Full-Scale Controlled Multi Azimuth Vertical Hydraulic Fracturing for ISCR and Permeability Enhancement

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TECHNOLOGY DEVELOPMENT

Controlled Vertical Hydraulic Fracturing (VHF) has been utilized extensively during construction of Trenchless Permeable Reactive Barriers (PRBs) throughout the United States for the last twenty (20) years. With over 10,000 tons of zero valent iron (ZVI) injected to construct miles of PRBs in variable lithologic environments nationwide, the single azimuth VHF technology has proven to be an effective method for constructing PRBs from 3-inch to 9-inches in thickness as deep as 150-feet below ground surface (bgs).

Although the concept was tested in the mid-2000s, development of the multi-azimuth VHF program has been an ongoing R&D effort across a broad spectrum of companies in the environmental, energy and petroleum industries. The initial multi-azimuth concept was originally beta tested as an extremely complicated single well, eight (8) wing stimulation casing. Since testing of the initial concept, the multi-azimuth concept has evolved into a production based casing system for single well steam assisted gravity drainage application in unconsolidated oil bearing units. Following commercialization of the large diameter single well completion technology, **GeoSierra Environmental, Inc.** (**GeoSierra**) combined the current single azimuth technology with the lessons learned during development of the multi-azimuth concept to commercialize a small diameter, easily implementable multi-azimuth VHF well system for source area permeability enhancement and expedited remediation activities. It is this scaled down multi-azimuth program that was implemented at the former McClellan Air Force Base outside of Sacramento, California in 2013 where **GeoSierra** was contracted to increase the extraction rates and mass removal of an existing pump and treat program to expedite the timeframe to closure (e.g. permeability enhancement).

DESIGN AND MODELING ACTIVITIES

Initially envisioned as a pneumatic fracturing permeability enhancement (PE) program aimed at increasing groundwater extraction rates in the shallow A-Zone extraction wells (110' – 130' bgs), the Air Force developed a performance based specification that included reduction of chlorinated volatile organic compounds (CVOCs) by 90% over the 8-year Period of Performance (POP) through increased mass extraction complimented with emplacement of an amendment to promote destruction of CVOCs using in-situ reduction with or without abiotic mechanisms. During Request for Proposal (RFP) evaluation **GeoSierra** evaluated and developed a bid that was responsive to the PE component of the RFP using both pneumatic and hydraulic fracturing concepts, but also included a VHF program using highly conductive ZVI for not only PE, but also to enhance in-situ chemical reduction (ISCR) of CVOCs. This combined PE/ISCR approach was developed concurrent to the recently commercialized multi-azimuth VHF program, and was selected for implementation at IC-29 on the former McClellan Air Force Base by URS in Sacramento. Following award, **GeoSierra** worked with URS to develop the design program inclusive of:

- Delineation, soil boring and monitoring well installation program developed and completed by URS;
- One to two quarters of baseline groundwater monitoring in April and July 2013 completed by URS;
- Lab based geotechnical confining stress evaluation (CPT) at **GeoSierra**'s Laboratory in Medford, New Jersey;
- 2-Dimensional fracture modeling utilizing a proprietary unconsolidated aquifer fracture model;
- Borate cross linked food grade hydroxypropyl guar rheology evaluation and non-Newtonian fluid settling analysis; and
- ZVI/Frac sand gradation design utilizing modified filter pack analysis.

With confining stresses ranging from 0.24 – 5.45 tons/square foot, depth intervals of 110' – 130' bgs, gel viscosities up to 15,000 centipoise and hydraulic conductivities ranging from 124 – 400 milli Darcies, 2-D fracture modeling inclusive of modified Geertsma-de Klerk and Perkins-Kern-Nordgren fracture models resulted in average single wing ZVI and frac sand fracture dimensions of up to 38' long and 0.60-inches thick. Based upon modeling results, a fifty-two (52) injection well layout was developed with a conservative 40-foot well spacing, two (2) patented expansion casings creating four (4) fractures per well, or a grid network of 208 total fractures site wide. Azimuth orientations varied across the site to target existing extraction wells for PE effect, specifically EW-330, while the monitoring network was installed to intentionally not intercept fractures and provide aquifer based monitoring of CVOC reductions, rather than monitoring well remediation results if fractures directly intersected monitoring wells.

SYSTEM INSTALLATION AND CONSTRUCTION

Finalization of the 100% Design Document was completed by **GeoSierra** in May 2013 with fabrication of the patented casings commencing in June 2013 and mobilization/drilling activities commencing in July 2013. Over the twenty-four (24) day drilling program, the fifty-two (52) VHF wells were installed to approximately 132-feet bgs. Orientation verification for upper and lower casings was completed utilizing a downhole camera and compass alignment tool to verify azimuth orientations within approximately 5-degrees from the design following installation and prior to grouting. Two specific zones were targeted for enhancement including ZVI in the deeper 120' – 130' bgs interval while 20/40 frac sand was targeted for the shallower 110' – 120' bgs interval. In addition, to target enhancement of specific extraction wells, 20/40 frac sand was injected in the lower zones as opposed to ZVI in VHF wells proximate to extraction wells to reduce the potential for ZVI intrusion into existing extraction well screens and potential damage to well screens or downhole pumping equipment.

With an incident free drilling program completed, the second phase of mobilization included delivery of a custom built, high efficiency trailer mounted gel mixing and hydraulic fracture system consisting of 3,000 gallon stainless steel mix tanks, mixing skid, blending unit, pumping skid and industrial scale system, gel QA/QC equipment, pressure monitoring systems and the design quantities of HPG, borate cross linker, enzyme, food grade acetic acid, 105-tons of ZVI and 70-tons of 20/40 frac sand to the site. Mechanical packers and high pressure drill rods were installed between the upper and lower casings in the first thirteen (13) wells and construction of the VHF PE system commenced in wells F1 – F13. Construction of the VHF PE system continued in this thirteen (13) well scenario for the duration of the project until all wells were fractured.

Following mixing and testing of the HPG fracture fluid for compliance with the specifications, ZVI and/or frac sand was mixed with the HPG inside the blender unit and the linear gel/proppant mixture was injected through a double plunger, 1,400-psi positive displacement fracture pump and crosslinked inline after the plunger pump immediately prior to injection. Casing dilation occurred during injection of the cross linked ZVI/sand fracture fluid. The casing dilation initiates the vertical fracture from each casing by mechanically separating the formation approximately 5/8-inch and providing the initial vertical fracture pathway. Following initiation, propagation of the fracture immediately commenced with continued injection of the HPG/proppant mixtures. Adjacent target wells along the intended azimuth of the fractures were opened to the atmosphere to promote pore pressure relief between the injection wells and it is this pore pressure relief concept that maintains the intended fracture alignment, providing azimuth control for each emplaced fracture.

Wellhead pressure monitoring was conducted during each injection to evaluate fracture casing opening and initiation pressures, fracture propagation pressures and adjacent fracture link up through sudden pressure decreases. Real time pressure-time curve plots are used in the field to evaluate the pressure profile during each stimulation event. These signatures, along with physical evidence of pore pressure relief from fracture fluid relief in adjacent wells were utilized in real time to evaluate for installation in accordance with the design.

A total of 105-tons of ZVI and 70-tons of 20/40 spherical fracture sand were mixed and injected to create 208 interconnected vertical fractures across the site. Injections were completed during a 34-day construction timeframe with continuous QA/QC monitoring of gel rheology and properties to ensure meeting the design gel specifications for pH, temp and viscosity, and to ensure clean break properties within 4 – 8 hours post injection.

MULTI-AZIMUTH CONCEPT TRIALS

ALIGNING CASING WITH DOWNHOLE CAMERA/COMPASS DURING CASING INSTALLATION

HYDRAULIC FRACTURING AT F11 - F24

VHF PE SYSTEM PERFORMANCE AND INITIAL MONITORING RESULTS

Data evaluation in the combined PE/ISCR system can be challenging as initial increases in VOC concentrations and mass removal rates should be expected from the PE effect due to increased mass transfer of VOCs into each extraction well, followed by a relatively quick decrease in both as a result of ISCR chemistry on TCE concentrations in the subsurface. As such, a number of metrics were and will continue to be evaluated to determine the success of the combined VHF PE/ISCR system at the McClellan Site.

There were three primary metrics developed during evaluation of the VHF PE strategy that would allow evaluation of analytical results and extraction rates in meeting the short and long term goals of the performance based solicitation. These metrics included:

1. Reduction in VOC concentrations (specifically TCE) in Performance Monitoring Wells by 90% over the remaining 6-years of the contract;
2. Increase in extraction well specific capacity (GPM/ft); and
3. Increase in peak TCE removal rates (lbs/day) in targeted A-zone extraction wells, specifically EW-330 (short term transitory effect).

Initial Performance Monitoring Well TCE Concentration Changes

Baseline groundwater sampling and one (1) post construction monitoring event has been completed to date. While reductions were not anticipated in the first quarter following completion of construction activities, seven (7) of the thirteen (13) monitoring wells designated as "Performance Monitoring Wells" have resulted in significant TCE reductions with reductions as high as 80% from Baseline sampling in April 2013. Results for monitoring well data indicate the following TCE reductions:

- MW-370 – 80%;
- MW-658 – 31%;
- MW-662 – 49%;
- MW-663 – 69%;
- PZ-211 – 72%;
- MW-665 – 8%; and
- MW-668 – 59%;

Concentration changes within the remaining six (6) monitoring wells range from increases of 3% to 22%, with one well, MW-660 resulting in a 302% concentration increase from 97-ug/L to 390-ug/L. These elevated concentrations should reduce rapidly as ISCR chemistry becomes the predominant removal mechanism over time and mass removal rates should equilibrate along with the new increased extraction rates.

Increases to Extraction Well Specific Capacities

Compared to simply evaluating extraction well flowrates, extraction well specific capacity comparisons provide a better metric for increases to well yields due to varying drawdown targets at the McClellan site. Because ZVI will corrode and ultimately become less reactive when subjected to unsaturated conditions, drawdown from extraction wells is maintained a minimum of 2 – 4 feet above the top of the ZVI fracture zone as opposed to drawdown to, or close to, the pump intake for maximum zone of influence effect. Based on this metric, the table below includes a comparison of pre and post construction specific capacities in the A-zone wells.

A Zone Extraction Well ID	May 2013 Specific Capacity (GPM/ft)	November 2013 Post Construction Specific Capacity (GPM/ft)	Post Construction Peak Specific Capacity (GPM/ft)*	Percent Difference Pre – Post Construction Specific Capacity
EW-321	0.127	0.33	0.33	159.4%
EW-323	1.733	2.43	2.59	49.2%
EW-330	0.395	0.16	1.67	322.2%
EW-460	2.586	2.30	2.71	4.7%

(*) – extraction wells continue to be adjusted to optimize well yields and balance flows from the four (4) wells.

Based on the results identified above, an average of approximately 134% increase in well specific capacities was realized in four (4) extraction wells within the treatment area, including a peak increase of 322% in the specifically targeted A-Zone extraction well EW-330. Adjustments to the extraction system and pump upgrades by URS continue at the site to optimize extraction system efficiency which will continue to affect rates and capacities.

Peak Extraction Well Mass Removal Rates

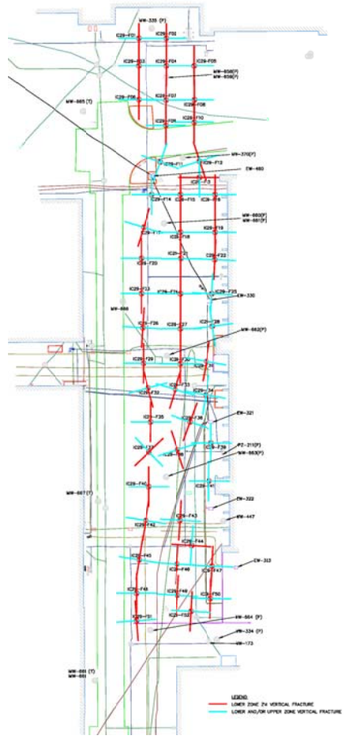
The second metric beyond simply concentration reductions in the performance monitoring wells utilized normalized mass removal rates for the four (4) targeted extraction wells in IC-29. Concentrations and flowrates in extraction wells were compared at three timepoints including Baseline results from April 2013 and a number of monthly sampling events from October 2013 to March 2014. Baseline TCE concentrations and the corresponding flowrates were utilized to evaluate mass removal increases prior to ISCR conditions dominating the subsurface conditions and reducing mass removal rates. These conditions are transitory; mass removal rates will actually decrease with time as TCE concentrations decline from continued ISCR conditions.

A Zone Extraction Well ID	Pre Construction Mass Removal (lbs/day)	Peak Post Construction Mass Removal (lbs/day)	Percent Change in Peak Removal Pre – Post Construction
EW-321	1.0×10^{-2}	2.5×10^{-2}	142%
EW-323	7.6×10^{-2}	6.6×10^{-2}	-13%
EW-330	3.0×10^{-4}	3.1×10^{-3}	912%
EW-460	3.1×10^{-2}	3.6×10^{-2}	19%

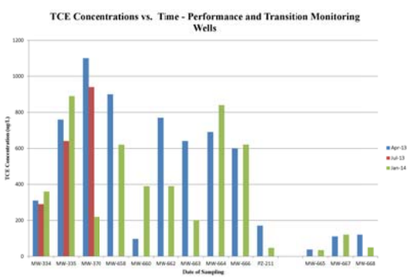
SUMMARY OF RESULTS

A novel multi-azimuth VHF PE system, combined with ZVI ISCR was implemented at the former McClellan Air Force Base outside of Sacramento, California to increase CVOC removal efficiencies while also expediting reduction of residual TCE concentrations in the saturated zones. Evaluating three different performance metrics relative to the long term performance based contract goals indicate that the VHF PE system has:

- Increased extraction well specific capacities resulting in higher well yields;
- Initially increased mass removal at extraction wells as much as 912%; and
- Resulted in up to 80% initial TCE reductions in performance monitoring wells approximately 6-months post construction with continued monitoring ongoing.



AS-BUILT SITE PLAN



INITIAL TCE MONITORING RESULTS