LAZ groundwater flow direction would lead to inefficient capture of the TCE plume by the ZVI-PRB proposed, and the TCE concentration data which showed approximately 95% of the TCE mass is present in the UAZ, focus was placed on constructing a ZVI-PRB to only target the UAZ TCE plume. Design and construction details for the final-design are provided in this RADP.

2.2 Design Details

The ZVI-PRB will be constructed using 22 ZVI injection wells (F1-F22) spaced ~3.7-meters (m) (12-feet [ft]) apart. The 12-ft spacing of the ZVI injection wells is based on the vendor's field experience from prior implementations and site-specific conditions to ensure complete coalescence of the ZVI-PRB. The ZVI-PRB will extend for a total of 80.5-linear meters (LM) (264-linear feet [LF]) in a "zig-zag" orientation, transecting the TCE plume in the UAZ (Figure 4). The ZVI-PRB will be one continuous permeable barrier comprised of four segments, Segment A through Segment D. Segment D consists of two sub-segments, Segment D_1 and Segment D_2, with different depth intervals. Figures 5 and 6 show cross-sections of the expansion casing construction, and details of each segment are provided in Table 2 and summarized below:

- Segment A will be 21.9-LM (72-LF) (F1-F6), oriented in a northeast to southwest alignment, installed from 13.7-m (45-ft) below ground surface (bgs) to 41.1-m (135-ft) bgs, and will have a cross-sectional area of ~602-square meters (m^2) (6,480-square feet [ft^2]).
- Segment B will be 25.6-LM (84-LF) (F7-F13), oriented in a northwest to southeast alignment, installed from 13.7-m (45-ft) bgs to 41.1-m (135-ft) bgs, and will have a cross-sectional area of ~702-m^2 (7,560-ft^2).
- Segment C will be 11.0-LM (36-LF) (F14-F16), oriented in a northeast to southwest alignment, installed from 13.7-m (45-ft) bgs to 41.1-m (135-ft) bgs, and will have a cross-sectional area of ~301-m^2 (3,240-ft^2).
- Segment D_1 will be 7.32-LM (24-LF) (F17-F18), oriented in a north-northwest to south-southeast alignment, installed from 13.7-m (45-ft) bgs to 41.1-m (135-ft) bgs, and will have a cross-sectional area of ~201-m^2 (2,160-ft^2).

- Segment D_2 will be 14.6-LM (48-LF) (F19-F22), oriented in a north-northwest to south-southeast alignment, installed from 13.7-m (45-ft) bgs to 36.6-m (120-ft) bgs, and will have a cross-sectional area of ~334-m^2 (3,600-ft^2).

Active resistivity mapping will be used to ensure complete coalescence and accurate construction of the ZVI-PRB. During injection, the ZVI mixture will be electrically energized with a low-voltage 100-Hertz (Hz) signal. Downhole resistivity receivers will be monitored to record the in-phase induced voltage by the propagating inclusions. From monitoring the carrier fluid induced voltages and utilizing an incremental inverse integral model, the carrier fluid geometry can be quantified and displayed during the installation process (Figure 7). Resistivity strings will be installed 7.3-m (24-ft) from the ZVI-PRB and will be installed using cone penetrometer technology (CPT). Resistivity strings are contained in clear braided polyvinyl chloride (PVC) tubing with spiral fabric reinforcement (3/4-inch [in.] inside diameter minimum). Each resistivity receiver is located ~1.5-m (5-ft) apart along the string and attached to individual wires. A total of 23 resistivity strings will be installed, with 19 resistivity strings containing 19 receivers from ~13.7- to 41.1-m (45- to 135-ft) bgs and the remaining 4 resistivity strings will consist of 16 receivers from ~13.7- to 36.6-m (45- to 120-ft) bgs. Figures 5 and 6 show the cross-sections of the resistivity strings for the ZVI-PRB.

Approximately 627-metric tons (691-tons) (~689-metric tons [760-tons] with 10% waste) of ZVI will be required to construct the proposed ZVI-PRB. This is determined based on a total ZVI-PRB surface area of 2,140-m^2 (23,040-ft^2), a thickness of 10-centimeter (cm) (4-in.), and an average ZVI density of 2,883-kilogram per cubic meter (180-pounds per cubic foot). The ZVI will be injected into the subsurface through the 22 injection wells. Based on subcontractor field experience, the general rate of injection is expected to be between 9.07-metric tons/day (10-tons/day) and 16.3-metric tons/day (18-tons/day). Prior to injection, the ZVI filings will be mixed with hydroxypropylguar (HPG) to produce an extremely viscous mixture that suspends the ZVI throughout. This mixture is then forced into the subsurface through 3.1-m (10-ft) long expansion casings oriented along the ZVI-PRB trace. The viscous mixture is able to fracture the subsurface and fill the void. After a few hours of injection, the HPG will degrade into sugars and water, leaving a permeable ZVI barrier which will degrade cVOCs through the reactions in Figure 8.

2.3 Design Activities

Initial design activities included review of geotechnical, hydrogeological, and groundwater chemistry data that was collected during previous investigations. After this review, it was determined that additional site-specific data was needed to better define the local extent of cVOC contamination and geologic parameters required to develop the design. The following activities were conducted under a Design Data Acquisition Plan for the PDI:

- Continuous coring and geophysical logging of select locations (Figure 9) along the original alignment of the ZVI-PRB (PRB003SB, PRB001SB, PRB004SB, PRB006SB, and PRB007SB) and of 4 LAZ monitoring well locations (PRW001C, PRW002C, PRW003C, and PRW004C);
- Installation of two monitoring well clusters upgradient of the ZVI-PRB (PRW001 and PRW003) and two monitoring well clusters downgradient of the ZVI-PRB (PRW002 and PRW004). Each well cluster consists of one upper UAZ monitoring well (DU designation), one lower UAZ monitoring well (DL designation), and one LAZ monitoring well (C designation) (Figure 9);
- Treatability study to determine contaminant degradation rates and long-term performance of the ZVI-PRB; and
- Hydraulic pulse interference testing (HPIT) of the new monitoring wells to collect aquifer permeability data.

Data collected as part of the PDI was then analyzed and used to develop a design that would meet the design criteria as described in Section 2.3. The following activities were completed to support the design and implementation of the removal action:

- Lithologic and hydrogeologic descriptions;
- Determination and characterization of the lateral and vertical extent of cVOC contamination (Figure 10);
- Determination of aquifer permeabilities across the ZVI-PRB;
- Review of iron reactivity treatability study completed to (1) quantify cVOC degradation rates on site groundwater and (2) address any potential precipitation or clogging issues of the iron filings proposed for use in the PRB;

- Locating the ZVI-PRB in a location that correlates to the width of the plume using site characterization data, groundwater concentration gradients and potentiometric surfaces; Design of the ZVI-PRB utilizing a probabilistic model for predicting effluent concentrations of cVOCs in the groundwater emanating from the PRB;
- Evaluation of ZVI-PRB construction methods suitable for the site;
- Preparation of construction drawings and specifications for installation and construction of the ZVI-PRB System;
- Survey of the ZVI-PRB area and design of a stone pad for stabilization of the area;
- Preparation of a Waste Management Plan (WMP) for consolidation of wastes; and
- Development of an EMP (Section 5.1).

2.4 Design Criteria

The design criteria for the ZVI-PRB in the PAGW OU are provided below:

- Reduce the TCE mass flux through the ZVI-PRB by ~80%;
- Ensure design calculations agree with the anticipated life expectancy of 25 years;
- Install in highly permeable zone of the UAZ, within the neck area to promote flow through the ZVI-PRB; and
- Design the ZVI-PRB with ZVI material that have a hydraulic conductivity equal to or greater than the existing permeable zones.

2.5 Design Data Test Results

2.5.1 Soil Boring Results

Nine (9) locations were continuously cored within the ZVI-PRB location to characterize the site-specific subsurface conditions. The cores were described in the field and the boreholes were geophysically logged in order to confirm stratigraphy of the formation (Figure 10). Three semi-confining units were observed from the borings. The first unit, designated as the Upper Tan Clay Confining Zone ranged in thickness between 1.5 and 4.6 m (5 and 15 ft) and was located between 24.4- and 32-m (80- and 105-ft) bgs, but was not observed in the northernmost soil boring (PRB003SB). A second confining unit, which is the transition between the UAZ and the LAZ is designated as the Lower Tan Clay Confining Zone and was consistently 3- to 4.6-m (10- to 15-ft) thick. The depth interval of this unit was present along the soil borings and monitoring wells between 35- to 42.7-m (115- to 140-ft) bgs. The lowermost confining unit, the Gordon Confining Unit, was observed between 48.8-m (160-ft) bgs to the south and 52.4-m (172-ft) bgs to the north, was a yellow to green-gray color, and very dense. The thickness of the unit ranged from 7.6- to 9.1-m (25- to 30-ft) thick. Identification of the confining units aided in the proposed design of the ZVI-PRB such that the ZVI-PRB would be keyed into one of the confining units to minimize flow below the ZVI-PRB. The presence of a stream bed feature (area of ~1- to 4-in. cobbles) was observed at borings conducted along the southern 30-m (100-ft) of the ZVI-PRB alignment at depths between 24.4- and 31.1-m (80- and 102-ft) bgs with the feature starting at four-feet thick at the southernmost monitoring wells then widening to 4.3-m (14-ft) thick and narrowing back to 3-m (10-ft) thick at the two southernmost borings.

Results from soil plugs were taken from the cores, starting at 9.1-m (30-ft) bgs and at select depths throughout, to conduct headspace analyses to determine cVOC contaminant extent. Analyses of the soil plug data indicated that the majority of TCE contamination existed at the well clusters (central portion of the ZVI-PRB) (Figure 11). Contamination was measured in the UAZ and LAZ of the ZVI-PRB area with maximum concentrations of 2,491-parts per billion (ppb) and 185-ppb, respectively. This data indicates that greater than 95% of the contaminant mass is present in the UAZ. Contaminant distribution was found to be extremely variable in the ZVI-PRB area with high concentrations sometimes found in low permeability formations. The coring data was used to determine the extent of contamination and to aid in selection of monitoring well screen depths.

2.5.2 Groundwater Analyses Results

Twelve monitoring wells were installed and developed in the ZVI-PRB area (Figure 9). Two monitoring well clusters were installed upgradient of the proposed ZVI-PRB and two monitoring well clusters were installed downgradient of the proposed ZVI-PRB. Each cluster consisted of one monitoring well screened in the LAZ (C designation), one screened in the lower UAZ (DL designation), and one screened in the upper UAZ (DU designation).

Initial TCE groundwater concentrations in the UAZ ranged between 2.92- to 535-µg/L and in the LAZ between 380- to 836-µg/L. However, maximum soil concentrations observed at the completed soil borings indicate UAZ TCE soil concentrations at 2,490-µg/kg while in the LAZ, maximum TCE soil concentrations were 198-µg/kg. Based on previous investigations, TCE water concentrations are normally 2 to 5 times greater than observed soil concentrations. Therefore, the range of UAZ TCE groundwater concentrations could be expected to range from 5,000 to 12,500 µg/L, which is consistent with P002U and P003U monitoring well groundwater data that ranged from 2,110- to 7,070-µg/L between 2011 and 2014. The observed TCE groundwater concentrations from the recently installed wells are much lower, which could be due to a combination of factors such as 1) sampling approach of wells, especially ones that are poor producers or pump dry; 2) portion of the well's screen installed in less contaminated media; and 3) insufficient time for potable water that was introduced during well installation to flush out. However, since higher measured concentrations were seen in the P002U, P003U, and upgradient monitoring wells, a maximum concentration of 7,700-µg/L was used as the conservative basis of design.

2.5.3 Hydraulic Pulse Interference Testing Results

The HPIT consists of cyclic injection of potable water into the source well with the pressure pulses measured in the receiver well. HPIT is used to compute the in-situ hydraulic properties (hydraulic conductivity and specific storage) of subsurface materials in the saturated groundwater zone between two wells by measuring a response at varying distances between the well pair(s). HPIT was performed on nine (9) existing monitoring well pairs at various distances to evaluate the baseline conditions of the hydraulic conductivity of the formation for comparison post-PRB installation. The testing program was designed to evaluate flow rates and pressure pulse dissipation (known herein as "shut in") intervals that provide the best signal response for the hydrogeologic conditions at the site, and subsequently determine over what distances signals could be reliably transmitted and received.

The HPIT was designed to determine the applicability of the technology to the site and identify any potential limitations based on site hydrogeologic conditions. HPIT well pairs are typically located in the direction of groundwater flow in order to obtain accurate results. Based on potentiometric surfaces plotted from recently (2018) installed monitoring wells in P Area, groundwater flow direction appears to be traveling either at 30 to 85 degrees across the well pairs (PRW well series) or perpendicular to the expected flow direction, depending on the zone. Another indication that groundwater flow direction was not in the direction of the well pairs during HPIT was evident by higher than typical required source flow rates to measure a response and dampened responses in the receiver wells.

Raw data from each of the 9 well pairs was analyzed against a verification program used to back calculate and plot theoretical receiver response using the test conditions. A comparison of the raw data against the theoretical data is used to estimate values for conductivity and storativity.

HPIT data did not consistently match the criteria for reproducibility and verification with the check program. Therefore, the results obtained during this HPIT were used along with other site supporting data for design purposes of the ZVI-PRB. Table 3 provides historical conductivity values as well as values calculated from HPIT.

2.5.4 Bench-Scale Treatability Test

A bench scale treatability test was conducted using groundwater collected from PRW003C and PRW003DL. Site-specific subsurface soil was also used during the test. The purpose of the treatability test was to determine the reactivity of the granular ZVI and long-term ZVI reaction by evaluating groundwater flow through columns of ZVI material. The ZVI material (14D, -12 to +200 US Standard Mesh Size) was procured from Peerless Metal and Abrasives of Detroit, MI and packed into two columns. Groundwater was spiked to a concentration of 7,700-µg/L and fed into the columns. Sample ports were positioned along the central axis of the columns at various distances from the inlet.

The objectives of the ZVI reactivity column test were to quantify degradation rates for the cVOCs in site groundwater, the generation and degradation of any cVOC daughter products, and the potential for precipitation and reduction of iron permeability due to changes in groundwater chemistry within the ZVI-PRB. The only variable between the two columns was the groundwater flow velocity at 0.64-m/day (2.1-ft/day) versus 0.18-m/day (0.6-ft/day). The higher flow rate was selected to evaluate long-term effects on the ZVI surface by groundwater geochemistry with more pore volumes; whereas, the slower flow rate was comparable to historical site estimates of groundwater flow velocities.

cVOC concentrations in groundwater in the column were measured until steady-state (unchanging) conditions were achieved. The groundwater cVOC concentrations can be related to the residence time of the groundwater in the presence of the iron. From such data, degradation half-lives of the cVOCs, daughter product generation rates, and their respective degradation half-lives were calculated (Table 4). Data from this treatability test has been used to estimate the effectiveness of the ZVI-PRB on treating site groundwater that will flow through the ZVI-PRB at the proposed alignment.

Analytical test data from the ZVI reactivity treatability study was used to evaluate the potential for precipitation and possible clogging of the ZVI-PRB. Based on the geochemical composition and estimated flux of the groundwater to pass through the full-scale ZVI-PRB, the potential for precipitation resulting in significant loss of porosity is considered very low. While the longevity of the iron's reactivity cannot be determined from the column tests, the tests did confirm that precipitation and/or clogging should not be an issue. To address uncertainty regarding the iron's long term reactivity and the very low potential for porosity loss, a minimum engineering safety factor of 2x in the ZVI volume design was recommended to assure long-term performance.

2.5.5 Design Modeling

Using data collected from the field and the test results described in the previous sections, a multi-constituent cVOC probabilistic model was used to quantify the overall reactive barrier system performance and the impact of system parameters on barrier performance, based on expected variability. The system parameters consisted of site hydraulic conductivity, hydraulic gradients, barrier thickness and porosity, cVOC degradation half-lives, cVOC daughter product generation and influent maximum observed (historical) cVOC concentrations. The probabilistic analyses quantified the sensitivity of the overall system performance to each system input parameter.

Numerous ZVI-PRB design cases were evaluated for the ZVI-PRB alignment as shown in Figure 4. The ZVI reactive barrier system performance was evaluated based on the ability of the system to reduce TCE concentrations in groundwater by 90% of the design influent concentration even though the design criteria is to reduce TCE mass flux by ~80%.

The results of the probabilistic analysis performed for design cases with properties representing the UAZ, indicate that a 1.5-inch average iron-effective thickness PRB is sufficient to bring cVOCs in site groundwater to 90% less than the design influent concentrations based on simulated effluent concentrations. An additional engineering factor of safety of 2.67 would provide a 4-inch iron-effective-thickness and would ensure that the desired concentration reductions are met in the effluent as well as account for potential precipitation/clogging of the iron with increased PRB longevity.

2.5.6 Iron Soil Analysis

Soil samples collected during the PDI were sent to CSRA Testing & Engineering, Inc. in Augusta Georgia for sieve analysis and hydrometer analysis. The grain size gradation coefficients of the iron and soil were compared to ensure the iron particles do not migrate into the site soils. Based on this evaluation, a blend of Peerless 14D (-12/+100 mesh) and coarser material from Peerless 850 (-8/+50) is suitable for injection resulting in a blend of -8/+100 mesh (0.15 to 2.36 mm). The grain size contrast between the iron and soil indicates that the iron is predominantly more conductive than the native soil.

2.6 Drawings

The figures and tables contained in this document serve as the design drawings for this project. No additional drawings are planned for this project. The drawings provided in this document, in conjunction with the construction requirements in Section 4.0, provide the basic requirements for implementation of the removal action design for the PAGW OU.

2.7 Surveys

Prior to the design phase of the removal action, the proposed PRB area was surveyed and site drawings were used to verify that no subsurface interferences would impact the ZVI-PRB. In addition to the figures and tables contained in the document, a lay-out survey that identifies possible subsurface interferences will be prepared for each injection and monitoring well location.

An As-Built survey will be completed for each monitoring well as well as final construction PRB details that will be included in the Removal Action Report (RAR).

2.8 Site Preparation

The PAGW OU ZVI-PRB will be installed in an open area along the outside of the P-Area complex. The site preparation will include drainage improvements and placement of a crusher run surface centered along the ZVI-PRB injection wells to provide a stable working area. A small area on the southern end of the PRB injection wells will need to be cleared and leveled to allow equipment access. The drainage improvements and areas to receive stone are shown in Figure 12. The prepared area is under 1-acre and therefore does not require a Stormwater Management and Sediment Reduction Plan/Pollution Prevention Plan.

3.0 PERMITTING REQUIREMENTS

The only permitting requirement for the removal action at the PAGW OU is an underground injection control (UIC) permit from SCDHEC for the ZVI mixture that will be injected to form the ZVI-PRB. A UIC permit application was submitted in April 2019 (SRNS 2019b).

4.0 CONSTRUCTION

4.1 Construction Strategy

ZVI-PRB injection wells will be installed using sonic drilling with mud to drill to the total depth and install the specialized expansion casings. A series of 3.1-m (10-ft) long expansion casings and 1.5-m (5-ft) long risers will be connected with set-screws (Figure 13) and grouted into the boreholes. The expansion casings are aluminum casings with “wings” on either side that expand when pressure is applied to produce a fracture along the azimuth of the PRB (Figure 14 and 15). The expansion casings and 1.5-m (5-ft) long steel risers alternate, such that injection well F1 will be constructed with an expansion casing from 38.1- to 41.1-m (125- to 135-ft) bgs, a steel riser from 36.6- to 38.1-m (120- to 125-ft) bgs, an expansion casing from 33.5- to 36.6-m (110- to 120-ft) bgs, a steel riser from 32.0- to 33.5-m (105- to 110-ft) bgs, an expansion casing from 29.0- to 32.0-m (95- to 105-ft) bgs, etc. Following the final expansion casing, steel riser will extend to the ground surface, with connections made using tack welding. While the injection wells are being constructed, the 23 resistivity strings will be installed 7.3-m (24-ft) offset from the ZVI-PRB. This spacing is based on the distance required for active resistivity mapping of the ZVI injections to monitor complete coalescence based on field experience and site-specific conditions. Resistivity strings will be installed using CPT to emplace braided PVC tubing that will hold the individual resistivity wires and stainless-steel collars. Figures 5 and 6 show cross-sections of the injection wells and resistivity strings.

Based on the design, ~627-metric tons (691-tons) (~689-metric tons [760-tons] allowing for 10% wash out) of ZVI will be emplaced using the 22 injection wells, set ~3.7-m (12-ft) apart, centered along the ZVI-PRB alignment (Figure 4). ZVI filings will be emplaced using a carrier fluid that ensures the consistency and viscosity needed to propagate the inclusions through the subsurface. The carrier fluid consists of HPG, ZVI, a cross-linker, and an enzyme. Table 5 provides the composition of the carrier fluid. The HPG will be pre-mixed with water in a 3,000-gallon mixing tank utilizing a venturi blender and then fed into a 757-liter (200-gallon) mixing/blending tank along with the ZVI filings. While in the mix unit, the HPG will be kept in a water soluble (uncross-linked) state with the ZVI filings suspended evenly throughout. The mixture will then be fed to the injection pump and mixed in-line with a cross-linker and enzyme instantly, causing the mixture to become cross-linked, water insoluble, and extremely viscous. This viscous mixture of HPG and ZVI filings will then be pumped into an expansion casing causing the casing to dilate, creating a controlled vertical inclusion pathway at the required azimuth orientation and depth. The pathway of each inclusion will be guided by pore pressure relief between casings, thus ensuring vertical and lateral coalescence of the ZVI filings between each expansion casing. The ZVI-PRB will be constructed in multiple sections using the individual expansion casings separated by packers. The ZVI-PRB will be constructed from the bottom at each injection well location. Because the void created by each ZVI inclusions will have a thickness less than the design thickness, multiple injections will be made in each injection well until the design thickness (10.2-cm [4-in.]) is reached or all ZVI has been injected. Expansion casings will be washed out using a water jet before each subsequent injection. Following injection of the ZVI, the enzyme causes the gel to biodegrade into water and sugars, leaving a permeable iron reactive treatment zone.

Eight UAZ monitoring wells (PRW001DU, PRW001DL, PRW002DU, PRW002DL, PRW003DU, PRW003DL, PRW004DU, PRW004DL) within the ZVI-PRB area have the potential to cause short circuiting during the ZVI injections. Short circuiting during the injection process could result in a ZVI-PRB that is not continuous and/or lead to surfacing of ZVI through the monitoring wells. To address this potential issue, the monitoring wells will be filled with sand and capped prior to ZVI injection. Following completion of the ZVI-PRB, the eight monitoring wells will be airlifted to remove the sand and redeveloped.

The ZVI-PRB installation will be monitored to determine the geometrical extent of the barrier, thus ensuring it is installed as designed using active resistivity mapping. A general layout of the resistivity monitoring system to be used during installation of the ZVI-PRB is shown on Figure 7. During injection, the ZVI-gel mixture will be electrically energized with a low voltage 100-Hz signal. Twenty-three downhole resistivity receivers will be monitored to record the in phase induced voltage by the propagating inclusion (See Figure 7). From monitoring the carrier fluid induced voltages and utilizing an incremental inverse integral model, the inclusion fluid geometry can be quantified and displayed during the installation process to provide a high-resolution image of the ZVI-PRB geometry.

Following injection of ZVI and construction of the ZVI-PRB, four injection wells will be retrofitted to monitoring wells. The four injection wells of interest (F5, F11, F17, and F21) will be washed out to depth using a water jet to remove iron filings. The installed one-inch diameter monitoring wells will be comprised of a well cap, a 6.10-m (20-ft), 0.0254-cm (0.010-in.) slot screen, and riser piper to grade. Since the proposed wells are being installed in-wall, the wells will not be constructed by typical installation methods. After the injection wells are flushed out and the well set, the annulus will be backfilled with ZVI. This will ensure continuity of the PRB and minimize impact on the long-term performance of the PRB. A cross-section of the in-wall monitoring wells is provided in Figure 16. The monitoring well details and EMP are described in more detail in Section 5.1.

4.2 Construction Activities

Construction activities required for this removal action include:

- Clearing vegetation, installing drainage improvements, and preparing the project area with stone (Figure 12) for the ZVI injection rig, mixing equipment, tanks, storage containers, associated piping, resistivity installation rig, and all other required equipment. All ZVI-PRB equipment is of a temporary nature and will be removed from the project area after completion of all the ZVI injections;
- Completion of the well pads for the PRW001, PRW002, PRW003, and PRW004 monitoring well clusters;
- Boring of injection well locations and installation of expansion casing systems;
- Installation of resistivity strings;
- ZVI injection with active resistivity mapping; and
- Installation of four (4) monitoring wells within expansion casing systems of the ZVI-PRB.

4.3 Removal Action Design Change Control

An engineering team will remain engaged during the NTC removal action activities. The subcontractor will provide technical oversight to all removal activities and consult/report to Environmental Compliance & Area Completion Projects engineering, who will review and approve any field modifications through a supplier deviation disposition request. Although a specific volume of ZVI and HPG mixture are planned for each injection location, the volume at an individual well point may be modified to account for field conditions. However, the subcontractor will attempt to inject the total volume of ZVI and HPG into the subsurface. Any, and all, changes will be documented as part of the project in the RAR. USDOE/SRNS will notify USEPA and SCDHEC within a reasonable time frame should problems result in a significant change of scope with any aspect of the NTC removal action process. Notifications will follow established protocols.

4.4 Waste Disposal and Transport

During installation of the ZVI-PRB, wastes that will be generated include:

- Typical drillings waste;
- Washout water from the expansion casings consisting of HPG, enzyme, cross-linker, and treated groundwater;
- Washout ZVI from expansion casings; and
- Typical job control waste.

Waste management (handling, disposal, and transportation of wastes) will meet the requirements of applicable SRS manuals and procedures (i.e., SRS C1 Procedure Manual, *Environmental Compliance and Area Completion Projects Administrative Procedures*, [SRS 2014a], SRS 1S Procedure Manual, *SRS Radioactive Waste Requirements Manual* [SRS 2014b], SRS 3Q Procedure Manual, *Environmental Compliance Manual* [SRS 2015a], etc.) and the project-specific WMP. Based on process knowledge of the ZVI-PRB construction along with the iron filing safety data sheet provided by the subcontractor, no hazardous waste will be generated. Any job control waste (non-hazardous) will be disposed of as sanitary waste by the subcontractor. Disposition of drilling fluids and byproducts from the ZVI injection process are summarized below.

During the installation of the 22 injection wells, drilling fluids will be discharged to the ground within the area of contamination (AOC) in accordance with the project-specific WMP and the approved SRS Investigative-Derived Waste Management Plan (WSRC 2013). Installation of the 23 resistivity strings will be via CPT or sonic drilling methods. Although no drilling waste associated with the installation of the resistivity wells is expected, resistivity string drilling waste will be handled in the same way as the injection well drilling waste. Any water generated during decontamination of the CPT rods will be discharged to the ground within the AOC in accordance with the project-specific WMP and the approved SRS Investigative-Derived Waste (IDW) Management Plan.

Washout fluid generated prior to injection of the ZVI in each of the wells will be comprised of groundwater, carrier fluid mix, and iron. This liquid will be stored in a roll-off container. The liquid portion will be decanted and dispositioned in accordance with the Savannah River Site IDW plan. Iron solids will be disposed of in the Three Rivers Solid Waste Authority Class Three Landfill (Three Rivers Landfill [Permit #024202-1101]), which is permitted to receive the material.

Based on process experience, occasional batches of the carrier fluid that do not meet the specifications must be dispositioned. The carrier fluid is a mixture of water, food-grade HPG, acetic acid, and sodium. The batches are tested, and discarded if necessary, prior to adding the cross linker or enzyme breaker. Table 5 provides the carrier fluid composition. Carrier fluid that is not able to be used in the injection process will be dispositioned within the AOC.

4.5 Quality Assurance

Quality Assurance for the PAGW OU NTC removal action is provided through the demonstrated adherence to performance requirements specified in this RADP. The RADP was developed in accordance with the SRS Procedure Manual E7, *Conduct of Engineering and Technical Support Procedure Manual* (SRS 2015b) and in conformance with the SRS 1Q Manual, *Quality Assurance Manual* (SRS 2014c). The subcontractor will be required to comply with an SRNS approved project-specific Quality Assurance Project Plan (QAPP) for execution of their tasks. The QAPP includes procedures for monitoring in real time to ensure mixture consistency, to determine the volume and weights of iron injected and to determine the geometrical extent of the barrier ensuring it is constructed as designed via a process involving electrical active resistivity mapping.

The following parameters will be monitored and controlled to ensure the injected mixture is consistent:

- Quantity of pH buffers, sodium or potassium chloride, and gel added to water to produce the guar fluid;
- Proportional rate of feed of iron, gel fluid, enzyme and cross-linker;
- Tests to ensure viscosity and resistivity of gel fluid is consistent and within specification;
- Batch tests to ensure iron filings are within specification;
- Calculating volumetric flow rates to document rates of feed; and
- Quantification of injected density of the iron/guar mixture.

Monitoring of the ZVI-PRB installation will include recording and controlling the following equipment parameters to maintain pressures, volumes, and weights injected:

- Well head pressure;
- Total time of injection; and
- Total volumes and weights injected per well.

The injected geometry of the ZVI-PRB will be recorded by a process involving electrical active resistivity mapping. The injected fluid is made more conductive (less resistive) than that of the substrata by adding sodium chloride to the gel fluid. The injected fluid is then electrically energized by a low voltage 100 Hz signal. The electrical field generated in the ground is monitored by down hole receivers. These down hole receivers detect the change in the induced voltages as the injected fluid propagates through the subsurface. From monitoring of the injected fluid induced voltages and utilizing an incremental inverse model, the injected geometry can be quantified during the installation process. The parameters that need to be monitored and controlled to ensure the injected geometry of the ZVI-PRB is quantified and constructed as planned are:

- Conductance (or resistivity) of iron/gel (measure in the gel) fluid is within specifications;
- Resistivity source, ground, and receivers are functionally within specification and are being recorded;
- Volumetric totals are recorded;
- Induced voltages are monitored by receivers and displayed; and
- Inverse and predictive models are computing and quantifying the injected fluid geometry.

The hydraulic effectiveness of the injected iron PRB is typically quantified from hydraulic pulse interference testing. Hydraulic pulse interference testing involves a cyclic injection of fluid into the source well, and by high precision measurement of the pressure pulse in neighboring wells, detailed hydraulic characterization between wells (and across the ZVI-PRB) can be made. Pulse interference testing is highly sensitive to hydrogeological properties between the wells and relatively insensitive to conditions immediately outside of the wells (borehole or skin effects). The time delay and attenuation of a hydraulic pulse enables the formation hydraulic properties between wells to be computed.

The injected carrier fluid (gel) has a high viscosity and transports the iron filings to the full extent of the induced inclusion. The gel "breaks" in a matter of hours, and the starches in the gel are converted to sugars, resulting in a ZVI-PRB with a permeability equivalent to the iron filings. To quantify that the gel has broken cleanly and not impacted the ZVI-PRB hydraulic properties, hydraulic pulse interference testing, both pre- and post-PRB installation, is conducted and compared. By pulsing a source well on one side of the ZVI-PRB alignment and recording the response on the other side, both pre- and post-PRB installation, the extent of the hydraulic impact of the ZVI-PRB can be typically quantified. Since the direction of groundwater is highly variable in the area of the ZVI-PRB and the well pairs tested are not directly in the groundwater flow direction, the HPIT pre- and post-PRB installation data will be compared to qualitatively evaluate any changes from construction.

4.6 Non-Conformances

All non-conformances will be evaluated, resolved, or rectified as described in the pertinent sections of this document. Design changes from the resolution of non-conforming conditions will be processed per Section 4.3, Removal Action Design Change Control.

4.7 Health and Safety Plan

An analysis of the hazards to workers from exposure to hazardous substances during removal activities for the PAGW OU ZVI-PRB will be conducted and documented in the Project Safety & Health Description. If the results of this analysis show that the activity described herein may expose workers to a level of hazardous chemicals that would be harmful to their health, then a Site-Specific H and Safety Plan meeting the criteria of 29 Code of Federal Regulation 1910.120 will be deployed to control health and safety aspects of this activity. At a minimum, an assisted hazards analysis will be completed will prepare a worker protection plan for the identification and analyses of hazards expected when performing the scope of work and which identifies controls to prevent/mitigate the hazards. This plan also will include types of emergencies that may occur and the subcontractor's response to the emergency, including arrangements with onsite security, fire department, medical facility, and emergency response teams to coordinate emergency services.

5.0 POST CONSTRUCTION

5.1 Effectiveness Monitoring Plan

Three existing upgradient well clusters (PRW001, PRW003, and P003) and three existing downgradient well clusters (PRW002, PRW004, P002) will be sampled prior to the start of the NTC removal action to establish a baseline, which included all analytes in Table 7. Three proposed downgradient well clusters (PRW005, PRW006, and PRW007), four proposed in-wall monitoring wells (PIW001D, PIW002D, PIW003D, and PIW004D), and the existing well clusters (Figure 17) will be used to monitor the PAGW OU treatment barrier effectiveness. The initial sampling event for the three proposed downgradient monitoring well clusters will include all analytes in order to establish a baseline. Station IDs, coordinates, and screen depths are provided in Table 6. The purpose of the in-wall monitoring is to provide rapid evidence of the ZVI effectiveness in destroying VOCs. In addition, the geochemical analyses proposed for in-wall monitoring wells will allow for evaluation of the reactions occurring between the contaminated groundwater and ZVI on the ZVI-PRB longevity related to possible precipitation, mineralization, and biofouling. The upgradient and downgradient monitoring well clusters will be analyzed for VOCs to assess the overall reduction in VOC mass in the plume over time. Because the downgradient monitoring wells are located in contaminated aquifer sediments it may be many years before evidence of VOC reduction is observed. The in-wall monitoring wells will be sampled bi-monthly for the first 3-months, monthly for the second 3-months, and quarterly for the next 4.5-years. The wells within the ZVI-PRB area will be sampled quarterly for the entire 5-years. The one well cluster farthest from the ZVI-PRB will be sampled annually for the entire 5-years. Table 7 provides the preparation/analytical methods for each analyte. Table 8 and Figure 18 present the sampling frequency for each well and Table 8 indicates which analytes will be analyzed.

The effects of the PAGW OU ZVI-PRB will be reported annually in the ZVI-PRB Effectiveness Monitoring Report.

5.2 Contingency Plan Implementation Strategy

The ZVI-PRB installation is intended to target the portion of the TCE mass in the cVOC plume that migrates from the source area to the distal area, passing through the ZVI-PRB in the neck area. It may be expected that contaminant data from monitoring wells downgradient of the PRB will not demonstrate a stable clean front and will not adequately assess the ZVI-PRB performance for several years. In-wall monitoring will be the primary factor in assessing successful degradation of TCE concentrations in the ZVI-PRB. Due to the observed presence of significant TCE concentrations in the low permeability zones, diffusion from these zones may result in distal plume contamination despite the local effectiveness of the ZVI-PRB. This will be assessed in the future with long-term monitoring of the PAGW OU in conjunction with ZVI-PRB effectiveness monitoring.

A treatability study conducted as part of the design of the ZVI-PRB (see Section 2.4.4) indicated that the potential for precipitation resulting in significant loss of porosity is considered to be very low. However, if long-term monitoring indicates a decline in effectiveness of the ZVI-PRB due to precipitation and/or or clogging of the iron, a treatment method may be implemented via the injection wells that will remain in place after construction.

It is anticipated that this removal action will become a component of the final remedial decision that will address the entire PAGW OU in the PAGW OU Record of Decision (ROD).

5.3 Operations, Maintenance, and Land Use Control

The ZVI injections for the ZVI-PRB installation constitutes a single event. No infrastructure remains for operation or maintenance, with the exception of monitoring wells. The monitoring wells will be maintained so that sampling can be conducted to evaluate the effectiveness of the NTC removal action.

There is no current or projected future use of groundwater or surface water as a drinking water source at the PAGW OU, and site access is currently controlled by SRS facility security and administrative controls. Site specific land use controls are expected to be part of the final remedial action for the PAGW OU.

5.4 Requirements for Project Closeout

The ZVI-PRB installed for this removal action in the PAGW OU is a permanent treatment technology with an anticipated life expectancy of at least 25 years. The annual effectiveness monitoring reports for the PAGW OU NTC removal action will continue until the PAGW OU Corrective Measures Implementation/Remedial Action Implementation Plan has been issued. The reporting frequency will be evaluated with the core team after 5 years of annual reporting. The monitoring reports will evaluate the overall effectiveness of the NTC removal action in reducing the TCE mass in the UAZ, and its sustainability. Any potential future actions would be addressed by the USDOE, USEPA, and SCDHEC as part of the final remedial decision process.

5.5 Schedule for Federal Facility Agreement Deliverables

The remaining Federal Facility Agreement deliverables associated with this action will be a RAR and annual Effectiveness Monitoring Reports. The RAR will be submitted 120 days after construction completion of the ZVI-PRB and monitoring wells. The first PAGW OU Annual Groundwater and ZVI-PRB Effectiveness Monitoring Report will be submitted 18 months after installation of all defined monitoring wells as listed in Table 6, to allow for one year of monitoring, lab analysis and reporting, and data interpretation.

6.0 REFERENCES

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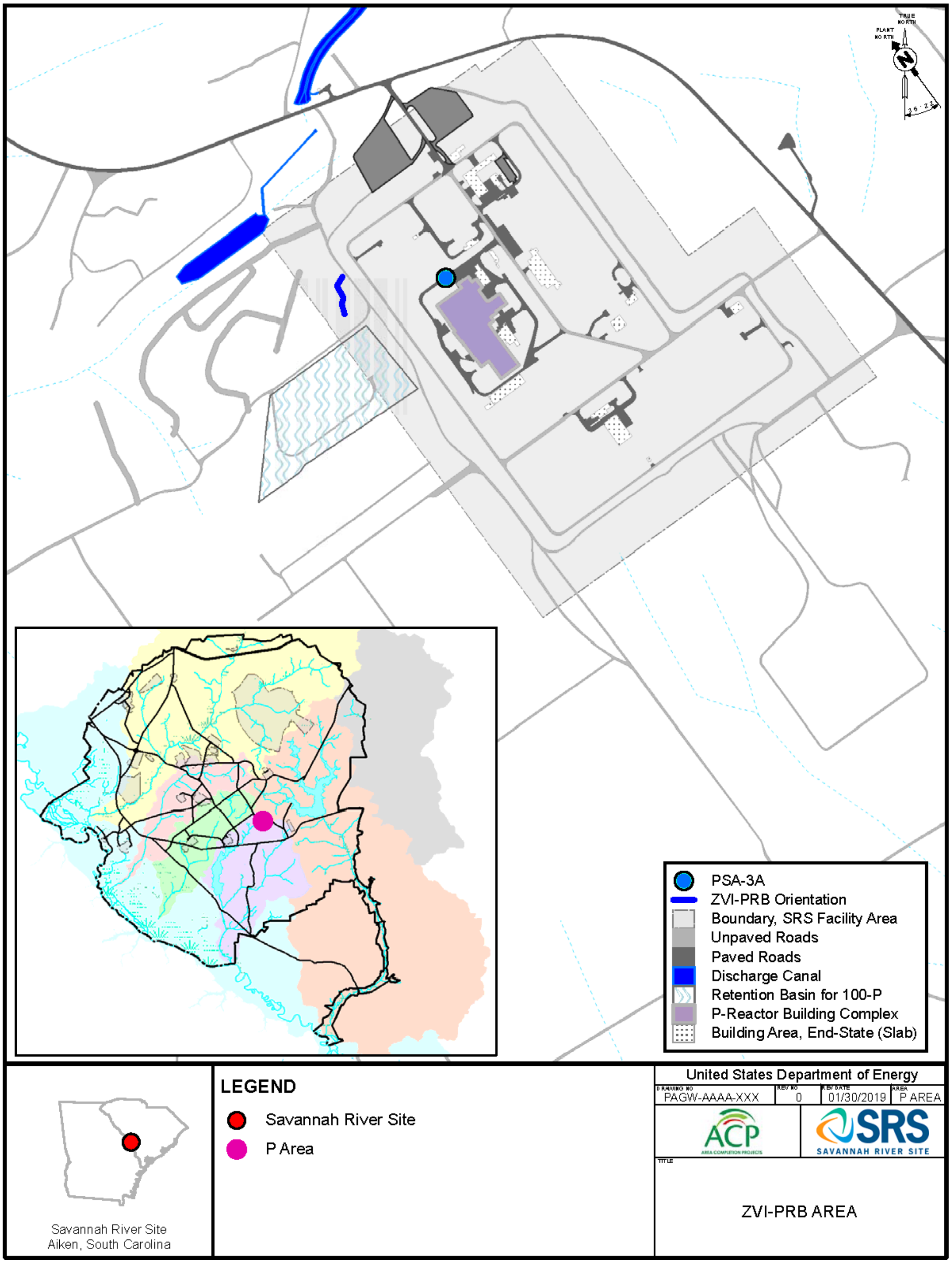

Figure 1. ZVI-PRB Area

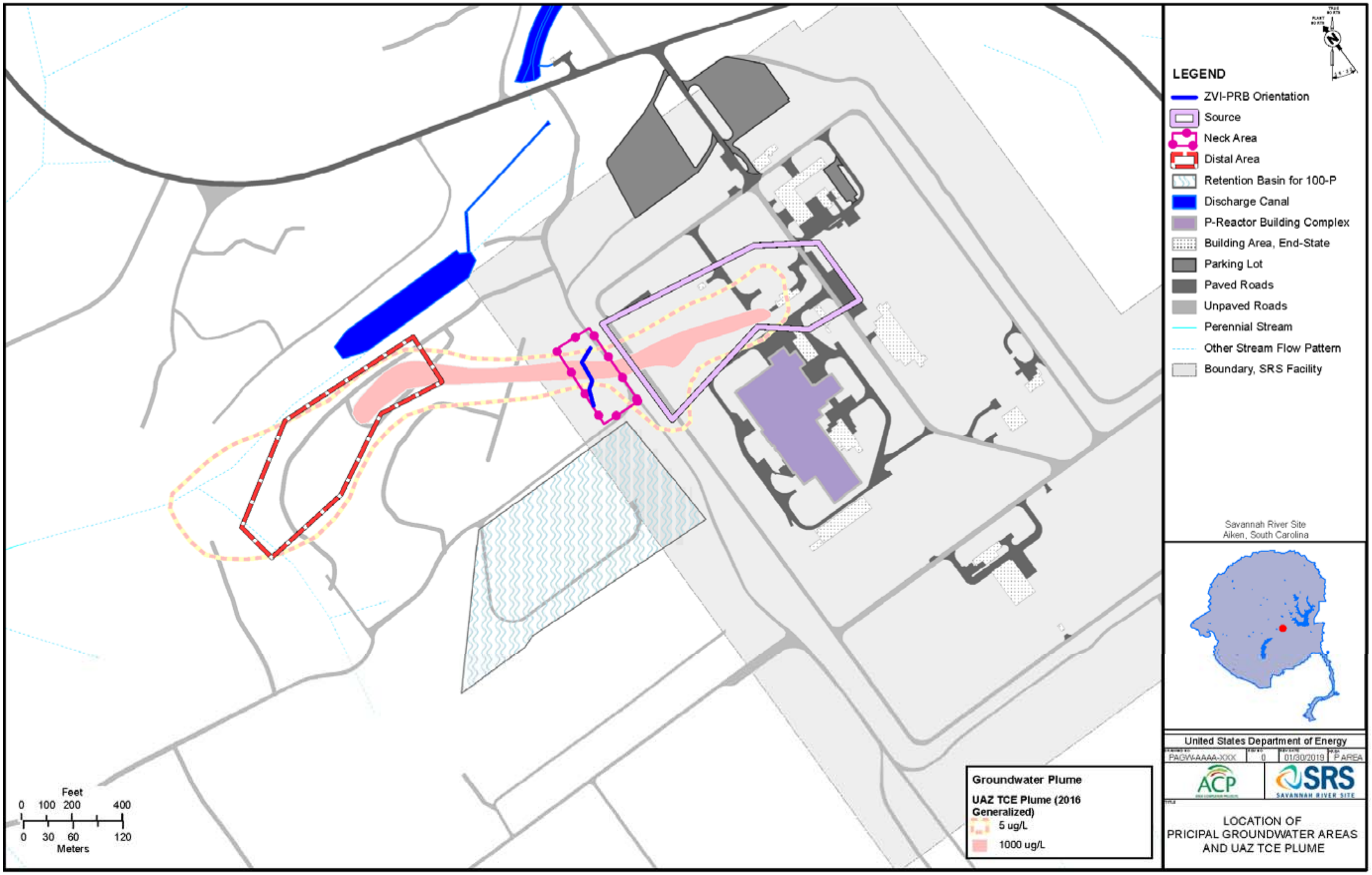

Figure 2. Location of Principal Groundwater Areas and UAZ TCE Plume

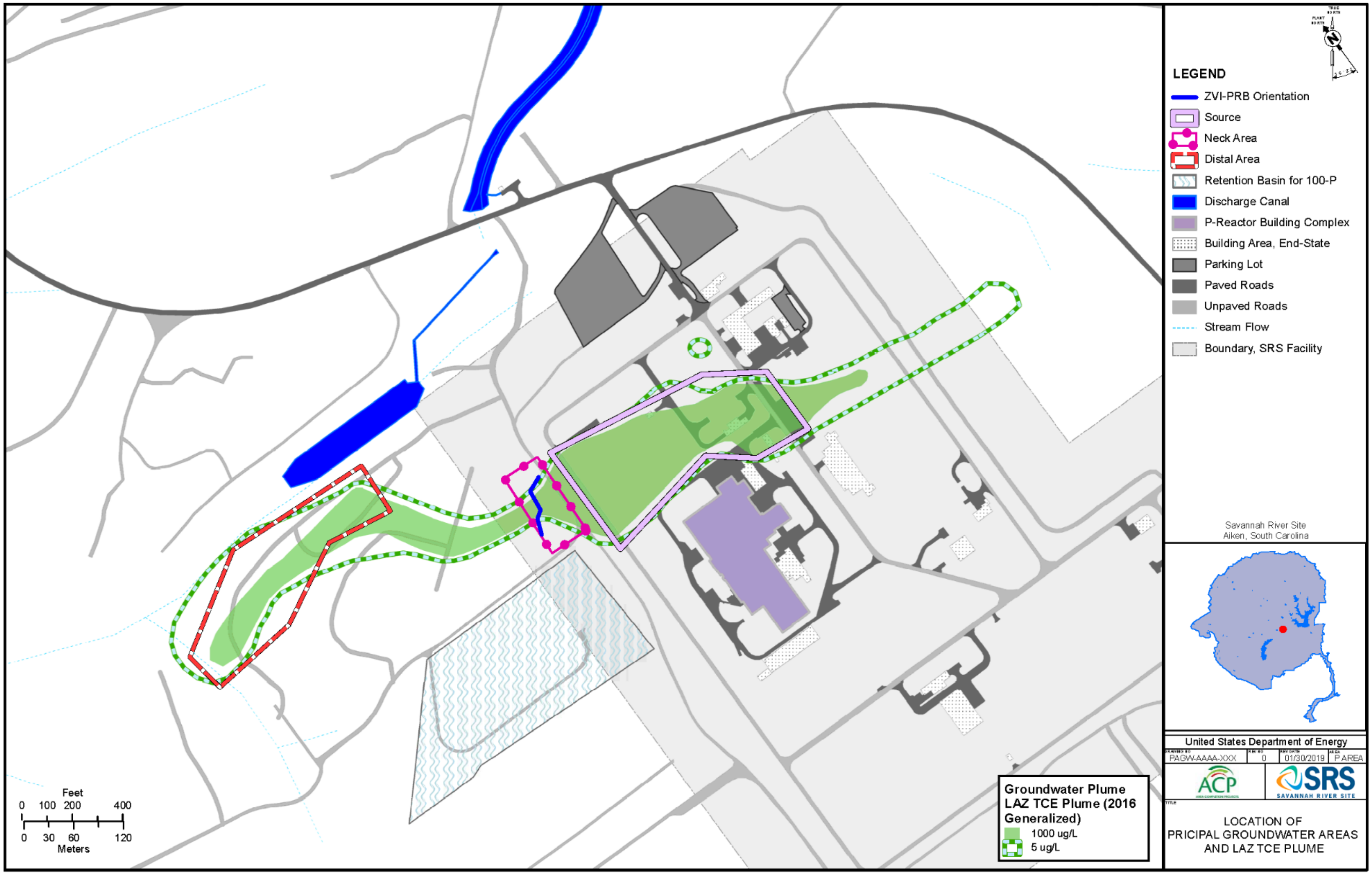

Figure 3. Location of Principal Groundwater Areas and LAZ TCE Plume

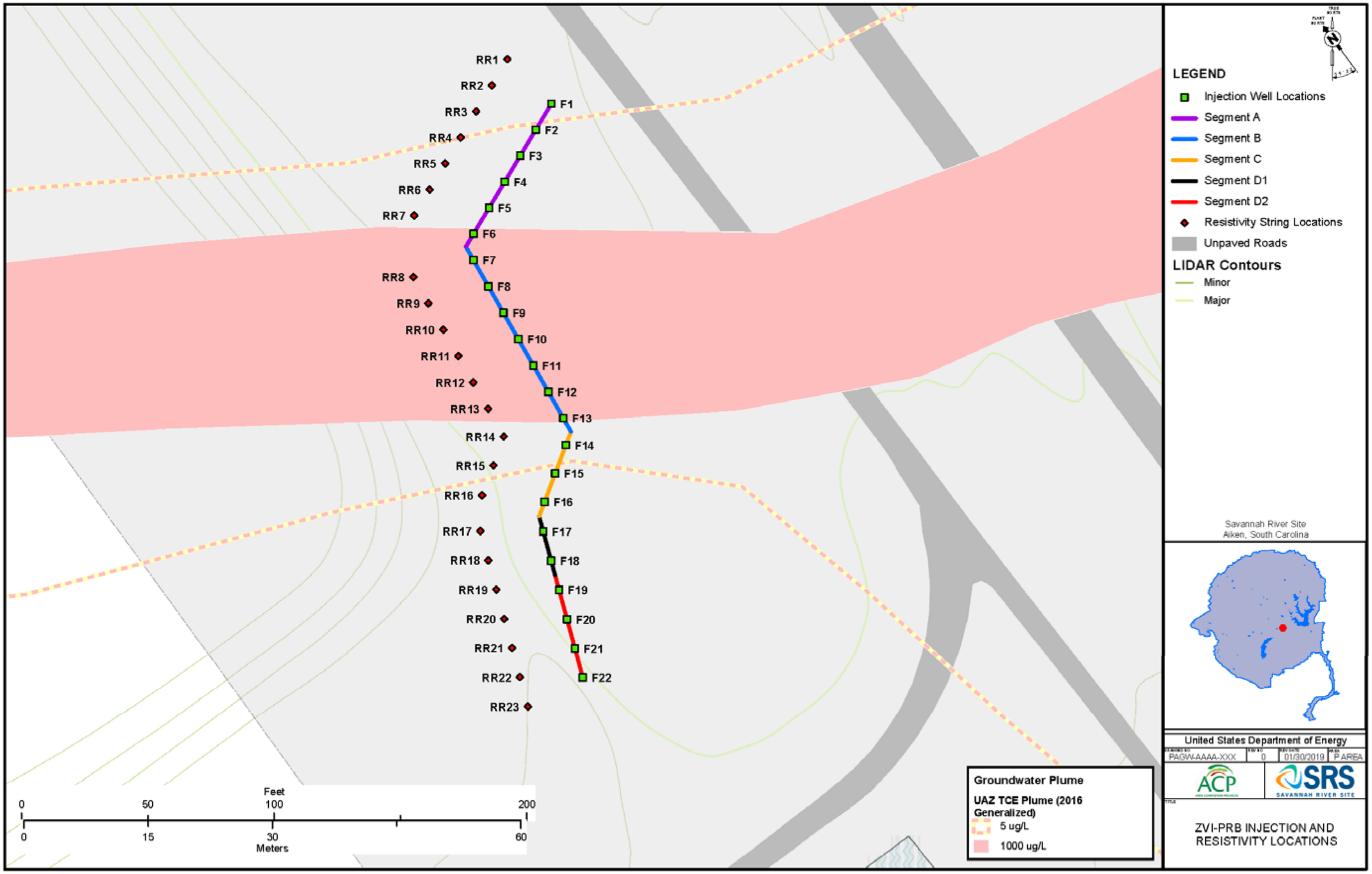

Figure 4. ZVI-PRB Injection and Resistivity Locations

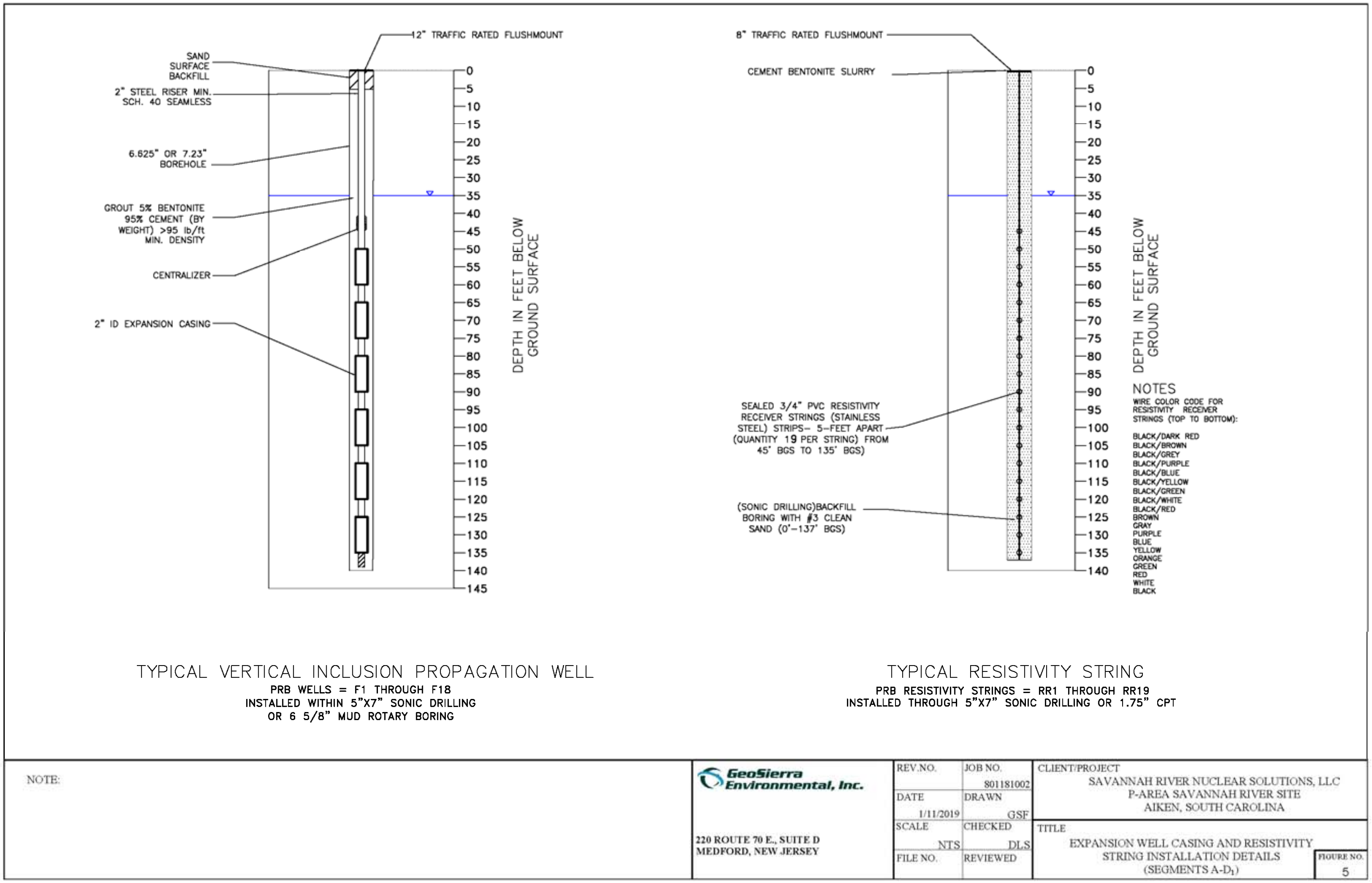

Figure 5. Expansion Well Casing and Resistivity String Installation Details (Segments A-D_1)

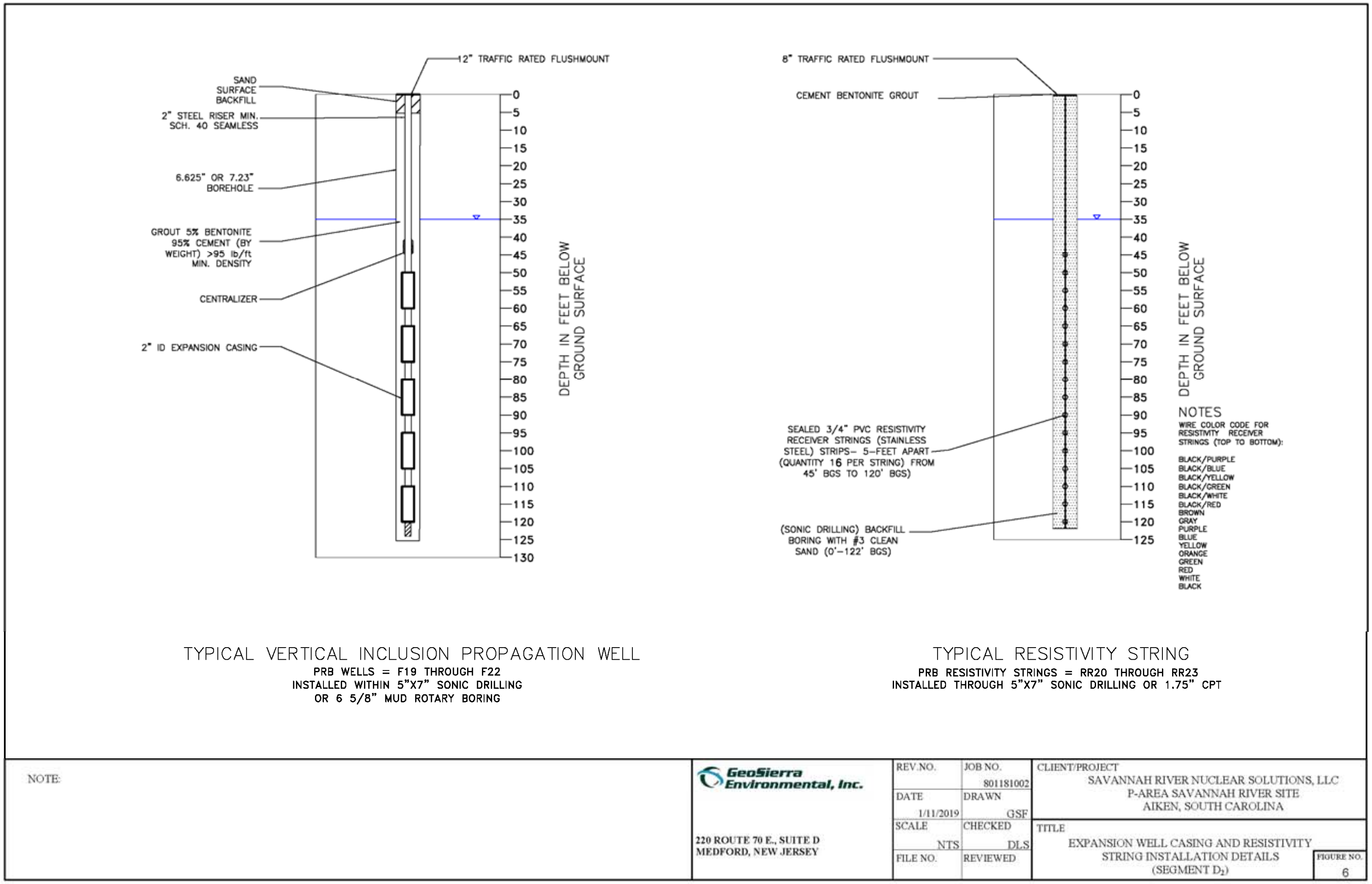

Figure 6. Expansion Well Casing and Resistivity String Installation Details (Segment D_2)

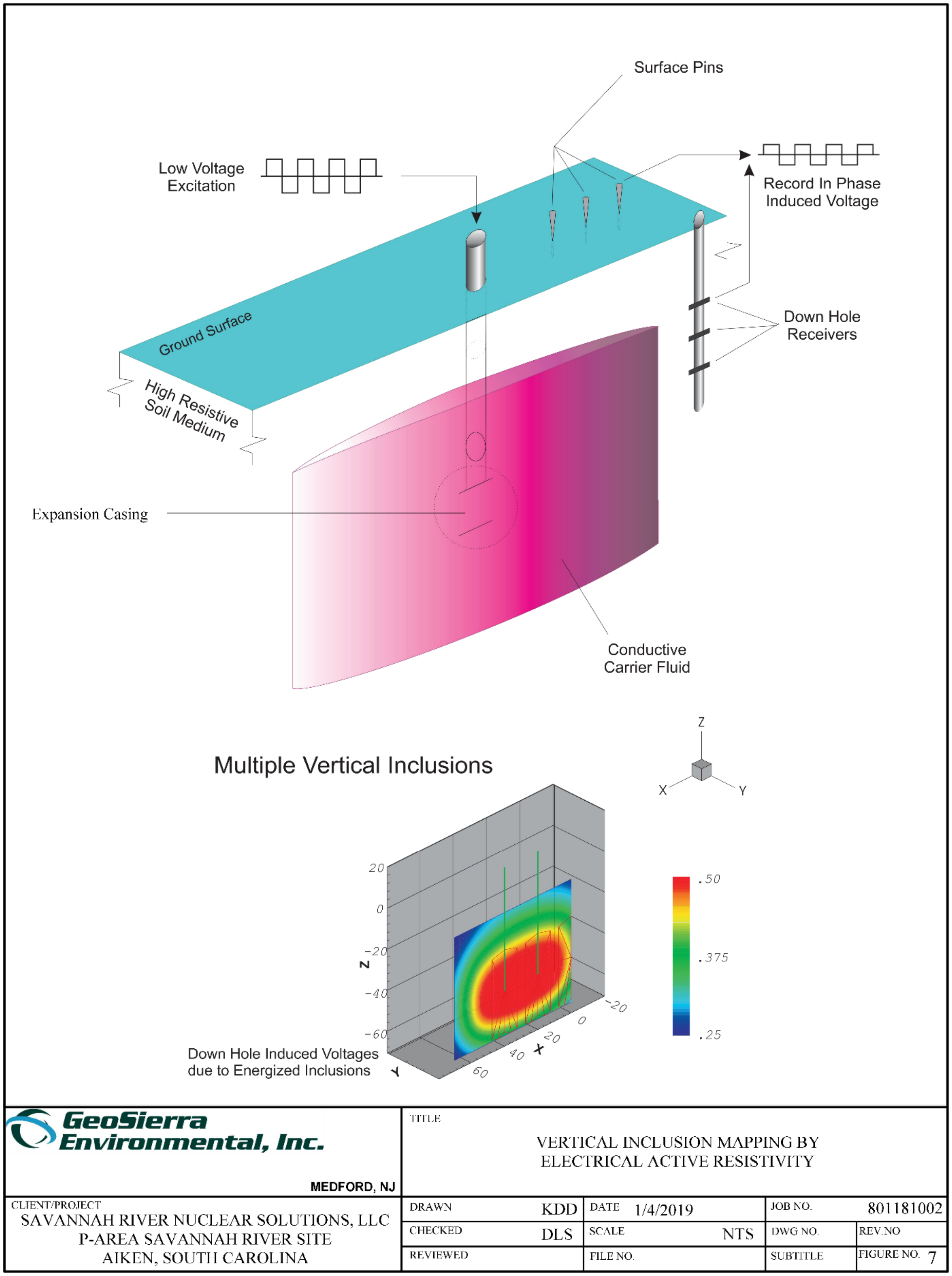

Figure 7. Vertical Inclusion Mapping by Electrical Active Resistivity

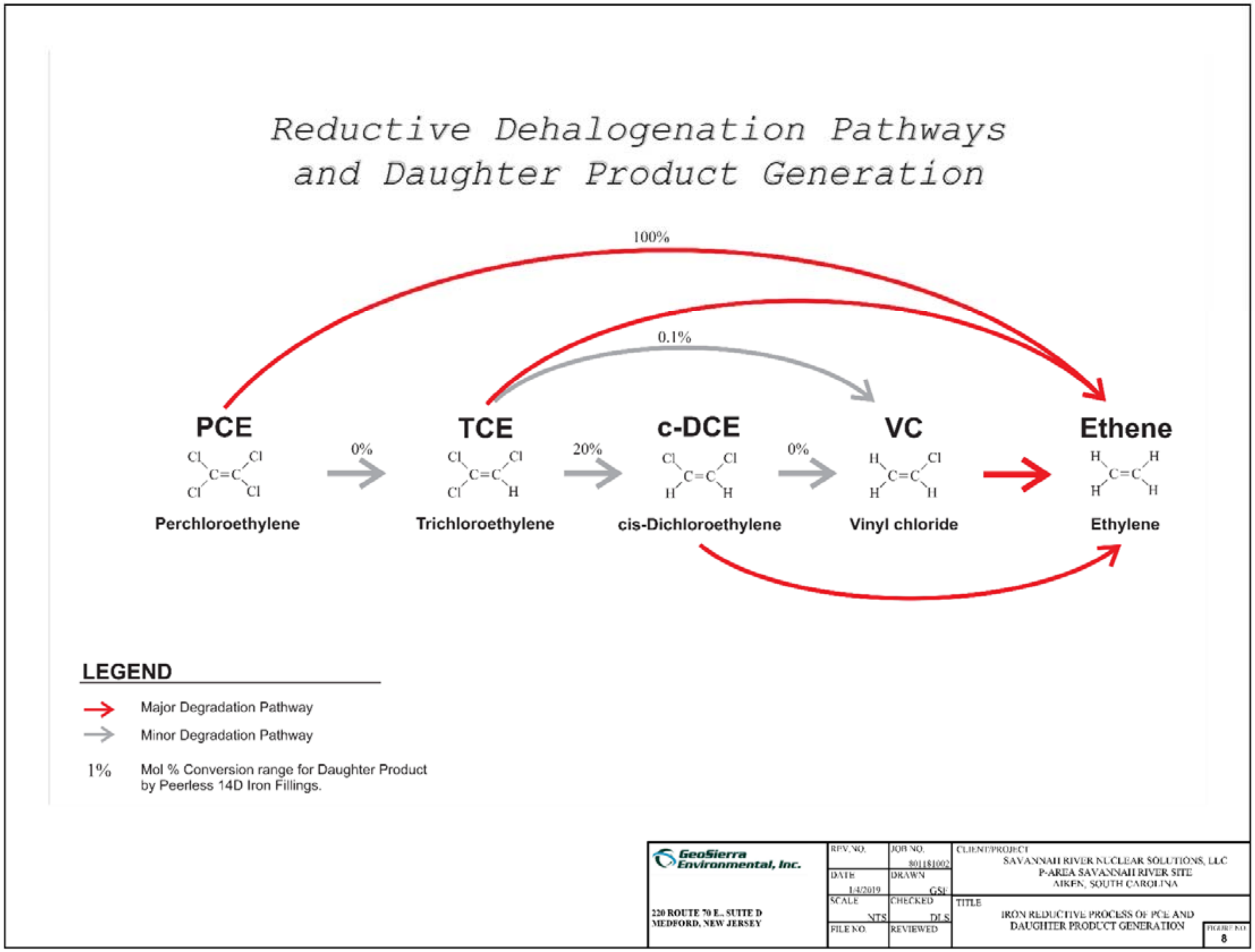

Figure 8. Iron Reductive Process of PCE and Daughter Product Generation

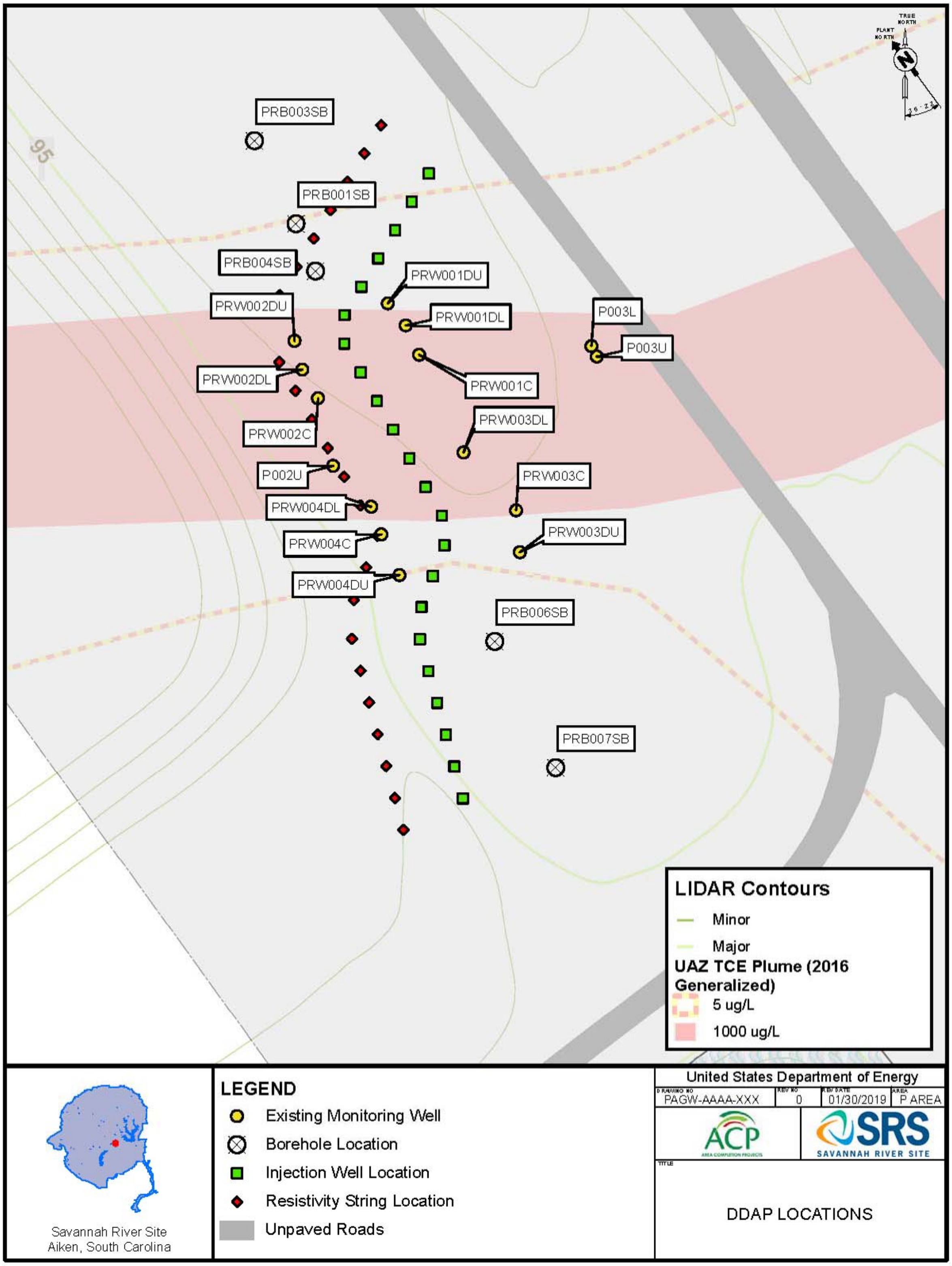

Figure 9. Design Data Acquisition Plan Locations

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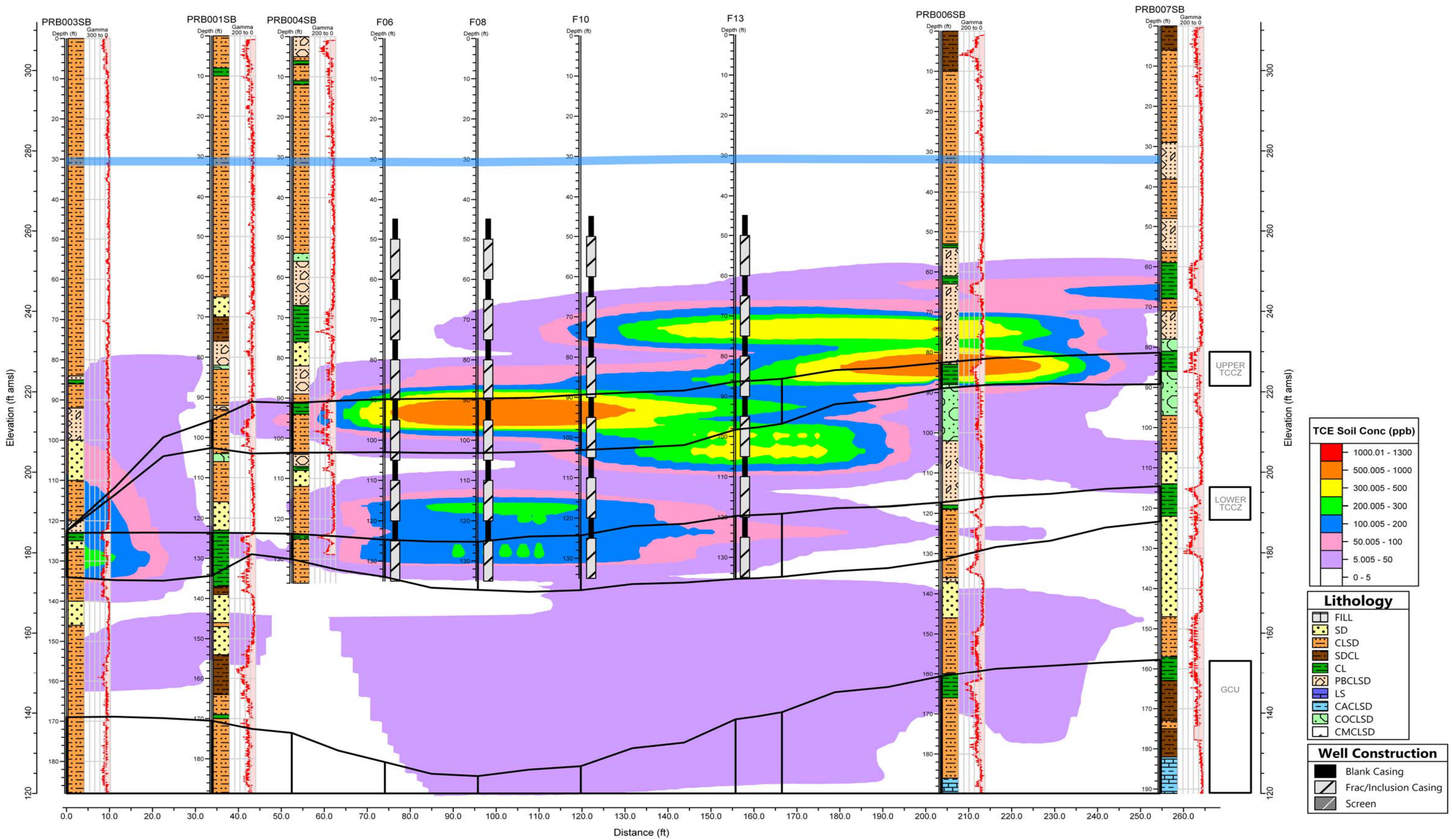

Figure 10. TCE Plume Cross-Section Perpendicular to Groundwater Flow Direction

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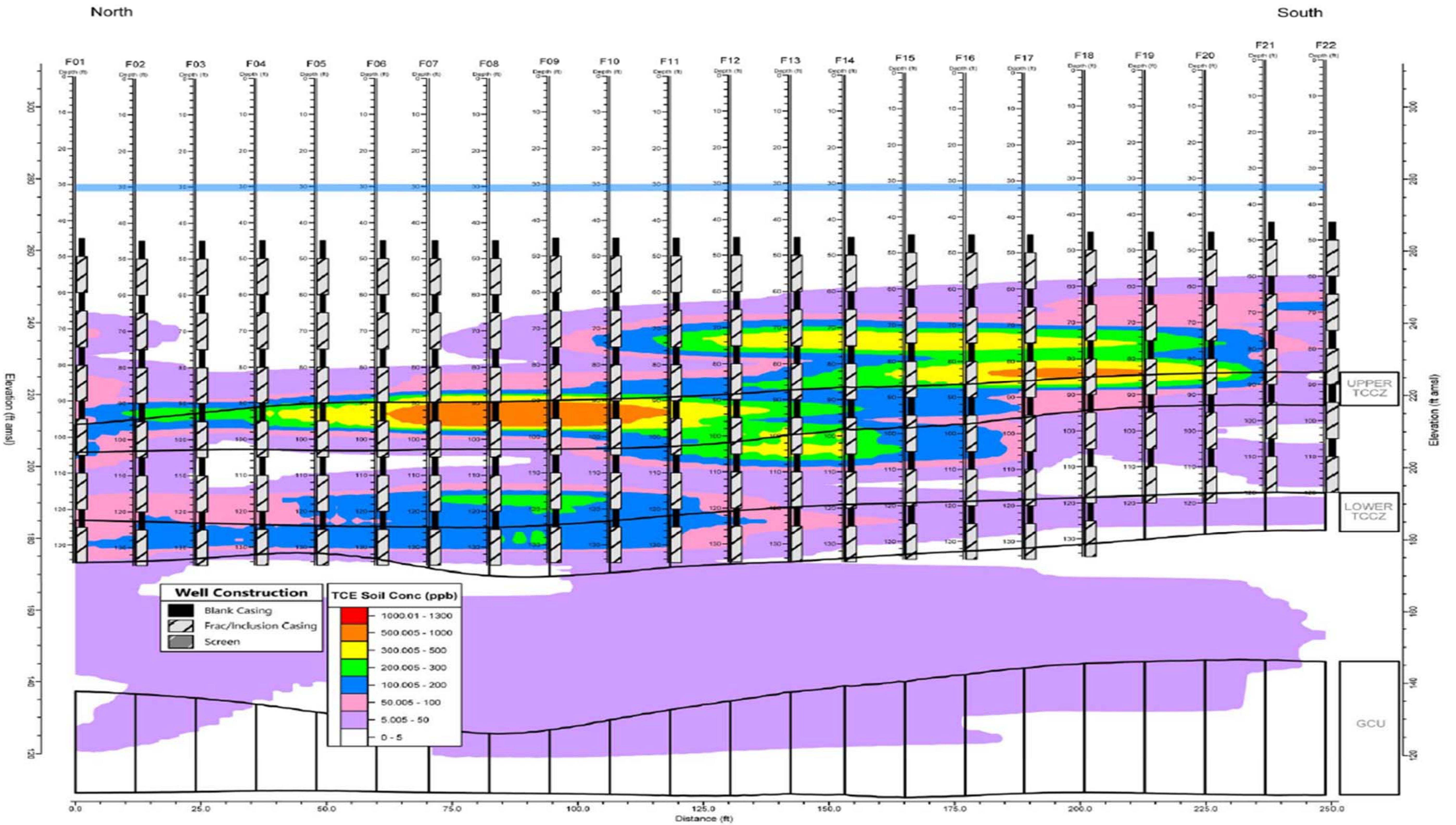

Figure 11. TCE Plume Cross-Section with ZVI-PRB Injection Wells

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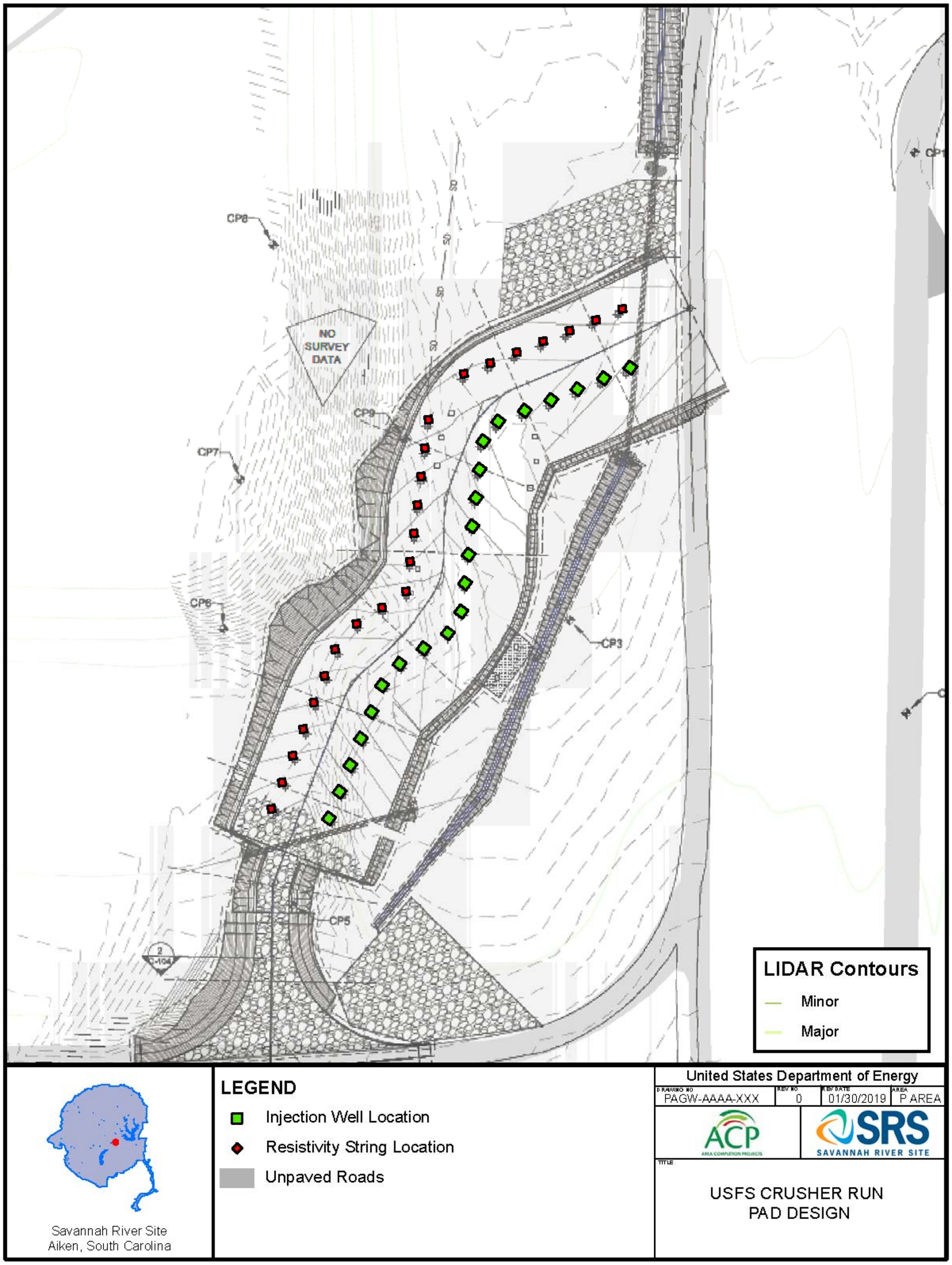

Figure 12. USFS Crusher Run Pad Design

Figure 13. Preparing Expansion Casing System for Installation

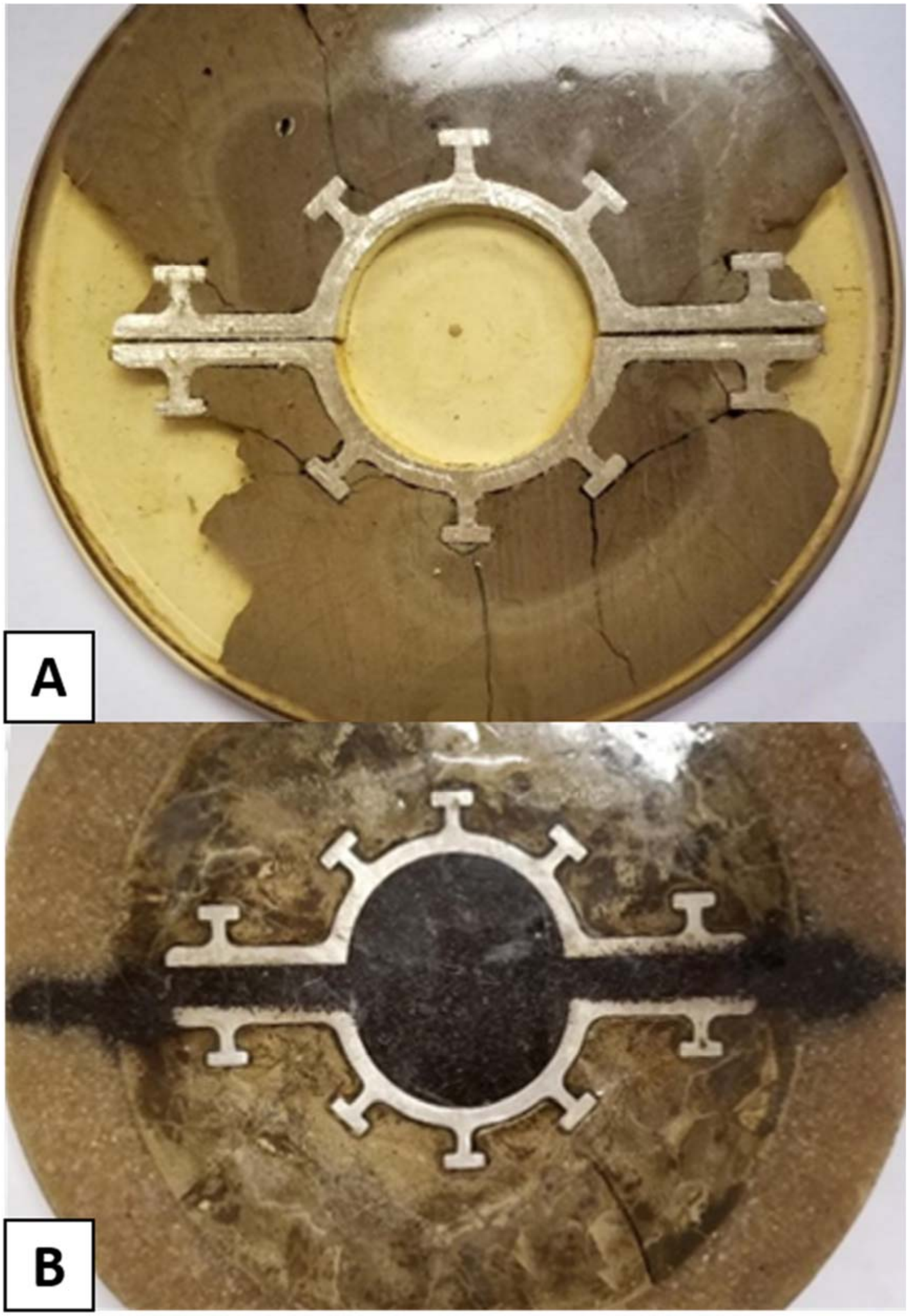

Figure 14. Demonstration of Expansion Casing Pressure Induced Fracture

Figure 15. Demonstration of Fracture Along Alignment of PRB

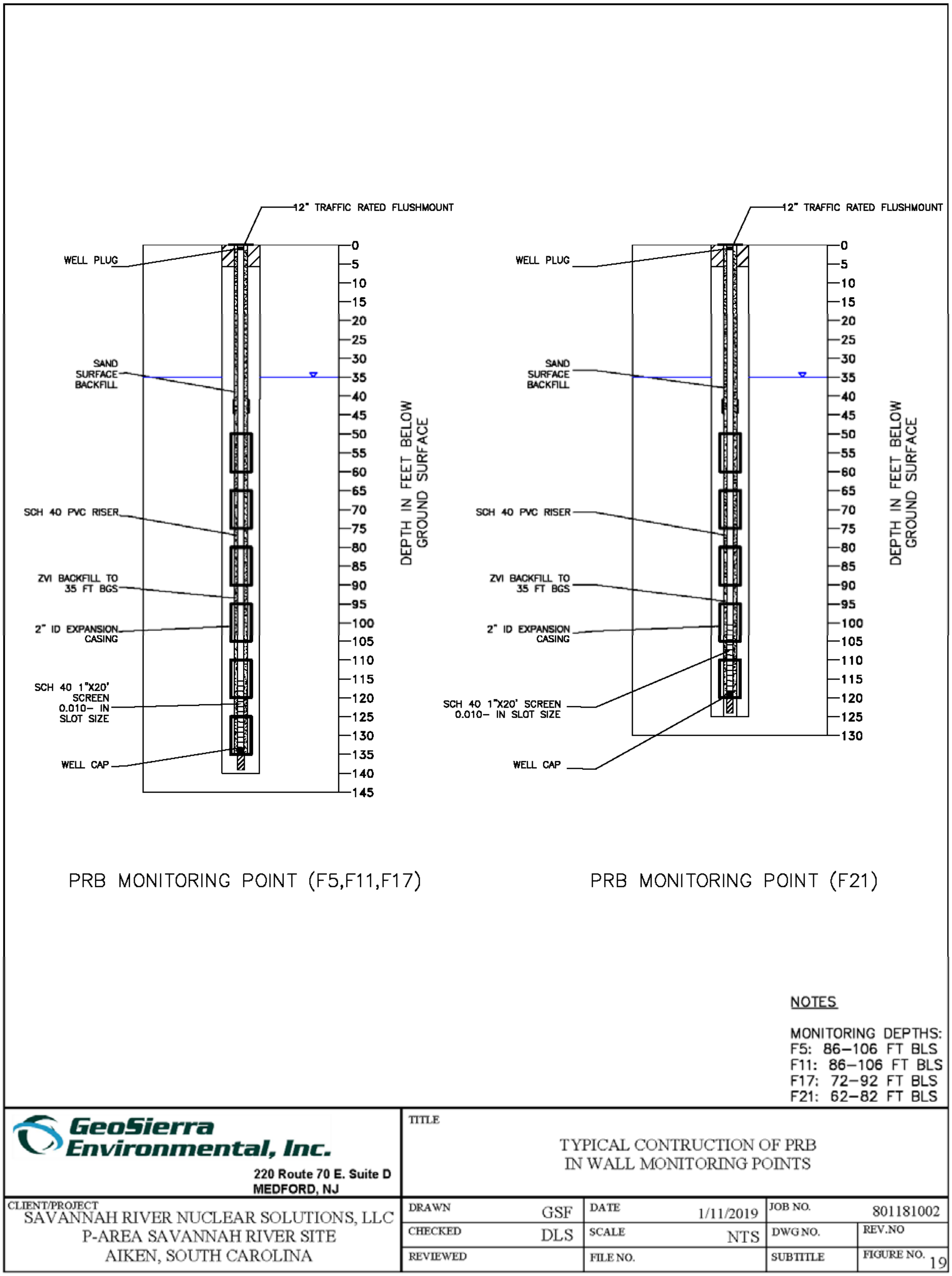

Figure 16. Typical Construction of PRB In Wall Monitoring Points

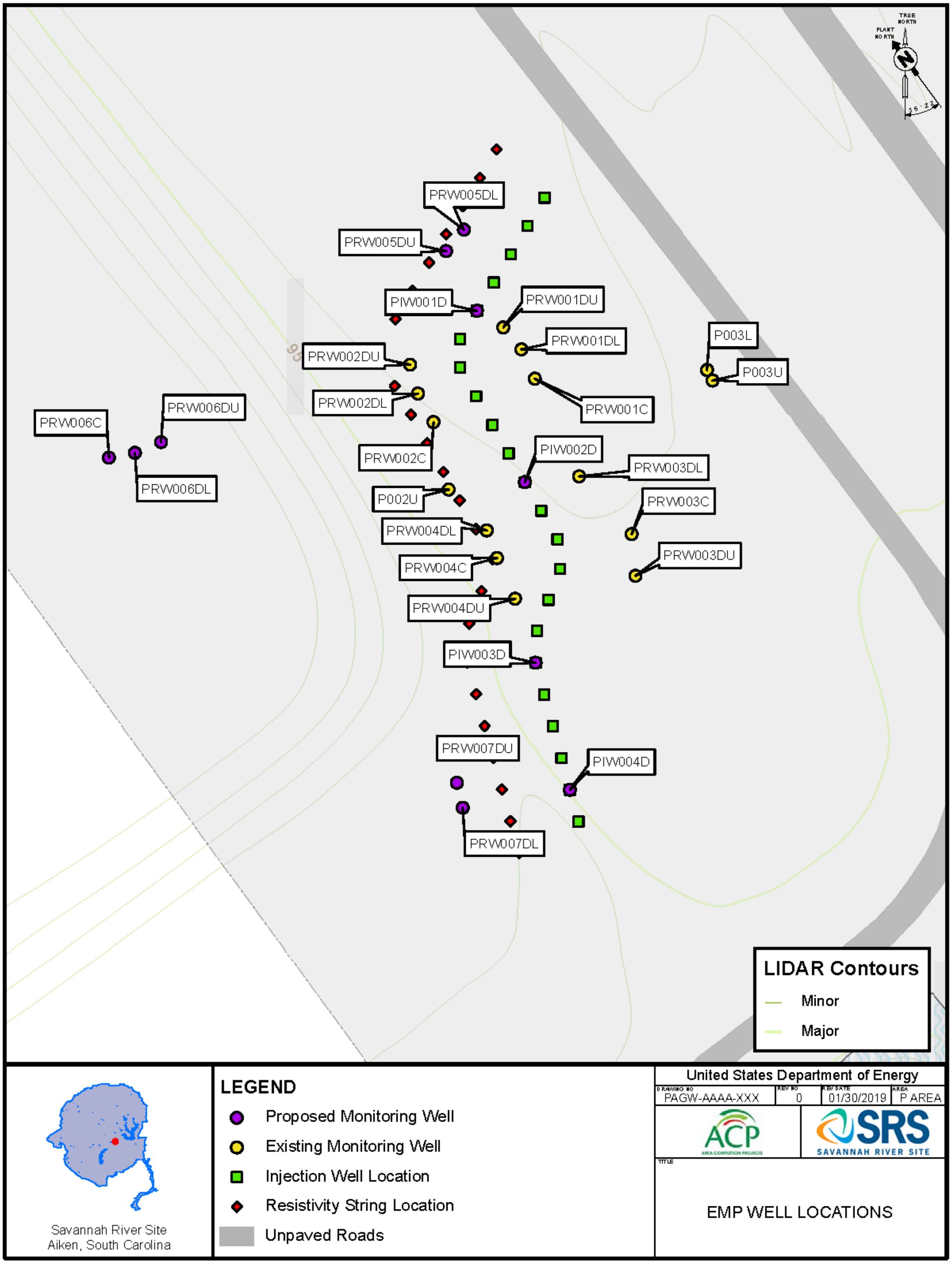

Figure 17. EMP Well Locations

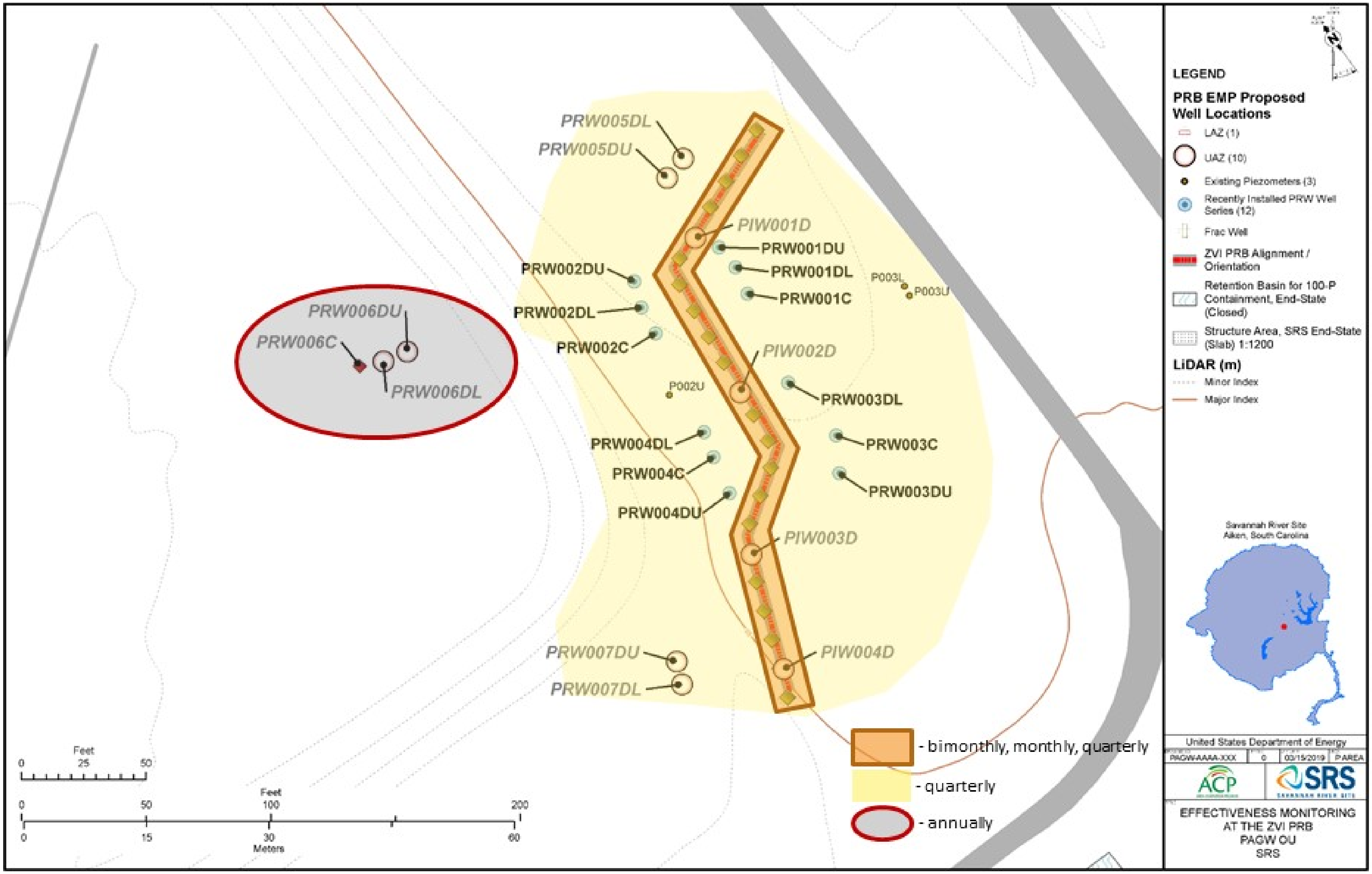

Figure 18. Effectiveness Monitoring at the ZVI-PRB

Table 1. Maximum Concentrations of TCE, PCE, and cis-DCE in the Three Areas of Interest

Contaminant	MCL[1] (μg/L)	Maximum Concentration in UAZ (μg/L)			Maximum Concentration in LAZ (μg/L)		
		Source Area	Neck Area	Distal Area	Source Area	Neck Area	Distal Area
TCE	5	3,140	4,120	7,440	7,710	1,500	7,600
PCE	5	260	50	25	100	<MDL[2]	2.09
cis-DCE	70	4,720	107	432	104	400	200

[1] MCL – maximum contaminant level
[2] MDL – minimum detection limit

Table 2. ZVI-PRB Segment Details

ZVI-PRB Segment	Number of Wells	Segment Length (LF)[1]	Injection Interval (ft bgs)[2]	Number of Expansion Casings
A	6	72	45 - 135	6
B	7	84	45 - 135	6
C	3	36	45 - 135	6
D_1	2	24	45 - 135	6
D_2	4	48	45 - 120	5

[1] LF – linear feet
[2] ft bgs – feet below ground surface

Table 3. Hydraulic Conductivity Values

HISTORICAL DATA

Well Location	Depth Interval (ft bgs)	K (cm/sec)	K (ft/day)	Groundwater Flow Velocity* (ft/day)	Source
POS001	47-99	1.50E-02	42.39	1.48	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 2, Saturated Zone Data)
POS002	55-117	2.61E-02	73.86	2.59	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 2, Saturated Zone Data)
POS003	51-117	2.16E-02	61.18	2.14	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 2, Saturated Zone Data)

SLUG TESTING DATA

Well Location	Depth (ft bgs)	K (cm/sec)	K (ft/day)	Groundwater Flow Velocity* (ft/day)	Source
POS001	66.42	3.95E-04	1.12	0.04	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS001	79.42	6.00E-05	0.17	0.01	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS003	64	6.56E-04	1.86	0.07	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS003	74	1.48E-03	4.20	0.15	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS003	89	6.24E-04	1.77	0.06	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)

SIEVE ANALYSIS

Well Location	Depth (ft bgs)	K (cm/sec)	K (ft/day)	Groundwater Flow Velocity* (ft/day)	Source
POS002	55	3.30E-02	93.52	3.27	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS002	87	5.08E-02	143.90	5.04	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS002	104	2.30E-07	0.0007	0.00002	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS002	117	2.05E-02	58.01	2.03	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS002	137.5	2.15E-03	6.10	0.21	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)
POS002	148.5	5.96E-02	168.84	5.91	SRNS, 2018 (Q-SOW-P-00013, Rev 2, Table 1)

HPIT DATA

Well Location	Well Screen (ft bgs)	Average K (cm/sec)	*Average K (ft/day)	Groundwater Flow Velocity* (ft/day)	Source
1DU/2DU	80-90	No Data	No Data	No Data	GeoSierra, March 2019 (ZVI-PRB Design Report)
1DL/2DL	107-117	7.15E-03	20.27	0.71	GeoSierra, March 2019 (ZVI-PRB Design Report)
3DU/4DU	65-75	1.06E-03	3.01	0.11	GeoSierra, March 2019 (ZVI-PRB Design Report)
3DL/4DL	112-122	1.20E-03	3.39	0.12	GeoSierra, March 2019 (ZVI-PRB Design Report)
2DU/1DU	82-92	2.06E-02	58.27	2.04	GeoSierra, March 2019 (ZVI-PRB Design Report)
2DL/1DL	110-120	3.13E-02	88.85	3.11	GeoSierra, March 2019 (ZVI-PRB Design Report)

Note: 0.007 ft/ft gradient and 20% porosity were used to calculate groundwater flow velocity

Note: *Average K values are an average of all reproduceable data which can be referenced in Table B-1

ft bgs : feet below ground surface
cm/sec : centimeters per second
ft/day : feet per day
K : hydraulic conductivity
HPIT : hydraulic pulse interference testing

Table 4. cVOC Degradation Half-Lives and Iron Properties

	Peerless Iron Filings
Hydraulic Conductivity (cm/sec)	6.47E-02
Porosity	0.47 - 0.59
Grain Size Distribution(1)	-12/+200
Grain Size Distribution(2)	-8/+100
D15 (mm)	0.2
D50 (mm)	0.43
D85 (mm)	0.85
Anticipated Field Design Half Lives ($t_{0.5}$)(3)	
PCE (hr)	1.35
TCE (hr)	0.87
cis-1,2-DCE (hr)	0.98
Vinyl Chloride (hr)(4)	1.19

Notes:
1) Grain size and permeability data from previous laboratory tests (Peerless 14D)
2) Grain size for PRB installation (Peerless 14D and 850)
3) The field half life values are based on the 2.1 ft/day laboratory column test half life values at ambient groundwater temperatures for Peerless iron.
4) The field half life values based on previous treatability studies.

Table 5. Iron PRB Carrier Fluid Composition

Material Description	Product per gallon of water	Product per liter of water
Zero Valent Iron	8-10 lbs	3.6-4.5 Kg
Gel (Hydroxypropyl Guar)	0.05-0.06 lbs	6.0-7.2 g
Acetic Acid	0.001-0.002 lbs	0.12-0.24 g
Gel Cross Linker	0.046-0.065 lbs	5.56-8.64 g
Gel Enzyme Breaker	0.001-0.002 lbs	0.13-0.24 g
Sodium Chloride	0.02-0.03 lbs	2.4-3.6 g

NOTE:
1) Mixture and quantities will depend on water mixing temperature, groundwater temperature and specified time for gel to biodegrade.
2) Approximately 760 tons of zero valent iron to be used to construct the subsurface iron PRB. Additional ZVI will be procured to account for loss (i.e. delivery/washout).
3) Mix identified is the anticipated mix design used in the previous PRB installations. The exact carrier fluid composition may vary slightly depending on site conditions.
4) Quantities have been normalized based on a 3,000 gallon batch of gel

Table 6. Effectiveness Monitoring Plan Well Details

Station ID	Location	Long-DMS[1] (NAD27)	Lat-DMS[2] (NAD27)	Screen Interval *(ft bgs)*[3]
PRW-001C*	Upgradient	-81°35'1.82"	33°13'44.13"	146 - 156
PRW-001DL*	Upgradient	-81°35'1.88"	33°13'44.24"	109.67 - 119.67
PRW-001DU*	Upgradient	-81°35'1.96"	33°13'44.32"	81.64 - 91.64
PRW-002C*	Downgradient	-81°35'2.26"	33°13'43.98"	148.06 - 158.06
PRW-002DL*	Downgradient	-81°35'2.32"	33°13'44.08"	107.21 - 117.21
PRW-002DU*	Downgradient	-81°35'2.36"	33°13'44.18"	80.66 - 90.66
PRW-003C*	Upgradient	-81°35'1.40"	33°13'43.58"	136.58 - 146.58
PRW-003DL*	Upgradient	-81°35'1.63"	33°13'43.78"	94.85 - 104.85
PRW-003DU*	Upgradient	-81°35'1.38"	33°13'43.42"	61.82 - 71.82
PRW-004C*	Downgradient	-81°35'1.98"	33°13'43.49"	144.38 - 154.38
PRW-004DL*	Downgradient	-81°35'2.02"	33°13'43.59"	111.45 - 121.45
PRW-004DU*	Downgradient	-81°35'1.90"	33°13'43.34"	64.91 - 74.91
P002U*	Downgradient	-81°35'2.19"	33°13'43.73"	87.5 - 92.5
P003U*	Upgradient	-81°35'1.06"	33°13'44.13"	84.3 - 89.3
P003L*	Upgradient	-81°35'1.08"	33°13'44.17"	113.6 - 118.6
PRW-005DL	Downgradient	-81°35'2.13"	33°13'44.67"	108 - 118
PRW-005DU	Downgradient	-81°35'2.20"	33°13'44.59"	86 - 96
PRW-006C	Downgradient	-81°35'3.65"	33°13'43.84"	160 - 170
PRW-006DL	Downgradient	-81°35'3.54"	33°13'43.86"	120 - 130
PRW-006DU	Downgradient	-81°35'3.43"	33°13'43.90"	90 - 100
PRW-007DL	Downgradient	-81°35'2.12"	33°13'42.59"	100 - 110
PRW-007DU	Downgradient	-81°35'2.15"	33°13'42.68"	65 - 75
PIW001D	In-Wall	-81°35'2.06"	33°13'44.39"	90 - 110
PIW002D	In-Wall	-81°35'1.85"	33°13'43.77"	85 - 105
PIW003D	In-Wall	-81°35'1.80"	33°13'43.13"	70 - 90
PIW004D	In-Wall	-81°35'1.64"	33°13'42.67"	60 - 80

[1] Long-DMS – longitude in degrees minutes seconds
[2] Lat-DMS – latitude in degrees minutes seconds
[3] ft bgs – feet below ground surface
[*] Existing monitoring wells

Table 7. Analytical Specifications Table for Lab Analyses

Analyte	Analyte ID	Preparation Method[A]	Analytical Method[A]	CRDL (μg/L)[B]
Volatile Organic Compounds (VOC)				
1,1-Dichloroethylene (DCE)	75-35-4	5021A,5030C,5031,5032	EPA8260B	1
Chloroethene (Vinyl chloride [VC])	75-01-4	5021A,5030C,5031,5032	EPA8260B	2
cis-1,2-Dichloroethylene (cis-DCE)	156-59-2	5021A,5030C,5031,5032	EPA8260B	1
Tetrachloroethylene (PCE)	127-18-4	5021A,5030C,5031,5032	EPA8260B	1
trans-1,2-Dichloroethylene (trans-DCE)	156-60-5	5021A,5030C,5031,5032	EPA8260B	1
Trichloroethylene (TCE)	79-01-6	5021A,5030C,5031,5032	EPA8260B	1
Geochemical Analyses				
Dissolved Organic Carbon (DOC)	744-44-0[C]			
Ethane	74-84-0			
Ethylene	74-85-1			
Methane	74-82-8	PM01G	AM20GAX	1
Total Organic Carbon (TOC)	744-44-0[C]	EPA9060A/SMS5310C	EPA9060A/SMS5310C	1,000
Alkalinity	CASID10001			
Calcium	7440-70-2			
Chloride	16887-00-6			
Fe^{3+}	20074-52-6			
Fe^{2+}	15438-31-0			
Iron	7439-89-6			
Magnesium	7439-95-4			
Manganese	7439-96-5			
Nitrate-Nitrite as Nitrogen	See Note C	EPA353.1/EPA353.2	EPA353.1/EPA353.2	500
Phosphate	CASID10247			
Potassium	7440-09-7			
Sodium	7440-23-5			
Sulfate	14808-79-8	EPA9056A	EPA9056A	1,000
Sulfide	18496-25-8			
Total Dissolved Solids (TDS)	CASID10052			

[A] Extraction and preparation methods differ depending upon media, concentration, instrument, laboratory, and analytical method. Preparation methods will also influence detection limits.
[B] CRDL – contract required detection limit.
[C] CAS# for carbon.
[D] Nitrate (NO_3^-) CAS# – 14797-55-8; Nitrite (NO_2^-) CAS# – 14797-65-0.

Table 8. Sampling Frequency and Analytes for EMP Monitoring Well Stations

Station ID	Location	Baseline Analytes 1Q2019	EMP Analytes	Sampling Frequency
PRW001C	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW001DL	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW001DU	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW002C	Downgradient	1,2	1	Quarterly for years 1 – 5
PRW002DL	Downgradient	1,2	1	Quarterly for years 1 – 5
PRW002DU	Downgradient	1,2	1	Quarterly for years 1 – 5
PRW003C	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW003DL	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW003DU	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW004C	Downgradient	1,2	1	Quarterly for years 1 – 5
PRW004DL	Downgradient	1,2	1	Quarterly for years 1 – 5
PRW004DU	Downgradient	1,2	1	Quarterly for years 1 – 5
P002U	Downgradient	1,2	1	Quarterly for years 1 – 5
P003U	Upgradient	1,2	1	Quarterly for years 1 – 5
P003L	Upgradient	1,2	1	Quarterly for years 1 – 5
PRW005DL	Downgradient	-	1	Quarterly for years 1 – 5
PRW005DU	Downgradient	-	1	Quarterly for years 1 – 5
PRW006C	Downgradient	-	1	Annually for years 1 – 5
PRW006DL	Downgradient	-	1	Annually for years 1 – 5
PRW006DU	Downgradient	-	1	Annually for years 1 – 5
PRW007DL	Downgradient	-	1	Quarterly for years 1 – 5
PRW007DU	Downgradient	-	1	Quarterly for years 1 – 5
PIW001D	In-Wall	-	1,2	Bimonthly for months 1 – 3 Monthly for months 4 – 6 Quarterly for month 7 – year 5
PIW002D	In-Wall	-	1,2	Bimonthly for months 1 – 3 Monthly for months 4 – 6 Quarterly for month 7 – year 5
PIW003D	In-Wall	-	1,2	Bimonthly for months 1 – 3 Monthly for months 4 – 6 Quarterly for month 7 – year 5
PIW004D	In-Wall	-	1,2	Bimonthly for months 1 – 3 Monthly for months 4 – 6 Quarterly for month 7 – year 5

1 – VOCs: PCE, TCE, cis-DCE, trans-DCE, VC, DCE

2 – Geochemical Analyses: TOC, alkalinity, chloride, nitrate-nitrite as nitrogen, sulfate, methane, ethane, ethylene, phosphate, calcium, iron, potassium, manganese, magnesium, sodium, DOC, Fe^{3+}, Fe^{2+}, TDS, sulfide