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Public Summary: **Final Cost and Performance Report**
Ferox^{sm} Injection Technology Demonstration
Parcel C, Remedial Unit C4, Hunters Point Shipyard
San Francisco, California, July 11, 2003

The U.S. Department of the Navy (Navy) has completed a final cost and performance report for an innovative and emerging remediation technology demonstration in Parcel C, Remedial Unit C4 (RU-C4), at Hunters Point Shipyard (HPS) in San Francisco, California. The project was conducted in association with, and partially funded by, the Navy's Alternative Restoration Technology Team (ARTT), Naval Facilities Engineering Service Center. In 2001, the Ferox^{sm} injection technology demonstration was one of two proposals selected nationwide by ARTT to demonstrate an innovative technology for field testing. The final cost and performance report summarizes the methods of technology implementation and performance and the demonstration cost and provides conclusions and recommendations related to its performance and any implementation issues.

Parcel C and RU-C4 Background

HPS is located in southeast San Francisco on a peninsula that extends east into San Francisco Bay. The shipyard is divided into six property parcels, A through F. Parcel C, the oldest portion of the shipyard, is located in the east-central portion of HPS along San Francisco Bay. Since the late 1800s, Parcel C has been used almost exclusively for industrial purposes. Past investigations indicated the presence of several contaminant plumes in groundwater beneath Parcel C. RU-C4 contains one of the largest of these plumes. The RU-C4 plume contains chlorinated volatile organic compounds (VOC) and is located near Buildings 272 and 281. Trichloroethene is the primary VOC, but tetrachloroethene, dichloroethene, and vinyl chloride are also present at lesser concentrations.

Possible sources of chlorinated solvents detected in groundwater at RU-C4 include (1) a former underground storage tank (UST) used for waste oil storage, immediately north of Building 272, and the associated floor drain and underground piping inside Building 272; (2) a grease trap, immediately north of Building 272 (east of the former UST), and the associated cleanout and underground piping inside Building 272; and (3) five steel dip tanks at a former paint shop in the southwestern portion of Building 281. Although the former contents of the Building 281 dip tanks are undetermined, it is possible that they contained degreasing solvents such as trichloroethene and tetrachloroethene. Similarly, solvents could have been present in the waste oil UST and grease trap, but such use has not been determined.

Purpose of the Technology Demonstration

At Navy and Marine Corps sites, ARTT is tasked with evaluating innovative remediation technologies to expedite regulatory acceptance and implementation of the technologies. Through the ARTT program, innovative technologies are developed, demonstrated, and validated to address pervasive Navy environmental problems, for which implementable and cost-effective solutions are not readily available. The ARTT program will provide demonstration and treatability study data for innovative treatment technologies needed by the Navy at many sites, including HPS.

The primary objective of the demonstration was to evaluate the technology's cost and performance in destroying VOCs in source areas at RU-C4. The final cost and performance report is intended to help evaluate groundwater remediation technologies as part of the Parcel C feasibility study at HPS, as well as at other Navy sites.

Remediation Technology Description

The Ferox^{sm} injection technology is an in situ subsurface remediation process for treating chlorinated VOCs. The treatment process involves the direct subsurface injection and dispersion of reactive zero-valent iron (ZVI) powder into the targeted contamination zone. Introduction of ZVI into the subsurface encourages chemical reduction of chlorinated VOCs (dechlorination). The technology uses pneumatic fracturing of the subsurface and subsequent liquid atomized injection of ZVI. This innovative ZVI delivery approach is designed to maximize the contact between ZVI powder and contaminants.

In situ reductive dechlorination using ZVI has been demonstrated using permeable reactive barriers. However, reactive barriers treat only the dissolved phase of contamination that migrates with groundwater. One advantage of the Ferox^{sm} technology is that it is capable of treating adsorbed insoluble contaminants bound to soil, including those in the contaminant source area. Another important advantage of the Ferox^{sm} technology is that ZVI is one of the most innocuous and safe reactants currently used to chemically treat contaminants *in situ*.

Information Repositories: A complete copy of the "Final Cost and Performance Report, Ferox^{sm} Injection Technology Demonstration at Parcel C, Remedial Unit C4, Hunters Point Shipyard, California" is available to community members at:

San Francisco Main Library
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For more information about environmental investigation and cleanup at HPS, contact Mr. Keith Forman of the Navy at (619) 532-0913 (phone), (619) 532-0995 (fax), or e-mail to formanks@efdsw.navfac.navy.mil.

A-E CERCLA/RCRA/UST STUDIES AND REMEDIAL DESIGN

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Cost and Performance Report
FEROX^{sm} Injection Technology Demonstration

Parcel C, Remedial Unit C4

Hunters Point Shipyard
San Francisco, California

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TETRA TECH, INC.

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COST AND PERFORMANCE REPORT FEROX^{sm} INJECTION TECHNOLOGY DEMONSTRATION

Parcel C, Remedial Unit C4, Hunters Point Shipyard San Francisco, California

July 11, 2003

Prepared for

DEPARTMENT OF THE NAVY
Mr. Patrick Brooks, Remedial Project Manager
Southwest Division
Naval Facilities Engineering Command
San Diego, California

Prepared by

TETRA TECH EM INC.
1230 Columbia Street, Suite 1000
San Diego, California 92101
(619) 525-7188

Rik Lantz, R.G.
California Registered Geologist, No. 6356

John McCall, P.E., Project Manager
Pennsylvania Registered Professional Engineer
No. PE-050653-E

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ACRONYMS AND ABBREVIATIONS

µg/L	Micrograms per liter
ARS	ARS Technologies, Inc.
ARTT	Alternative Restoration Technology Team
bgs	Below ground surface
DCE	Dichloroethene
DNAPL	Dense nonaqueous-phase liquid
DO	Delivery Order
HPS	Hunters Point Shipyard
mV	Millivolts
Navy	U.S. Department of the Navy
NJIT	New Jersey Institute of Technology
ORP	Oxidation-reduction potential
PCE	Tetrachloroethene
PRC	PRC Environmental Management, Inc.
psig	Pounds per square inch gauge
QC	Quality control
RU-C4	Remedial Unit C4
TCE	Trichloroethene
Tetra Tech	Tetra Tech EM Inc.
UST	Underground storage tank
VOC	Volatile organic compound
ZVI	Zero-valent iron

ACKNOWLEDGEMENTS

This project was selected for field implementation, and partially funded by, the U.S. Department of Navy's (Navy) Alternative Restoration Technology Team (ARTT), Naval Facilities Engineering Service Center. The goal of projects coordinated by the ARTT is to demonstrate and validate innovative technologies to expedite regulatory acceptance and implementation of innovative remediation technologies at Navy and Marine Corps sites. Through this program, Naval Facilities Engineering Command develops, demonstrates, and validates new technologies to address pervasive Navy environmental problems for which implementable and cost-effective solutions are lacking. Dr. D.B. Chan and Mr. Richard Mach served as the key technical representatives for the ARTT on this project.

This demonstration project was completed by Naval Facilities Engineering Command, Southwest Division; the ARTT; Tetra Tech EM Inc. (Tetra Tech); and ARS Technologies, Inc. The late Mr. Tom Holm-Hansen of Tetra Tech performed the initial research that the team used to complete this very successful project. Our friend and mentor, who passed away during the initial phases of the project, will be missed by many. Also from Tetra Tech, Mr. John McCall served as the project manager, and was supported by Dr. Greg Swanson, senior technical advisor, and Mr. Hwakong Cheng, field manager. Mr. Steve Chen, ARS Technologies, Inc., served as the Ferox^{sm} injection supervisor. Mr. Michael Work from the U.S. Environmental Protection Agency, Mr. Michael Kenning from the California Department of Toxic Substances Control, and Ms. Julie Menack from the California Regional Water Quality Control Board provided valuable input during preparation of the demonstration work plan and sampling and analysis plan. Mr. Patrick Brooks served as the Remedial Project Manager for the Navy.

EXECUTIVE SUMMARY

Ferox^{sm} injection is a patented technology of ARS Technologies, Inc. (ARS) for in situ subsurface remediation of source areas of chlorinated volatile organic hydrocarbons (VOC). The Ferox^{sm} technology involves injection of liquid atomized zero-valent iron (ZVI) powder into targeted subsurface zones, using a packer system to isolate discrete depth intervals within open boreholes. A ZVI slurry is delivered to the subsurface in a liquid atomized form using pure nitrogen gas as a carrier fluid. If needed, ARS employs pneumatic fracturing as a first step prior to the injections to promote movement of the ZVI through the subsurface and contact with contaminants. Introduction of ZVI into the subsurface encourages chemical reduction of chlorinated VOCs.

To evaluate the Ferox^{sm} technology's performance in treating chlorinated VOCs, the U.S. Department of the Navy conducted a Ferox^{sm} injection technology demonstration at Remedial Unit C4 (RU-C4) in Parcel C at Hunters Point Shipyard in San Francisco, California. At RU-C4, an approximate 10-foot layer of artificial fill overlies fractured bedrock. At RU-C4, chlorinated VOCs, primarily trichloroethene (TCE), are present in both soil and groundwater. Before treatment began, TCE concentrations in groundwater were as high as 88,000 micrograms per liter. Pneumatic fracturing was employed, and ZVI was injected into four boreholes to treat soil and groundwater contamination in the vertical profile from the groundwater table (about 7 feet below ground surface) to about 32 feet below ground surface.

Following ZVI injection, strongly reducing conditions in groundwater were observed out to a radius of 15 feet from each of the four injection boreholes. Within this 15-foot radius, which was considered to be the area of full treatment, the average oxidation-reduction potential was reduced to -372 millivolts. The depth of the treatment zone was estimated to extend from the top of the water table (about 7 feet bgs) to 32 feet bgs. Thus, the treated area covered approximately 1,818 square feet, and the treated subsurface volume was approximately 1,683 cubic yards.

Based on 12 weeks of groundwater monitoring results following ZVI injection, near complete, reductive dechlorination of all chlorinated VOCs was achieved. Reduction of TCE, the predominant contaminant, to ethene and chloride was rapid and nearly complete, with a reduction of 99.2 percent within the treatment zone. No significant increases in TCE degradation intermediates (such as cis-1,2-dichloroethene and vinyl chloride) were observed. Significant rebound of chlorinated VOC concentrations did not occur even as of the last sampling event, which was 3 months after ZVI was injected. A statistical analysis of changes in contaminant concentrations outside of the treatment zone further supports the conclusion that TCE destroyed rather than displaced as a result of the injections. Thus, it was concluded that the Ferox^{sm} injection technology provided effective in situ remedial treatment of the source zone of chlorinated VOCs at this site.

The total cost of the field-scale implementation of the Ferox^{sm} injection technology at RU-C4 was $289,274, or $172 per cubic yard of the treatment zone. Excluding costs for sampling, analysis, and management of demonstration-derived wastes, the total cost was $196,665, or $117 per cubic yard. Economies of scale for certain cost elements, such as mobilization and demobilization, could result in somewhat lower unit costs for larger-scale applications.

1.0 INTRODUCTION

Tetra Tech EM Inc. (Tetra Tech) received Delivery Order (DO) 013 from the U.S. Department of the Navy (Navy), Naval Facilities Engineering Command, Southwest Division, under Indefinite Quantity Contract for Architectural–Engineering Services to Provide CERCLA/RCRA/UST Studies No. N68711-00-D-0005. Under DO 013, Tetra Tech and ARS Technologies, Inc. (ARS) conducted a Ferox^{sm} injection technology demonstration from November 2002 to March 2003 at Remedial Unit C4 (RU-C4) of Parcel C at Hunters Point Shipyard (HPS) in San Francisco, California. The primary objective of the demonstration was to evaluate the technology's cost and performance in destroying chlorinated volatile organic compounds (VOC) in source areas at HPS. This cost and performance report summarizes the results of the demonstration.

1.1 REPORT ORGANIZATION

This report contains the following sections:

- Section 1.0 – Introduction. Section 1.0 describes the report organization, the technology used, and the site at which the technology was implemented.

- Section 2.0 – Technology Implementation. Section 2.0 describes the specific tasks and approaches associated with conducting the Ferox^{sm} injection technology demonstration, including the Ferox^{sm} design, the steps employed during the implementation, monitoring of the Ferox^{sm} injection process, and sampling and analysis.

- Section 3.0 – Technology Performance. Section 3.0 summarizes the performance of the technology, including the horizontal zone of influence, percent reduction of VOCs, potential plume displacement, and results of metals and nitrate analyses.

- Section 4.0 – Cost Summary. Section 4.0 summarizes the cost of applying the Ferox^{sm} technology at RU-C4, including mobilization and demobilization, equipment and supplies, labor, drilling services, sampling and analysis, and demonstration-derived waste disposal as well as other costs. This section also provides a comparison of the costs against a comparable technology.

- Section 5.0 – Conclusions and Implementation Issues. Section 5.0 provides the conclusions and recommendations of Ferox^{sm} technology demonstration at RU-C4 considering implementation issues that may have arose during the project.

- Section 6.0 – References. Section 6.0 lists the references used to prepare this report.

Figures and tables used to prepare this report are presented after Section 6.0.

1.2 TECHNOLOGY DESCRIPTION

Ferox^{sm} injection is a patented technology of ARS for in situ subsurface remediation of chlorinated VOCs. The treatment process involves the injection of liquid atomized and reactive zero-valent iron (ZVI) powder into a targeted contamination source area. Introduction of ZVI into the subsurface encourages chemical reduction of chlorinated VOCs.

The success of the Ferox^{sm} injection in destroying chlorinated VOCs depends on the ability of the system to disperse ZVI into the treatment zone. In low-permeability formations, pneumatic fracturing is conducted as a first step to maximize ZVI dispersal in the treatment zone. Pneumatic fracturing occurs when nitrogen gas is injected into the subsurface at a pressure that exceeds the natural in situ stresses (such as formation overburden and cohesive stresses). This pressure creates or opens fractures that radiate from the injection borehole, thereby increasing the bulk permeability of the formation. The expanded fracture network increases secondary porosity and pore space connectivity allowing for increased contact between the ZVI and the contaminants. The pneumatic fracturing process is a proprietary technology licensed to ARS by the New Jersey Institute of Technology.

During the Ferox^{sm} injection process, ZVI powder is suspended in potable water to create a ZVI slurry that is then injected into the subsurface in a liquid atomized form using nitrogen gas as a carrier fluid. Use of the Ferox^{sm} technology includes the following advantages:

- ZVI treats adsorbed contaminants bound to soil, including those in the contaminant source area
- ZVI is one of the most innocuous and safe reactants currently used to chemically treat contaminants in situ

One of the primary mechanisms for reducing chlorinated VOCs is sequential dechlorination, which involves the direct electron transfer from the ZVI to the chlorinated VOCs. This mechanism is driven by the oxidation of iron from the zero-valent state (or Fe^0) to ferrous iron (or Fe^{2+}). In sequential dechlorination, the electrons then reduce the contaminant (in this case, trichloroethene [TCE]) to its daughter product (1,2-dichloroethene [-DCE]), and then to vinyl chloride and ethene. The overall reduction is shown in the following chemical half reactions:

$$Fe^0 \rightarrow Fe^{2+} + 2e^-$$

$$C_2HCl_3 + 3H^+ + 6e^- \rightarrow C_2H_4 + 3Cl^-$$

Another mechanism for reducing chlorinated VOCs is hydrogenation, which involves the production of hydrogen gas during the corrosion of ZVI under anoxic conditions. This reduction is illustrated in the following chemical equations using TCE as an example:

$$Fe^0 + H_2O \rightarrow Fe^{2+} + 2OH^- + H_{2\,(gas)}$$

$$C_2HCl_3 + 3H_{2\,(gas)} \rightarrow C_2H_4 + 3Cl^- + 3H^+$$

In either case (sequential dechlorination or hydrogenation), the end product is ethene, a nontoxic gas that does not persist in soluble form. The byproduct of the reductive dechlorination process is chloride, a naturally occurring anion.

The ZVI powder is a "sponge" iron of high purity (greater than 95 percent) that exhibits a high surface area because of its small particle size (40 microns) and internal porosity. The powder is produced from iron ore (hematite or magnetite) in a gas-reduction process.

1.3 SITE DESCRIPTION

This section describes the site, RU-C4, including the site history, the site hydrogeology, and groundwater characteristics.

1.3.1 Site History

HPS is situated on a long promontory, located in the southeastern portion of the City and County of San Francisco that extends eastward into San Francisco Bay (Figure 1). HPS consists of 928 acres, 496 of which are on land. From 1869 through 1986, HPS operated as a ship repair, maintenance, and commercial facility. In 1991, the Navy designated HPS for closure under the federal Base Closure and Realignment Act. As a result of various investigations that characterized contamination in soil and groundwater, HPS was divided into six separate geographic parcels (Parcels A through F) to facilitate the closure process.

Parcel C is located in the eastern portion of HPS. Past investigations have identified several contaminant plumes in groundwater beneath Parcel C. The plume at RU-C4 consists of chlorinated solvents, primarily TCE, in shallow groundwater beneath the northern portion of Building 272.

Possible sources of chlorinated solvents detected in groundwater at RU-C4 include (1) a former underground storage tank (UST) used for waste oil storage, immediately north of Building 272, and the associated floor drain and underground piping inside of Building 272; (2) a grease trap, immediately north of Building 272 (east of the former UST), and the associated cleanout and underground piping inside Building 272; and (3) five steel dip tanks at a former paint shop in the southwestern portion of Building 281. Although the former contents of the Building 281 dip tanks are undetermined, it is possible that they contained degreasing solvents such as TCE and tetrachloroethene (PCE). Similarly, solvents could have been present in the waste oil UST and grease trap, but this has not been determined.

1.3.2 Site Hydrogeology

Topography at HPS is dominated by relatively level lowlands that were constructed by excavating portions of surrounding hills and placing nonengineered fill materials along the margin of San Francisco Bay. The remaining land is a moderate to steeply sloping, northwesttrending ridge. Ground surface elevations at Parcel C generally range from 8 to 10 feet above mean sea level.

Two aquifers and one water-bearing zone have been identified at HPS: the A-aquifer, the B-aquifer, and the bedrock water-bearing zone. Groundwater flow patterns are complex because of heterogeneity in the hydraulic properties of the fill materials and weathered bedrock, tidal influences, effects of storm drains and sanitary sewers, and variations in topography and drainage.

RU-C4 hydrogeology is characterized by shallow bedrock with a rolling and uneven surface overlain predominantly by artificial fill material of variable hydraulic conductivity. In locations where the artificial fill directly overlies the weathered zone at the bedrock interface, both the fill material and the weathered bedrock are considered part of the A-aquifer. The A-aquifer is unconfined and directly overlies the bedrock water-bearing zone. In the western portion of Parcel C where bedrock is present at shallow depths, B-aquifer zones are isolated and mostly absent. At RU-C4, the B-aquifer is present from approximately midway through Building 272 and further to the east. An aquitard separates the A- and B-aquifers in a small area near the eastern edge of the building; however, the two aquifers are in direct contact east of this point, based on lithologic logs of nearby borings and wells (Tetra Tech 2003). At RU-C4, the A-aquifer predominantly consists of Artificial Fill and weathered bedrock located about 1 to 15 feet below ground surface (bgs). The bedrock water-bearing zone occurs as fractured portions of the Franciscan Complex Bedrock. Groundwater of the bedrock water-bearing zone is primarily within discrete fractures and shear zones.

During this demonstration, groundwater levels were consistent with previous measurements at this site and ranged from an average of 6.8 feet bgs in December 2002 to an average of 6.2 feet bgs in January 2003. Numerous historical investigations have indicated that the permeability of fill material present at Parcel C is variable. At RU-C4, based on slug tests, hydraulic conductivity in the A-aquifer ranged from 26.6 to 43 feet per day, and hydraulic conductivity in the bedrock water-bearing zone ranged from 5.2×10^{-2} to 40 feet per day. Notably, most hydraulic conductivity estimates are at the lower end of this range, and the higher value (40 feet per day) was observed in monitoring well IR28MW211F (PRC Environmental Management, Inc. [PRC] and others 1997).

Because San Francisco Bay essentially surrounds RU-C4 on three sides, groundwater gradients are generally flat, with a historically measured gradient of about 0.0025 (Tetra Tech 2003). Groundwater flow directions at RU-C4 can be variable, depending on the specific location and time of year, but generally trend south-southwest toward Dry Dock 4.

1.3.3 Groundwater Characteristics

Groundwater at RU-C4 is generally fresh in composition, with total dissolved solids concentrations ranging from about 300 to 900 milligrams per liter (Tetra Tech 2002).

Groundwater characterization conducted before this demonstration indicated that TCE was present at high concentrations in shallow groundwater in an isolated area beneath the northeastern portion of Building 272 (PRC and others 1997; Tetra Tech 2003). These concentrations suggested the likely presence of dense nonaqueous-phase liquid (DNAPL) in a small portion of the TCE plume. However, investigations using oil-water interface probes at RU-C4 during a previous study in 2002 (Tetra Tech 2003) and during the baseline sampling of this study did not detect DNAPL in any of the monitoring wells.

In November and December 2002, baseline groundwater sampling was conducted to characterize the target treatment prior to the ZVI injections. Results from the baseline sampling were generally consistent with previously reported concentrations and further refined the spatial extent of the plume, as shown on Figure 2, which presents horizontal baseline TCE isoconcentration contours. Figure 2 also shows that TCE was present in groundwater at concentrations above 5,000 micrograms per liter (µg/L) over an approximate area of 60 feet by 30 feet in size. The near radial dispersion of the TCE plume reflects the flat groundwater gradient at RU-C4, as noted above. Figure 3 presents hydrogeologic cross sections and horizontal and vertical baseline TCE isoconcentration contours.

2.0 TECHNOLOGY IMPLEMENTATION

This section describes the following specific tasks and approaches associated with conducting the Ferox^{sm} injection technology demonstration:

- Section 2.1, Ferox^{sm} Design
- Section 2.2, Pneumatic Fracturing and Ferox^{sm} Injection Process
- Section 2.3, Ferox^{sm} Injection Monitoring
- Section 2.4, Sampling and Analysis

2.1 FEROX^{SM} DESIGN

Ferox^{sm} injections were conducted in four open boreholes. Figure 2 shows the locations of the four injection boreholes and surrounding monitoring wells. The injection boreholes are designated as F1, F2, F3, and F4 and were located to create an adequate treatment zone based on the extent of the TCE plume.

The four injection boreholes were each drilled to a depth of 32 feet bgs using a 4.25-inch, solid-flight auger; this depth is 2 feet beyond the bottom of the injection zone to accommodate the packer assembly. Temporary 4⅝-inch-diameter steel casings with disposable tips were then pushed to depth using a direct-push rig to prevent caving prior to injection. Injection boreholes were drilled to a depth below where DNAPL would potentially be observed, and injections were performed from the bottom up, to minimize the potential risk of displacing DNAPL horizontally or downward into the bedrock water-bearing zone.

After the injections were performed, borehole F2 was over drilled using a hollow-stem auger and converted into monitoring well IR28MW362F. The three other injection boreholes were abandoned by tremmie backfilling with cement-bentonite grout.

The design dosage of ZVI powder was 16,000 pounds. This dosage was based on (1) the estimated mass of TCE, which makes up most of the total chlorinated VOCs; (2) the estimated mass of soil within the treatment zone; and (3) the mass ratios of iron-to-TCE and iron-to-soil. The design dosage factored these two mass ratios, as well as safety factors, to account for fluctuations in historic TCE concentrations, unknown sources, and less than ideal distribution of the ZVI powder.

Previous bench-top treatability studies have shown that an iron-to-TCE mass ratio of at least 500 is generally required. This ratio is significantly higher than the stoichiometric ratio of about 1.3 to 1 because the electron transfer mechanism or the hydrogenation process is never 100 percent efficient. The mass of TCE within the treatment zone was estimated to be about 14 pounds: 11.1 pounds in groundwater and 2.9 pounds in soil. Successful emplacement of 16,000 pounds of ZVI would achieve an iron-to-TCE mass ratio of about 1,100.

In general, an iron-to-soil mass ratio of 0.004 is necessary to achieve a sufficient reductive environment for the degradation of TCE to occur, regardless of the mass of TCE. Based on an estimated dimension for the treatment zone of about 900 square feet by 22 feet in thickness, the mass of soil within the treatment zone was estimated to be about 1,980,000 pounds. As a result, successful emplacement of 16,000 pounds of ZVI would achieve an iron-to-soil mass ratio of about 0.008.

2.2 PNEUMATIC FRACTURING AND FEROX^{SM} INJECTION PROCESS

Field work for the injections was conducted between December 5 and 23, 2002. The field effort consisted of installing four injection boreholes (2 work days), setting up and testing injection equipment (2 work days), performing injections (6 work days), and converting one injection borehole to a permanent monitoring well and developing the well (1 work day).

The injection process integrated the pneumatic fracturing and Ferox^{sm} delivery into one process, with nitrogen gas used as both fracturing and injection fluid. Injections were conducted sequentially in each of the four boreholes at 3-foot intervals, starting at the bottom of 30 feet bgs and proceeding upward to at least 10 feet bgs. This series of injections was expected to vertically cover the zone from 32 feet bgs to about 7 feet bgs (the approximate water table), or the zone where significant concentrations of chlorinated VOCs had been measured.

Injections were completed within each interval by introducing pressurized nitrogen gas during the pneumatic fracturing phase. Subsequently, ZVI slurry was added to the nitrogen stream being injected during the ZVI injection phase. Figure 4 is a schematic diagram of the pneumatic fracturing and Ferox^{sm} injection process.

The pneumatic fracturing system included a specialized injection module that reduced and regulated the flow of compressed nitrogen to pressures used for both fracturing and injection. A bulk tube trailer supplied compressed nitrogen. The nitrogen was routed through the injection module to a proprietary injector, which was lowered to the desired depth intervals. Fracturing pressures ranged from 55 to 230 pounds per square inch gauge (psig) (ARS 2003). Table 1 summarizes the approximate fracturing pressures recorded at each injection borehole and within each pressure interval.

For each injection, ZVI powder and potable water were combined in the Ferox^{sm} injection trailer, at a ratio of 1 kilogram of ZVI powder to 1 gallon of water, to create the ZVI slurry. Two pneumatic diaphragm pumps maintained ZVI suspension in the tank and delivered the slurry to the injection piping. Typically, after 15 to 20 seconds of nitrogen-only pulsing, the ZVI slurry was introduced into the nitrogen stream and dispersed into the formation. Subsurface pressures during the injection process ranged from 40 and 180 psig (ARS 2003). Table 1 summarizes the approximate injection pressures recorded at each injection borehole and within each injection interval.

Prior to beginning the injection process within each interval, the temporary steel casing was raised to expose the injection assembly to the formation. The injection assembly consisted of double-straddle pneumatic packers and nozzles. The inflated packers isolated 3-foot intervals by sealing against the formation both above and below the injection tooling. After the injection process was completed at each interval, the packers were deflated and the injection assembly was raised to the subsequent injection interval. The injection process took about 5 to 20 minutes for each 3-foot interval, depending on the achievable flow rates.

Nitrogen and slurry flow rates were optimized in the field based on site conditions. Initial responses to injections indicated that gas dissipated slowly through the formation. Most injections were conducted using pulses of nitrogen, instead of steady flows, to minimize the amount of nitrogen introduced to the injection and to prevent excessive buildup of pressure and surface heave. Injection pressures used at shallow depths (less than 15 feet bgs) were generally lower to reduce daylighting and potential surface heave because of reduced formation overburden. In particular, the following modifications were made at injection borehole F1 to account for site-specific responses to the injections:

- At the intervals of 13 to 16 and 16 to 19 feet bgs, the formation was sufficiently loose that liquid atomized injections were performed without initial pneumatic fracturing.

- At the interval of 9 to 12 ft bgs, ZVI slurry was hydraulically pumped without using nitrogen gas for fracturing or as a carrier fluid. At this borehole, nitrogen gas and limited volumes of slurry were observed daylighting through joints in the concrete flooring during previous injection intervals. As a result, hydraulic pumping was used to minimize the total volume of fluid injected into the formation and to reduce the risk of contaminant vapors escaping.

The quantity of ZVI injected within each interval varied based on the duration and number of injections in each borehole. A total of 16,289 pounds of ZVI powder was injected into the four injection boreholes. Table 1 summarizes the amount of ZVI powder injected at each borehole and within each interval.

2.3 FEROX^SM INJECTION MONITORING

Soil-vapor extraction wells, vapor monitoring wells, and a floor drain within the expected treatment zone were grouted before injection to prevent them from serving as pressure relief points. Packer assemblies were also installed in monitoring wells within the treatment zone. During each injection, maximum pressures at each packered monitoring point were recorded by pressure gauges outfitted with drag arm indicators. These pressure data were used to estimate the distribution of the injected nitrogen, thereby providing a qualitative indication of the distribution of ZVI. The pressure data showed generally uniform pressurization in all directions and noted a discernable influence as far as 35 to 40 feet from the injection point (ARS 2003).

Heave of the concrete floor surface was monitored during each injection using surveying transits in conjunction with a heave rod. The heave rod was placed near each injection borehole, and the location was surveyed for heave both during and after each injection. While some surface heave was generally observed during shallow injections at each point, residual heave was found only after the injections at borehole F1 (about 1 inch) and borehole F3 (about 0.25 inch) (ARS 2003).

Tetra Tech monitored organic vapors during injection activities using a photoionization detector for health and safety reasons; no elevated concentrations were detected in the breathing zone. Underground utilities were monitored for potential influx of groundwater or ZVI slurry resulting from the Ferox^sm injections. Specifically, the nearby storm drain inlet, located outside the northeastern corner of Building 272, was inspected every 5 minutes during the injection process. There was no indication that either groundwater or ZVI slurry entered the storm drain during the injections.

2.4 SAMPLING AND ANALYSIS

Tetra Tech conducted four rounds of groundwater sampling to evaluate the effectiveness of the ZVI injections. A baseline round was conducted prior to the injections, and three post-injection rounds were conducted 2, 6, and 12 weeks after the injections. Eighteen monitoring locations were selected for sampling to represent the areas within, upgradient, cross-gradient, and downgradient of the expected treatment zone. These wells are screened in the zone of vertical coverage of the ZVI injections (7 feet to 32 feet bgs). One well located within the horizontal extent of the treatment zone, but below the vertical coverage of the ZVI injections, was also selected for sampling to represent the area below the treatment zone. Table 2 lists the screened intervals for each monitoring well.

Groundwater samples were collected using low-flow sampling methods except for one grab groundwater sample, which was collected during the baseline round at the location that would become injection borehole F2. This borehole was converted to monitoring well IR28MW362F after the injections were completed.

Tetra Tech measured groundwater samples for time-sensitive parameters in the field. Additional samples were sent to a State of California-certified laboratory for further analysis. Table 2 summarizes the groundwater sampling requirements, including the analytical methods used. Both field and laboratory quality control (QC) samples were processed in the laboratory in accordance with the sampling and analysis plan (Tetra Tech 2002).

A data quality review was conducted to ensure that the evaluation of the technology's performance would produce valid data that were suitable for their intended use. The data quality review used the results of field and laboratory QC samples for VOCs and metals. This review also consisted of a full data validation of 20 percent of the groundwater sample analytical results for VOCs and metals and a cursory data validation of 80 percent of the results. The only significant qualification of the data was the estimated nature of 6.6 percent of the results due to exceedances of accuracy acceptance criteria (0.6 percent), calibration violations (1 percent), and results that were below the reporting limit in the work plan (5 percent) (Tetra Tech 2003). Also, 1.3 percent of the data were rejected due to calibration violations for laboratory instruments. Although some qualifiers were added to the data, a final review of the data set indicated that the data were of good overall quality and generally consistent with U.S. Environmental Protection Agency guidelines for definitive data. The precision, accuracy, representativeness, completeness, and comparability characteristics of the data are acceptable.

3.0 TECHNOLOGY PERFORMANCE

This section summarizes the evaluation of the Ferox^{sm} technology's performance at RU-C4. As stated in Section 1.0, the primary objective of the demonstration was to evaluate the technology's cost and performance in destroying chlorinated VOCs in source areas at HPS. Sections 3.1 through 3.5 present the results of the performance evaluation with respect to the following specific objectives established in the work plan and sampling and analysis plan (Tetra Tech 2002):

- Assess the horizontal zone of influence
- Evaluate the percent reduction of four chlorinated ethenes of concern (TCE, PCE, 1,2-DCE, and vinyl chloride), total chlorinated ethenes, and two additional VOCs of concern (chloroform and carbon tetrachloride)
- Evaluate potential plume displacement that could result from the injection
- Evaluate potential mobilization of metals in groundwater
- Evaluate potential nitrate formation in groundwater

Data summarized in the performance evaluations in Sections 3.1 through 3.5 are often represented in terms of the change in concentration for a certain parameter (post-injection versus pre-injection), or the percent reduction. The post-injection concentration used to calculate percent reductions was the mean concentration observed over the three post-injection sampling rounds. When laboratory analytical results were reported as "not detected," a value of one-half the reporting limit was used to calculate mean concentrations or changes in concentrations. This value was also used to represent nondetected concentrations on Figures 5 and 6.

3.1 HORIZONTAL ZONE OF INFLUENCE

When injected into the formation at various intervals, ZVI slurry is expected to flow radially into fractures and pore spaces that either already existed or were created by the pneumatic fracturing. A key question about this technology is the horizontal extent to which the ZVI slurry is emplaced and provides treatment. To address this question, measurements of various groundwater parameters that indicate the presence of iron or the occurrence of dechlorination reactions were compared the distance from the nearest injection point.

Previous studies indicated that a value of less than –200 millivolts (mV) of oxidation-reduction potential (ORP) is required for significant dechlorination (Gillham and others 1997; PRC 1995). As a result, Tetra Tech took field measurements of ORP in each groundwater sample to assess the horizontal zone of influence of the ZVI injections. Tetra Tech supplemented the ORP data by qualitatively evaluating the following measurements: pH, dissolved iron, dissolved gases (ethene, ethane, and hydrogen), and chloride. Reaction of ZVI with water increases pH and dissolved iron concentrations. Ethene, chloride, and hydrogen gas are produced as byproducts of the dechlorination and iron oxidation processes. Ethane is produced by subsurface reactions and degradation processes.

Table 3 presents the ORP results for each monitoring well during each of the four rounds of groundwater sampling and the difference (or Delta) between the baseline and average post-injection results. Figure 5 graphically presents the baseline and mean post-injection ORP readings versus distance to the nearest injection borehole. This figure shows all wells screened within the vertical extent of coverage of the ZVI injections (7 feet to 32 feet bgs). Baseline ORP readings were independent of distance, as shown on Figure 5. As presented in Table 3 and on

Figure 5, ORP results less than –200 mV were observed at distances of 15 feet or less from the nearest injection borehole.

Increases in pH also indicated treatment (Table 4); however, the results are less clear because pH increased after injection at all but two locations: monitoring wells IR28MW934F5 and IR28MW351F. Monitoring well IR28MW934F5 is located 13.1 feet from the nearest injection borehole (F3), and monitoring well IR28MW351F, which is screened below the targeted treatment zone at 51 to 59 feet bgs, is located 4.8 feet from the nearest injection borehole (F4). However, inside of the treatment zone, pH increases observed within 15 feet of an injection point were typically 1 to 2 pH units, whereas changes in pH outside of the treatment zone were typically less than 0.5 pH units.

Changes in concentrations of dissolved gases (ethane, ethene, and hydrogen) were comparable with those for pH, providing a similar indication of the extent of the treatment zone (Table 5). Increases in ethane and ethene concentrations were observed at most locations 15 feet or less from the nearest injection borehole. Dissolved hydrogen results did not indicate the extent of the treatment zone because it was not detected during the baseline sampling round and was detected at only three locations after the injection process was completed (Table 5).

Although increases in chloride concentrations could be expected to result from the ZVI injection, chloride concentrations actually decreased at all but four locations (Table 6). The four locations were at various distances from injection. Because background chloride concentrations in groundwater are relatively high, it is likely that the variations in background concentrations outweighed any chloride production that resulted from treatment. Alkalinity concentrations decreased at all locations within the treatment zone and did not change significantly beyond the treatment zone (Table 7).

The data discussed above supports the conclusion that the treatment zone extended to distances of at least 15 feet from the point of injection, covering an area of about 1,818 square feet. The depth range of the treatment zone was estimated to extend from the top of the water table (about 7 feet bgs), which is 2 feet above the highest injection interval of 9 feet, to 2 feet below the lowest injection (32 feet bgs). This depth range comprises an overall subsurface treatment volume of 1,683 cubic yards.

Figure 6 graphically presents mean ORP, TCE, and dissolved gas concentrations versus time at monitoring wells within 15 feet of the injection boreholes. As shown on the figure, the trends in these mean concentrations over time are indicative of treatment, with ORP decreasing, TCE concentrations decreasing, and dissolved gases increasing.

3.2 PERCENT REDUCTION OF VOLATILE ORGANIC COMPOUNDS

Tetra Tech collected groundwater samples for analysis of VOCs before and after the injection process. Results of these samples were used to estimate percent reduction of the following VOCs of concern: four chlorinated ethenes (TCE, PCE, 1,2-DCE, and vinyl chloride), total chlorinated ethenes, and two additional chlorinated VOCs (chloroform and carbon tetrachloride). Percent reduction was calculated for these compounds by comparing concentrations within the treatment zone before and after ZVI injection. Post-injection concentrations were represented by the average concentration measured during the three post-injection sampling rounds. Table 8 presents the monitoring results, the mean percent reduction, and the change within the treatment zone and at each individual monitoring location for each VOC of concern.

The percent reduction calculated based on the arithmetic mean of concentrations within the treatment zone is considered more meaningful because the calculated values account for both decreases and increases in concentrations at individual monitoring locations. For example, TCE concentrations increased at locations IR28MW361F and IR28MW933F5, representing a negative percent reduction. However, because TCE concentrations decreased significantly at the other eight locations within the treatment zone, the overall percent reduction within the treatment zone was determined to be significantly positive.

As discussed in Section 3.1, an evaluation of ORP and other parameters concluded that the treatment zone extended at least 15 feet from the injection boreholes. Therefore, analytical results for the 10 monitoring locations within this range were used to estimate percent reduction of VOCs within the treatment zone.

Results of TCE monitoring in groundwater can be used as an indicator of performance at this site because TCE is the primary chlorinated VOC contaminant. The highest pre-injection concentration (88,000 µg/L) of TCE was observed at injection borehole F2, which was later converted to monitoring well IR28MW362F, and post-injection results at this borehole averaged at a concentration of 31 µg/L, reflecting a percent reduction for this individual location of 99.96 percent. In the treatment zone, the overall mean pre-injection concentration of TCE was 27,000 µg/L and the overall mean post-injection concentration was 220 µg/L. These concentrations represent an overall percent reduction of TCE within the treatment zone of 99.2 percent. Figures 7, 8, and 9 present horizontal isoconcentration contours of TCE observed during each of the three post-injection rounds of groundwater sampling. These figures show the substantial lateral reductions in TCE concentrations compared with baseline conditions (Figure 2). Figure 10 presents hydrogeologic cross sections and horizontal and vertical TCE isoconcentration contours for the final round of groundwater sampling (post-injection round 3). The vertical isoconcentration contours on Figure 10 show the substantial reduction of TCE concentrations as compared with baseline conditions shown on Figure 3.

Reduction of TCE to ethene and chloride was nearly complete, since no significant formation of intermediate degradation products (cis-1,2-DCE, trans-1,2-DCE, 1,1-DCE, and vinyl chloride) was observed. Percent reduction within the treatment zone for the remaining VOCs of concern was also significant, as shown in Table 8. The overall reduction percentages within the treatment zone for the VOCs of concern were as follows: TCE (99.2 percent), PCE (99.4 percent), cis-1,2-DCE (94.2 percent), vinyl chloride (99.3 percent), total chlorinated ethenes (99.1 percent), chloroform (92.6 percent), and carbon tetrachloride (96.4 percent).

3.3 POTENTIAL PLUME DISPLACEMENT

As discussed in Section 3.1, an evaluation of ORP and other parameters concluded that the treatment zone extended at least 15 feet from the injection boreholes. As described in Section 3.2, groundwater within this treatment zone experienced a significant reduction in VOC concentrations. Decreases in VOC concentrations coinciding with strongly reducing conditions and increases in other parameters such as pH, dissolved iron, and dissolved gases indicate the breakdown of chlorinated VOCs. However, because a reduction in VOC concentrations could also be interpreted as the result of plume displacement rather than treatment, sampling locations outside the treatment zone were monitored for potential increases in contaminant concentrations; any such increases would suggest some degree of contaminant displacement. To assess whether these increases were significant, post-injection contaminant concentrations at these locations, including one monitoring well location screened beneath the treatment zone, were statistically compared with baseline concentrations based on a two-tailed t-test at the 95 percent confidence level.

At locations outside of the treatment zone, the mean concentration of TCE in groundwater decreased by 740 µg/L (Table 8). However, this overall decrease is largely due to a particularly significant decrease in the TCE concentration at IR28MW360F. At this location, concentrations decreased from a baseline of 7,400 µg/L to a post-injection mean of 640 µg/L. Increases in ethane and ethene concentrations were also observed at well IR28MW360F; however, the overall increase in ORP and the distance of this well from the nearest injection borehole suggest that this location is outside the treatment zone. This well may lie in a transition zone that displays a mixture of characteristics typically seen either within or outside of the treatment zone. Excluding this well, the mean concentration of TCE in groundwater at locations outside the treatment zone increased slightly after injection, by 15 µg/L. This increase is minor in comparison with the decrease of the mean concentration of TCE by 27,000 µg/L within the treatment zone. A two-tailed t-test demonstrated that the increase of 15 µg/L outside of the treatment zone is not statistically significant at the 95 percent confidence interval. Similar minor increases in the mean concentrations of PCE, total chlorinated ethenes, and chloroform outside the treatment zone were not significant at the 95 percent confidence interval. A minor increase in TCE concentrations below the treatment zone at the deep well IR28MW351F, from 39 µg/L to a post-injection mean of 41 µg/L, also was not significant.

3.4 METALS ANALYSIS

Metals analyses were conducted to evaluate the potential mobilization of arsenic and manganese from subsurface soil and increases of iron in groundwater as a result of the Ferox^{sm} injections. Table 9 summarizes the results for dissolved arsenic, total iron, dissolved iron, and dissolved manganese in samples from nine locations within and outside the treatment zone. Within the treatment zone, arsenic was not detected during any of the sampling rounds, and the mean concentrations of dissolved manganese decreased slightly. Increases in the mean concentrations of total iron and dissolved iron within the treatment zone can be attributed to the injection of ZVI.

Post-injection concentrations of arsenic and manganese were statistically compared with baseline concentrations to assess whether changes were significant based on a two-tailed t-test at the 95 percent confidence interval. Statistical evaluations for arsenic and manganese demonstrated that the changes were not significant at the 95 percent confidence interval. Comparisons were made for each metal for wells within the treatment zone, outside of the treatment zone, and for all wells combined.

3.5 NITRATE ANALYSIS

Sampling for nitrate was included during this demonstration to evaluate potential nitrate formation in groundwater as a result of the Ferox^{sm} injections. Tetra Tech collected groundwater samples from six monitoring wells, located at distances up to 19.5 feet from injection boreholes, for analysis of nitrate. Table 10 presents the results of nitrate monitoring at the six wells, including four wells within the treatment zone and two wells outside the treatment zone. Within the treatment zone, the average nitrate concentration was reduced from a baseline of 3,400 μg/L to 230 μg/L after the injection process was complete. This reduction indicates a decrease of 3,200 μg/L, or 94.1 percent. In addition, results indicate that chemical reduction of nitrate was occurring in the treatment zone as a result of the strongly reducing conditions present after the injection process was complete. At the two monitoring wells outside the treatment zone (at 18.6 and 19.5 feet from the injection boreholes), the average nitrate concentration was 2,600 μg/L before and injection.

4.0 COST SUMMARY

This section summarizes the cost for the field-scale application of the Ferox^{sm} technology at RU-C4 (Section 4.1) and provides a comparison of the cost to implement the Ferox^{sm} technology against a comparable remedial technology, in situ chemical oxidation (Section 4.2).

4.1 COST FOR FIELD-SCALE APPLICATION AT RU-C4

While the costs associated with a Ferox^{sm} technology application at another location will vary based on the scale of the application, contaminant types and levels, and regulatory criteria, this summary provides a representative example of a small, field-scale application.

Since certain management and administrative costs of the engineering consultant (Tetra Tech) were incurred for demonstration aspects of the project only, the costs associated with the following work elements of the engineering consultant were excluded from this summary:

- Demonstration plans (work plans, health and safety plan, and demonstration-derived waste plan)
- Project management, including project coordination, progress reporting, and contractor procurement
- Contractor oversight and health and safety oversight

It should also be noted that minimal permitting and regulatory costs were incurred due to the nature of this demonstration and that long-term groundwater monitoring, which may or may not be required at some sites, was not included in this project.

Table 11 summarizes the costs incurred to conduct the field-scale technology demonstration in the following categories: (1) mobilization and demobilization, (2) equipment and supplies for injection, (3) labor for injection, (4) drilling services for injection, (5) sampling and analysis, (6) demonstration-derived waste disposal, and (7) other. The basis for each of these cost elements is discussed in the sections below.

The total cost of the field-scale application at RU-C4 was $289,274, or $172 per cubic yard of the treatment zone. Excluding sampling, analytical, and demonstration-derived waste management costs, the total cost was $196,665, or $117 per cubic yard.

4.1.1 Mobilization and Demobilization

Mobilization costs included transporting the Ferox^{sm} equipment and labor for the technology vendor's three-person field team. Lodging and per diem were also included for the vendor's personnel to drill the injection boreholes and conduct injection operations. For this field-scale application, ARS mobilized equipment and personnel from New Brunswick, New Jersey, to San Francisco, California (3,000 miles). ARS subcontracted a licensed driller who was local to the area (Section 4.1.4).

4.1.2 Equipment and Supplies for Injection

Costs for equipment used by the injection technology vendor included a Ferox^{sm} injection trailer, injection nozzles and packer assemblies, survey equipment, water pumps, generator, support truck, and forklift. Costs for supplies used by the technology vendor included ZVI powder, compressed nitrogen, health and safety supplies, and other consumables such as equipment parts. For the water source, nominal costs were incurred for rental of hose and fittings to connect to a nearby fire hydrant, and no costs were incurred for water use.

4.1.3 Labor for Injection

Costs for labor were incurred by ARS Technologies, the Ferox^{sm} technology vendor. Labor for the field-scale application included a three-person field team, consisting of a project engineer and two remediation technicians. Labor also included the vendor's principal, regional manager, and corporate health and safety officer. Labor was conducted to develop the technology design, plan field work, assemble and operate equipment in the field, and prepare a field summary report.

4.1.4 Drilling Services for Injection

Costs for drilling services are for a licensed driller to install the four injection boreholes, lower and raise injection and packer equipment, assist the Ferox^{sm} technology vendor with equipment operation and maintenance, and convert one of the four injection boreholes to a permanent monitoring well. The driller used 4.25-inch solid flight augers using a Deep Rock Model 10K drill rig to install four boreholes to a depth of 32 feet. Immediately following borehole installation, the driller installed steel casings with a 4⅝-inch diameter using a Precision SD-1 vibratory direct-push rig. During injection, the driller lowered and raised injection equipment as needed and assisted with other equipment. After injection, the monitoring well was completed to a depth of 20 feet with a polyvinyl chloride casing (2-inch diameter) and a screened interval of 10 to 20 feet.

4.1.5 Sampling and Analysis

Sampling and analysis costs included sampling labor, equipment, supplies, laboratory analysis, and data validation costs. Groundwater samples were collected from 19 locations during each of four rounds of sampling. Sampling equipment and supplies included an organic vapor monitor, water level meter, water quality meter, pump, bailers, hose for purging, generator, filters (for dissolved analyses), and sample shipment supplies. Analyses were conducted for VOCs, dissolved gases (ethane, ethene, and hydrogen), dissolved arsenic, dissolved iron, total iron, dissolved manganese, chloride, alkalinity, and nitrate. A data validation vendor conducted validation of VOC and metal data.

4.1.6 Demonstration-Derived Waste Disposal

Costs for demonstration-derived waste disposal included analysis and off-site disposal of soil cuttings from the four injection boreholes as well as decontamination and purge water. Demonstration-derived water waste was discharged to the local publicly owned treatment works.

4.1.7 Other

The process technique of pneumatic fracturing, which was used at RU-C4, is a proprietary technology licensed to ARS by the New Jersey Institute of Technology (NJIT). Because ARS employs pneumatic fracturing to augment in its Ferox^{sm} method of ZVI delivery to the subsurface, other costs incurred for the demonstration included a royalty to NJIT.

4.2 COST COMPARISON

To obtain perspective on the economic benefits of the Ferox^{sm} technology, the unit cost of implementing the Ferox^{sm} technology as part of the field demonstration at HPS was compared with the cost of a comparable for VOCs, chemical oxidation. As with the Ferox^{sm} technology, chemical oxidation involves delivery of a reagent by injection into the contaminant zone to achieve in situ treatment. Application of in situ chemical oxidation involves the injection of chemical oxidants such as hydrogen peroxide, potassium permanganate, or sodium permanganate, while the Ferox^{sm} technology delivers ZVI to the contaminant zone. Thus, the primary difference between these two technologies is that the Ferox^{sm} technology relies on chemical reduction of contaminants whereas in situ chemical oxidation relies on oxidation.

Unit costs for remediation using either the Ferox^{sm} technology or chemical oxidation are affected by several factors, primarily including the size of the contaminant zone, reagent cost (such as ZVI or chemical oxidant), field implementation costs (such as drilling and infrastructure), monitoring requirements, and cleanup goals. Depending on the site characteristics and the distribution and quantity of contaminants, the unit cost for the same contaminants with the same technology at different locations could be quite different.

Unit costs were reported for in situ chemical oxidation in a technology evaluation report on in situ chemical treatment (Yin and Allen 1999). Unit costs for in situ chemical oxidation by injecting potassium permanganate, the most common chemical oxidant utilized with this technology, were reported to range from $40 to $240 per cubic meter, or $31 to $183 per cubic yard. This range of unit costs was reported for three different delivery methods: soil fracturing with potassium permanganate oxidative particle mixture ($40 per cubic meter), soil mixing with potassium permanganate injection ($170 per cubic meter), and horizontal well flushing with potassium permanganate ($240 per cubic meter).

5.0 CONCLUSIONS AND IMPLEMENTATION ISSUES

This section summarizes the conclusions of this demonstration, considering the objectives established for the project, and recommendations based on implementation issues that arose during the project. The overall objective of the demonstration was to evaluate the technology's cost and performance in destroying chlorinated VOCs in the source area at RU-C4. The following specific objectives were established in the work plan and sampling and analysis plan (Tetra Tech 2002):

- Assess the horizontal zone of influence
- Evaluate the percent reduction of four chlorinated ethenes of concern (TCE, PCE, 1,2-DCE, and vinyl chloride), total chlorinated ethenes, and two additional VOCs of concern (chloroform and carbon tetrachloride)
- Evaluate potential plume displacement that could result from the injection
- Evaluate potential mobilization of metals in groundwater
- Evaluate potential nitrate formation in groundwater

With respect to the specific project objectives stated above, the following conclusions were drawn based on operational data and groundwater measurements taken during this demonstration:

- Injections were successfully completed over a vertical interval from about 7 to 32 feet bgs in the treatment zone. Over 16,000 pounds of ZVI powder were injected at four injection boreholes, causing strongly reducing conditions in groundwater within 15 feet of the boreholes and covering an area of about 1,818 square feet. Therefore, the estimated subsurface treatment volume was 1,683 cubic yards.

- The mean ORP decreased from a baseline average of 87.4 mV to a post-injection mean of –372 mV within the treatment zone. The reducing conditions still existed 12 weeks after injection (as of post-injection sampling round 3), with a mean ORP of –335 mV.

- TCE concentrations within the treatment zone decreased from a baseline average of 27,000 μg/L to a post-injection average of 220 μg/L. Reduction percentages for TCE and other target VOCs were as follows:
  - TCE: 99.2 percent
  - PCE: 99.4 percent
  - cis-1,2-DCE: 94.2 percent
  - Vinyl chloride: 99.3 percent
  - Total chlorinated ethenes: 99.1 percent
  - Chloroform: 92.6 percent
  - Carbon tetrachloride: 96.4 percent

- TCE was reduced almost completely to ethene and chloride based on the achievement of similar overall reductions in the concentrations of TCE and its intermediate degradation products (cis-1,2-DCE, trans-1,2-DCE, 1,1-DCE, and vinyl chloride).

- Treatment of TCE occurred rapidly, with most reductions observed within 3 weeks after the injection process was complete.

- Reducing conditions, coincident with increases in the concentrations of the dissolved gas byproducts of dechlorination (ethane, ethene, and hydrogen), provided direct evidence of treatment.

- Concentrations of TCE and other target chlorinated VOCs did not increase significantly outside of the treatment zone, providing evidence that no significant displacement of contaminants occurred away from the treatment zone, either laterally or downward.

- No significant increases in the concentration of arsenic or manganese were observed after injection.

- Results of nitrate monitoring before and after injection indicated that denitrification was occurring in the treatment zone as a result of the reducing conditions present after ZVI was injected.

- The total cost of the field-scale application at RU-C4 was $289,274, or $172 per cubic yard of the treatment zone. Excluding sampling, analytical, and demonstration-derived waste management costs, the total cost was $196,665, or $117 per cubic yard.

- The unit cost per volume of treatment zone is primarily dependent on the scale of the application; specifically, the size of the treatment zone and the amount of iron needed to initiate the reducing conditions required for chemical dechlorination. The unit costs for larger-scale applications are expected to be somewhat lower due to economies of scale for some cost items.

The following recommendations for future applications of this technology are based on implementation issues that arose during the demonstration:

- The reducing environment created by the injection of ZVI at RU-C4 did not adversely affect metals and nitrate concentrations. Pending regulatory approval, future applications should not require these parameters for groundwater monitoring.

- Although a strongly reducing environment was still present in the subsurface 12 weeks after the injection process was complete, most treatment of TCE occurred within 3 weeks. Future applications should require fewer or less frequent post-injection rounds of groundwater monitoring.

- Near complete destruction of chlorinated VOCs occurred within the treatment zone, and no significant displacement was observed outside the treatment zone. Depending on site conditions, future applications may require fewer monitoring locations to evaluate potential displacement.

- A temporary steel casing was installed at each injection borehole in RU-C4 after drilling to prevent caving of loose formation materials. Future applications should evaluate the threat of caving and whether a temporary casing is required prior to injections.

6.0 REFERENCES

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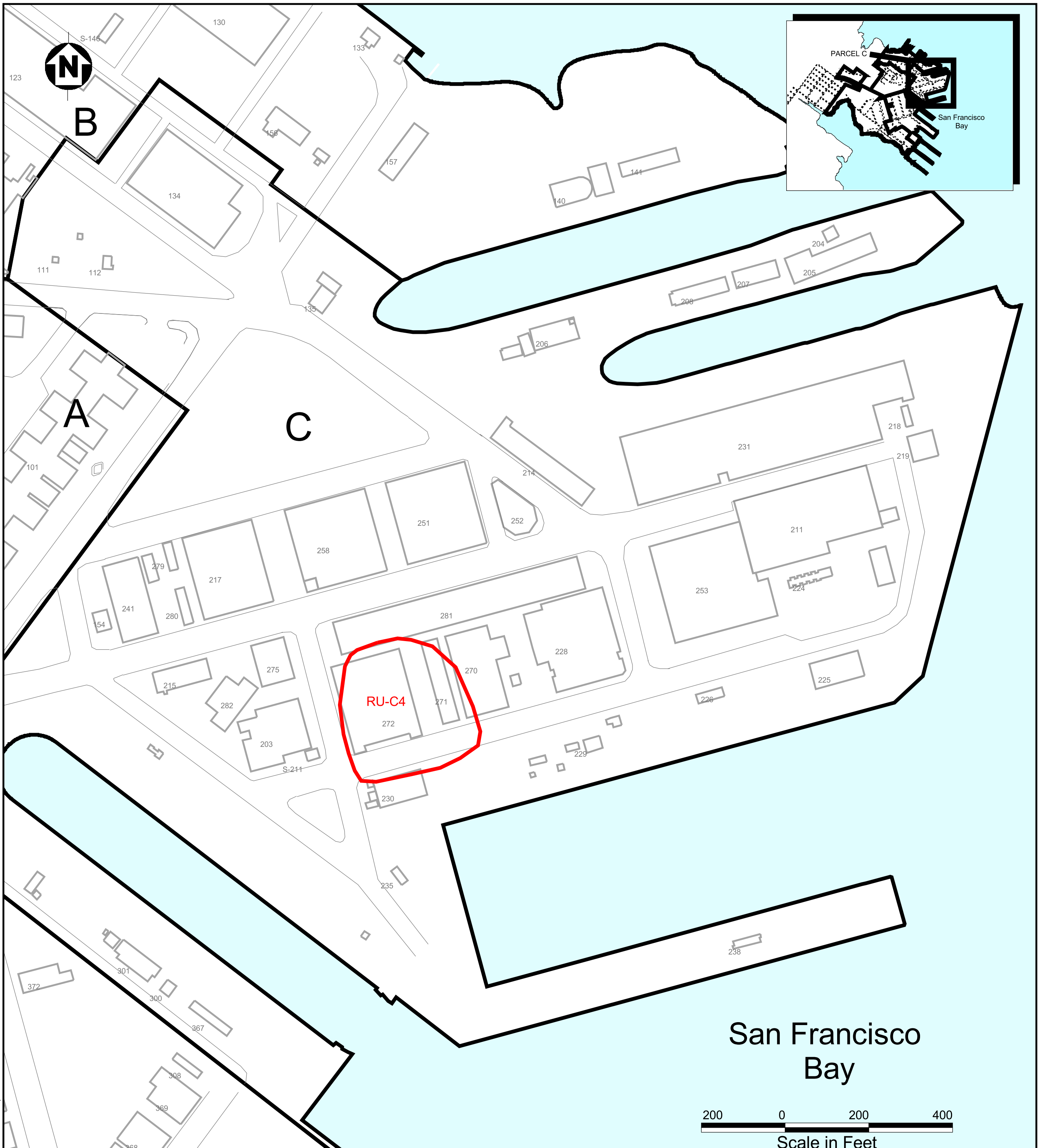
FIGURES



Remedial Unit Boundary
Road
369 Building/Building Number
Parcel Boundary

Tetra Tech EM Inc.

Hunters Point Shipyard, San Francisco, California
U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 1
SITE LOCATION

Final Cost and Performance Report
Ferox(SM) Injection Technology Demonstration

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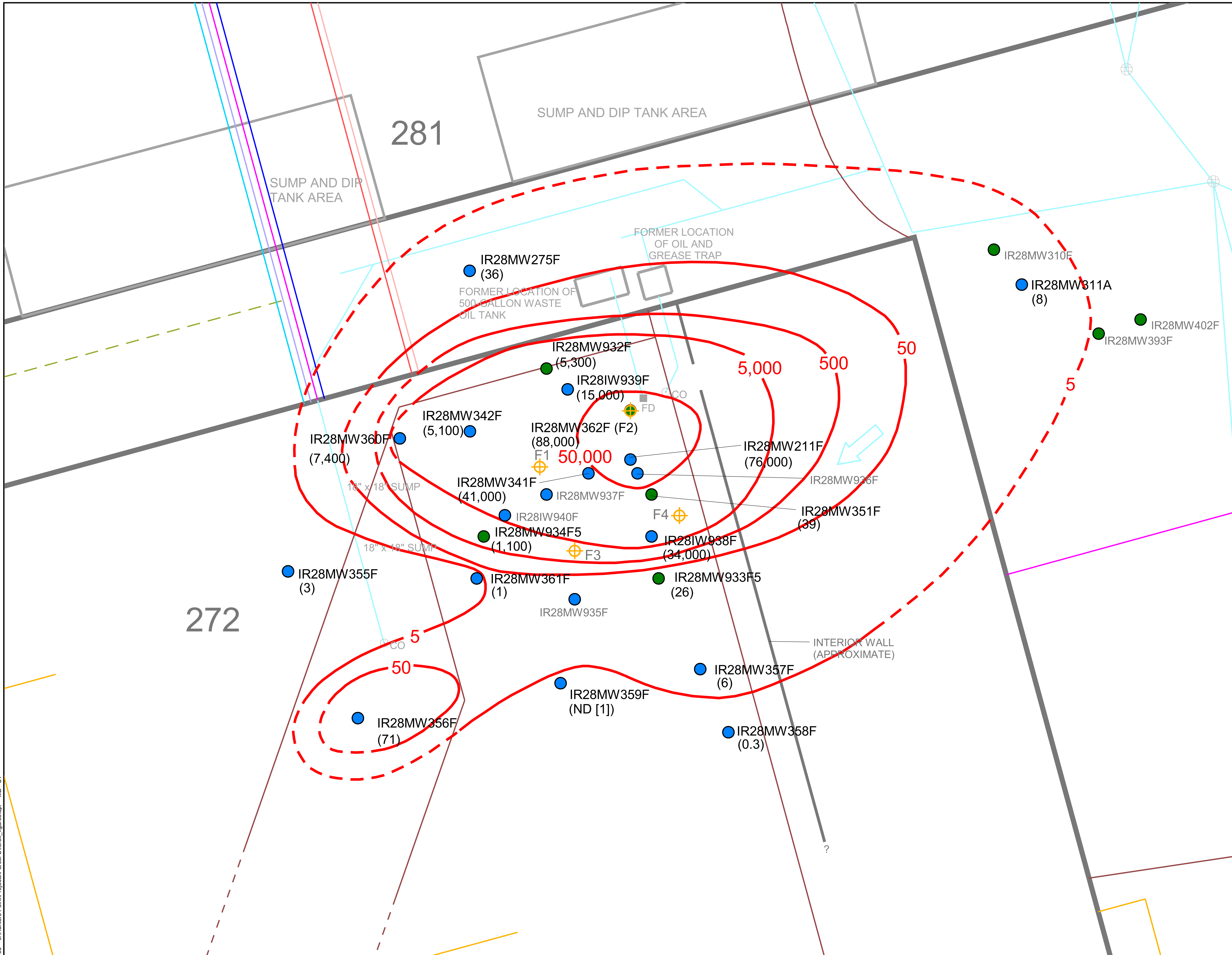
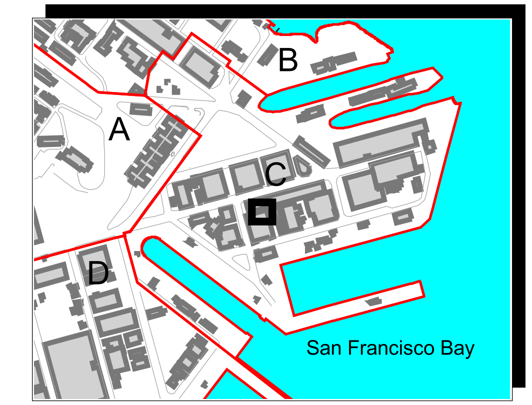




Location Map

- A-Aquifer Monitoring Well
- Bedrock Water-Bearing Zone Monitoring Well
- IR28MW311A (8) — TCE Concentrations (micrograms per liter)
- IR28MW351F — Well Not Sampled
- Injection Borehole
- TCE Isoconcentration Contour (micrograms per liter) (dashed where inferred)
- CO — Clean Out
- FD — Floor Drain
- Storm Drain Inlet
- Approximate Direction of Groundwater Flow
- 272 — Building/Building Number
- Air not verified
- Electrical overhead not verified
- Electrical underground not verified
- Fresh water not verified
- Gas not verified
- Saltwater not verified
- Sanitary sewer not verified
- Steam condensate not verified
- Steam not verified
- Storm drain

Notes:

1. Utility locations taken from U.S. Navy drawing Quad. D-2, August 3, 1955 and Tetra Tech EM Inc., Hunters Point Shipyard Index Drawing No. 0712.
2. Utilities dashed where inferred

TCE Trichloroethene

? Not verified

N

12 0 12

Scale in Feet

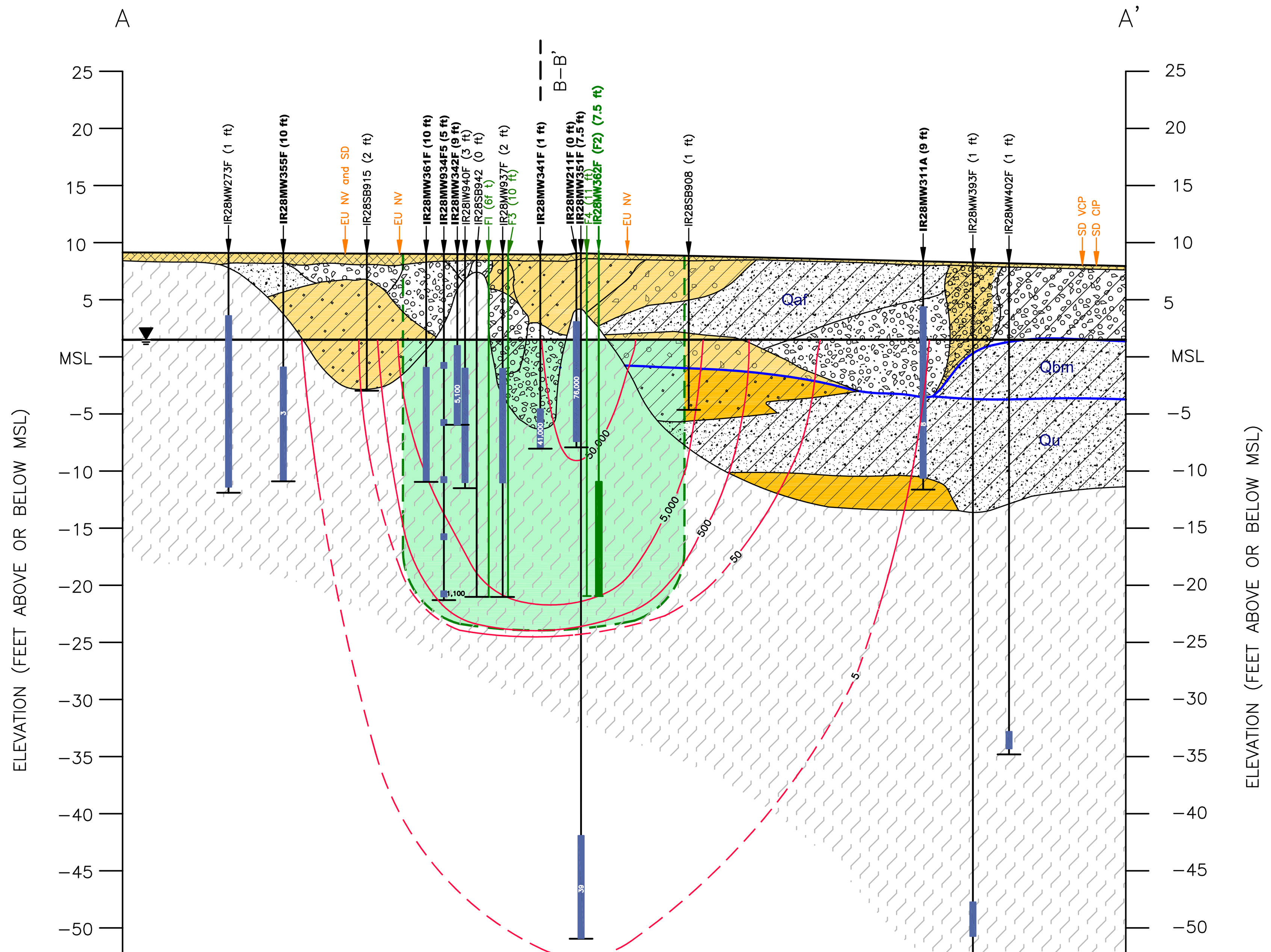
Tetra Tech EM Inc.

Hunters Point Shipyard, San Francisco, California

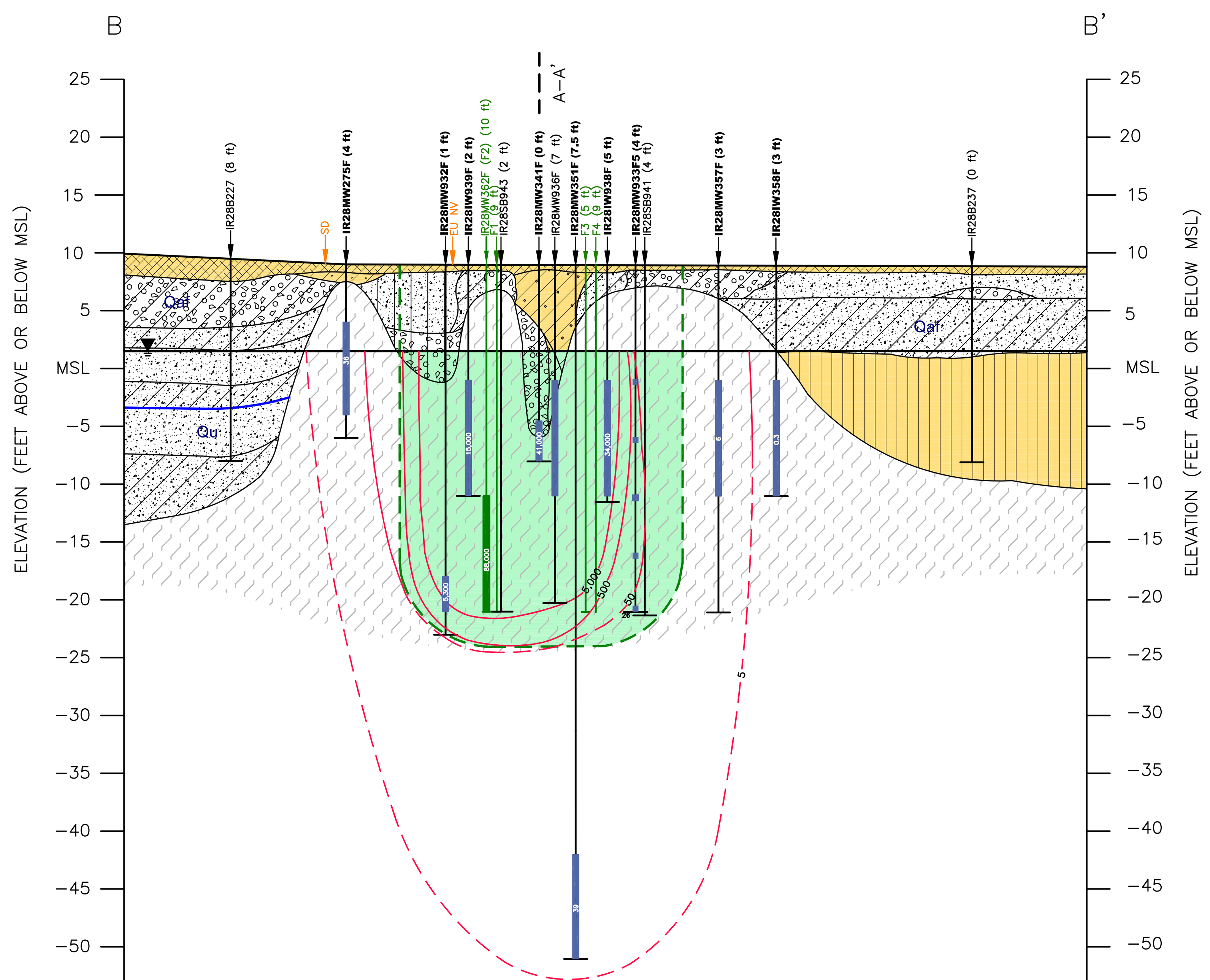
U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 2
BASELINE TCE ISOCONCENTRATION CONTOURS

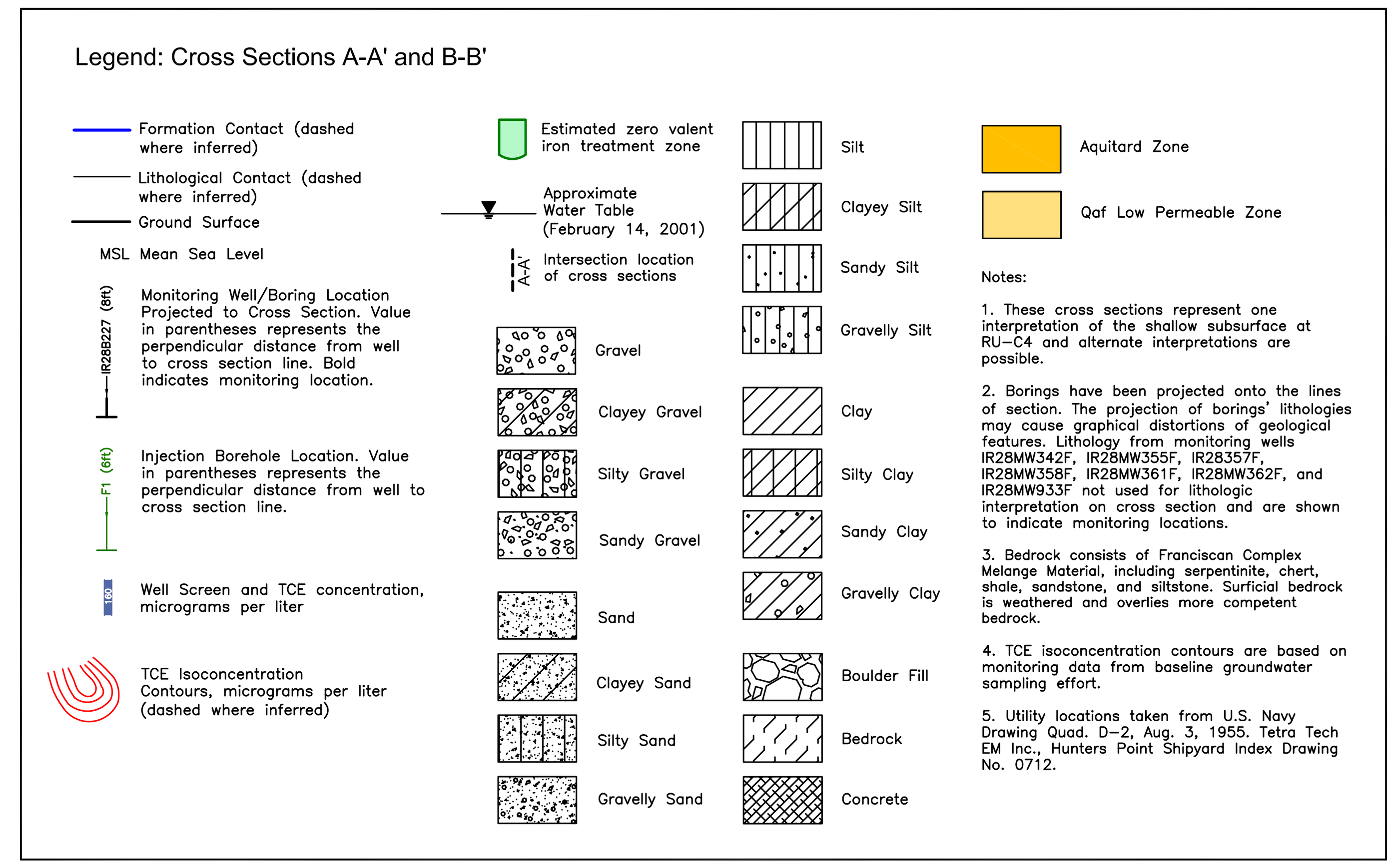
Final Cost and Performance Report
Ferox[SM] Injection Technology Demonstration

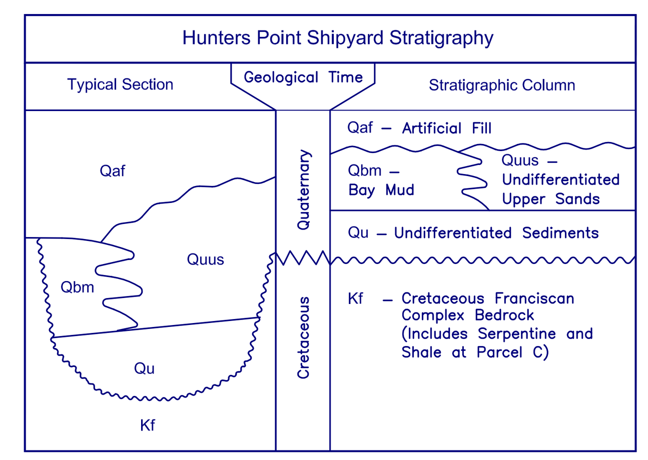


Cross Section A-A'

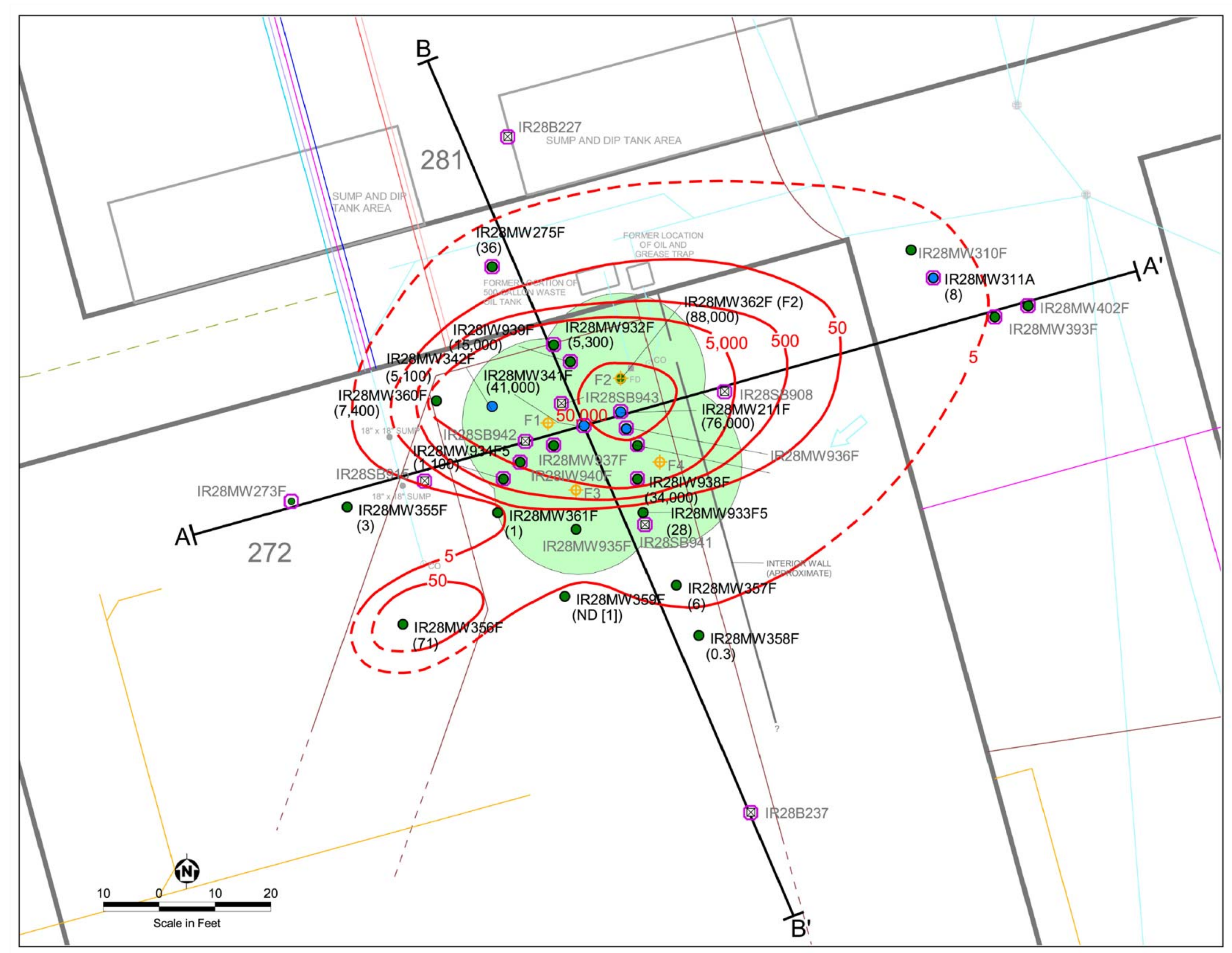


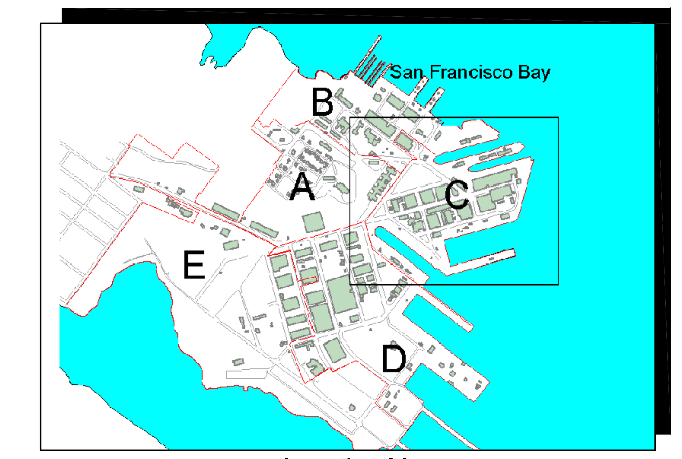
Cross Section B-B'



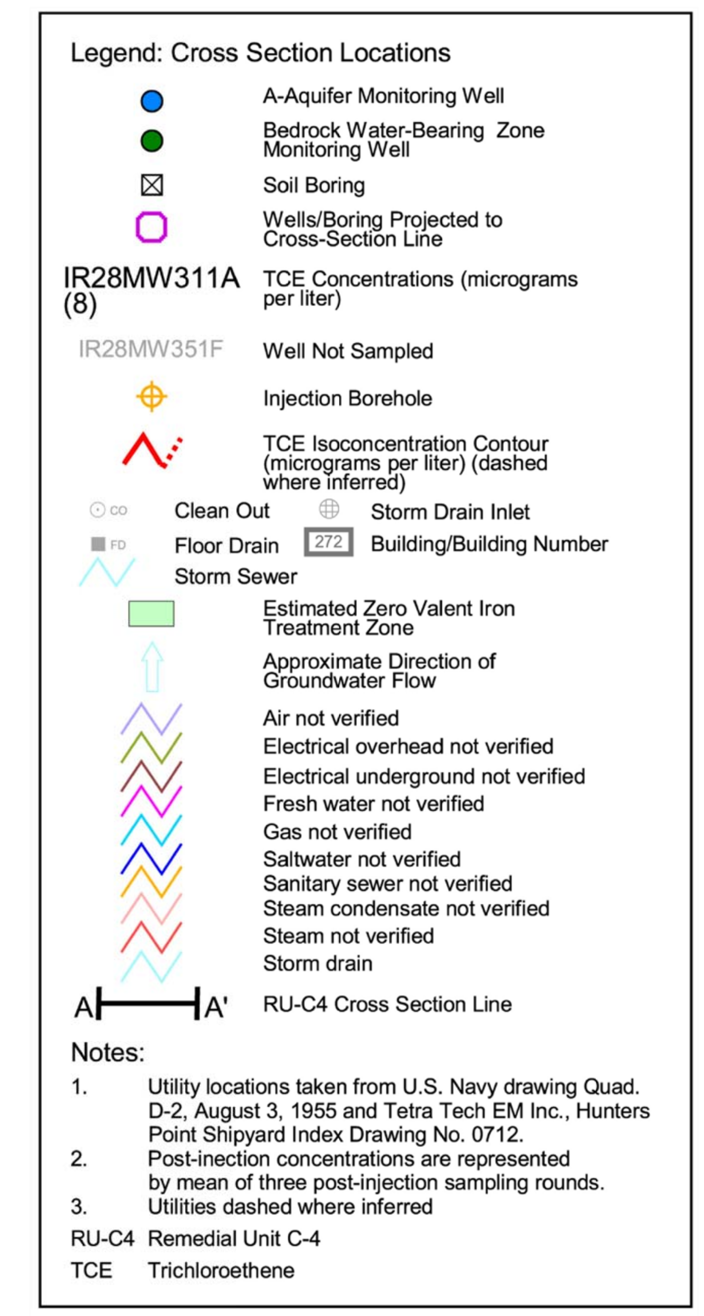


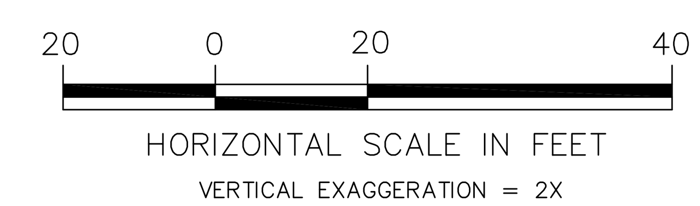
Cross Section Locations





Location Map





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U.S. Navy Southwest Division, NAVFAC, San Diego

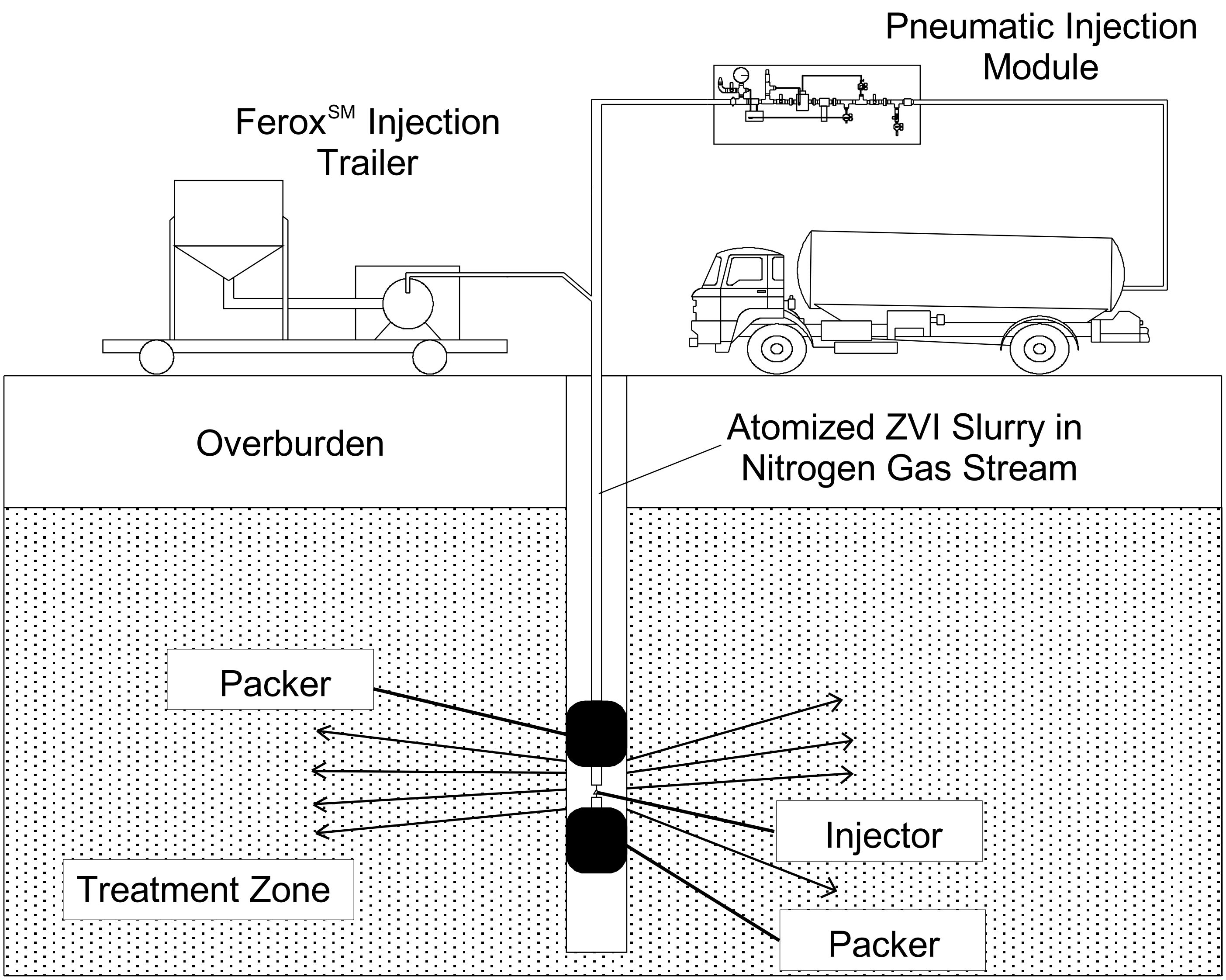
FIGURE 3

HYDROGEOLOGIC CROSS SECTION AND BASELINE TCE ISOCONCENTRATION CONTOURS

Final Cost and Performance Report

Ferox[SM] Injection Technology Demonstration

DATE: 07/09/03 DRIVE:\PATH GH SEATTLE, WASHINGTON



Note:
ZVI - Zero-valent iron

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U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 4
SCHEMATIC DIAGRAM OF THE FEROX^{SM} INJECTION PROCESS

Final Cost and Performance Report
Ferox^{SM} Injection Technology Demonstration

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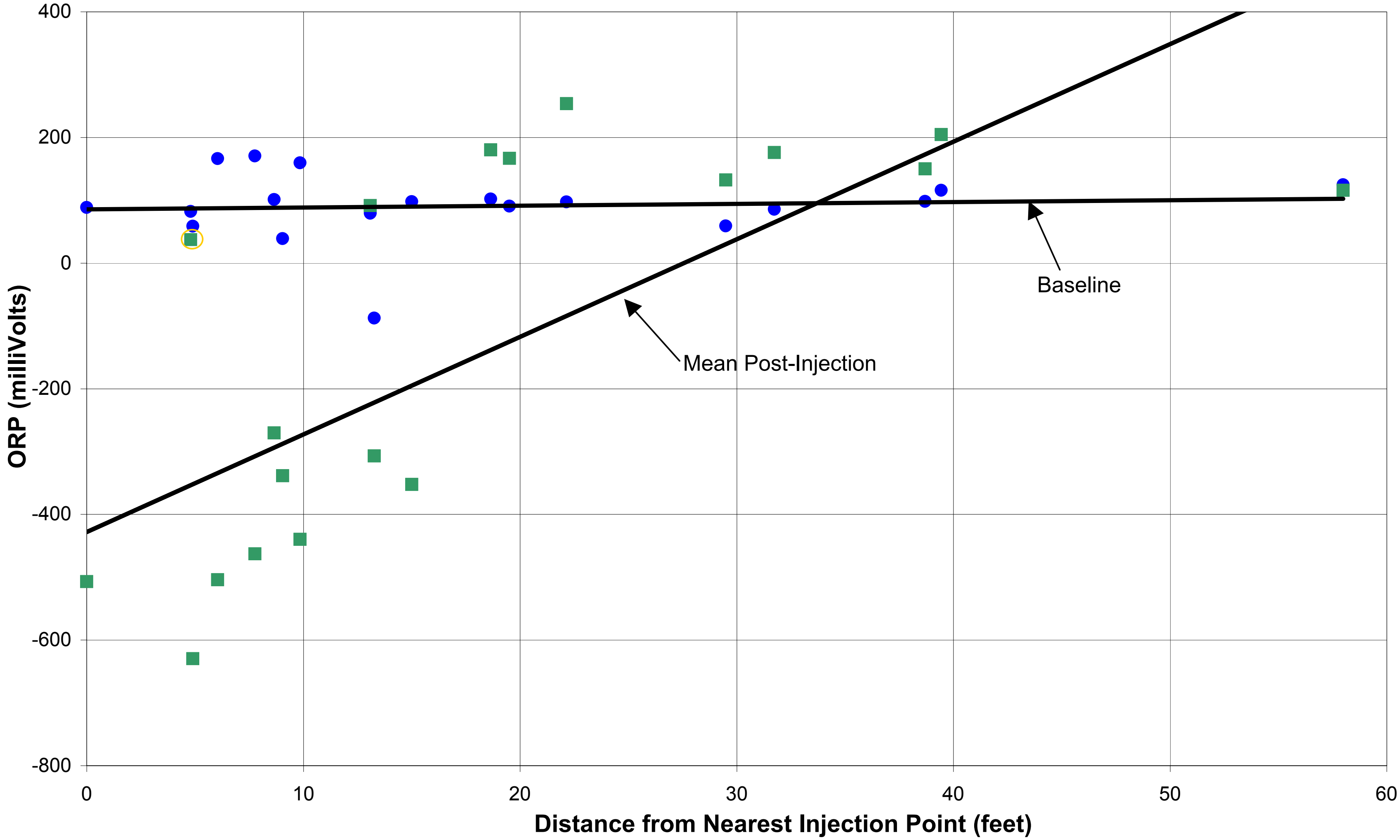

- Baseline data point
- Mean post-injection data point
- Result from monitoring well screened below treatment zone and excluded from trendline analysis of post-injection results

Notes: Post-injection concentrations are represented by the mean of three post-injection sampling rounds.

ORP Oxidation-reduction potential

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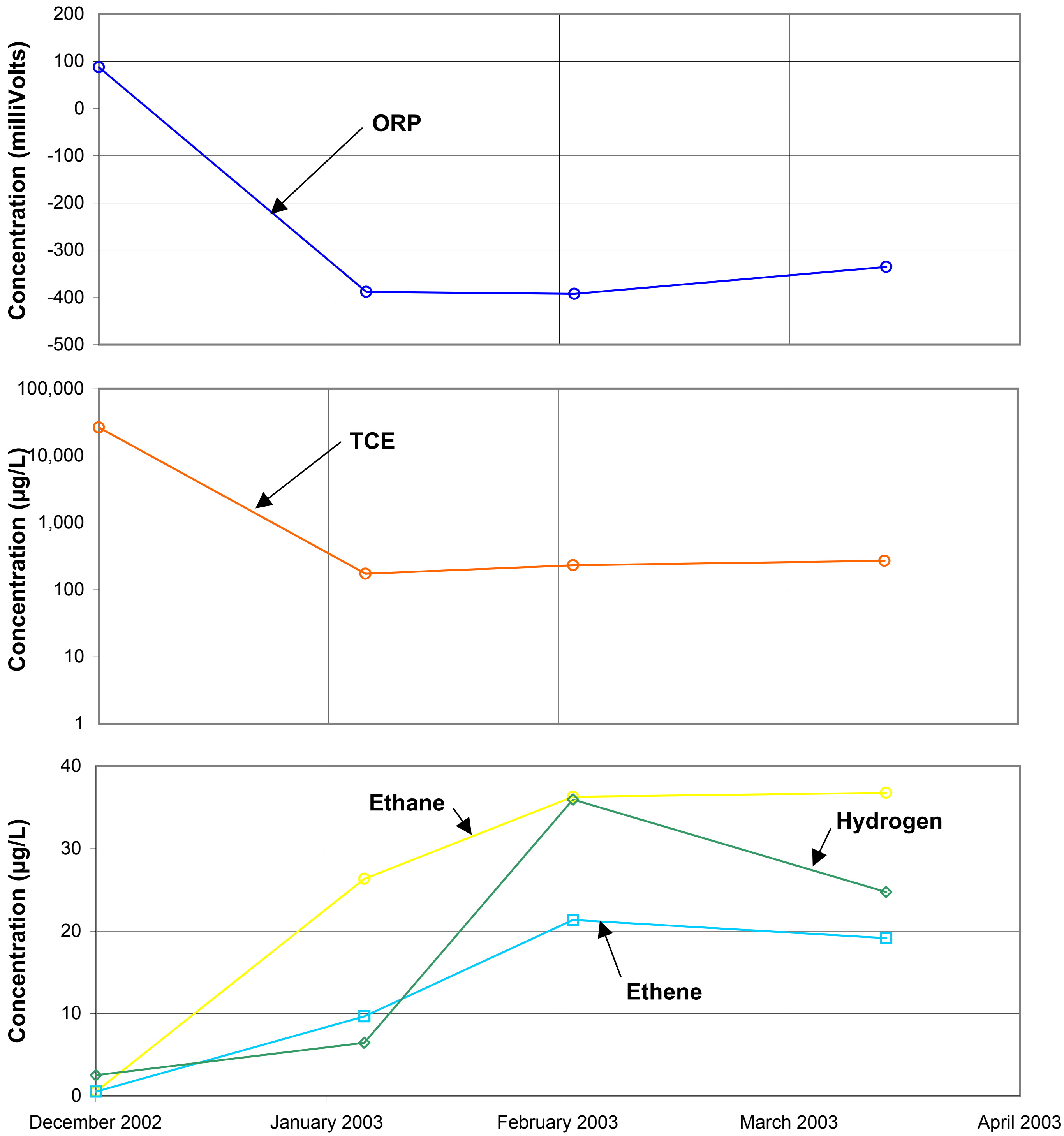
U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 5
BASELINE AND POST-INJECTION ORP

Final Cost and Performance Report
Ferox^{SM} Injection Technology Demonstration



Tetra Tech EM Inc.

Notes:

µg/L	Micrograms per liter
ORP	Oxidation-reduction potential
TCE	Trichloroethene

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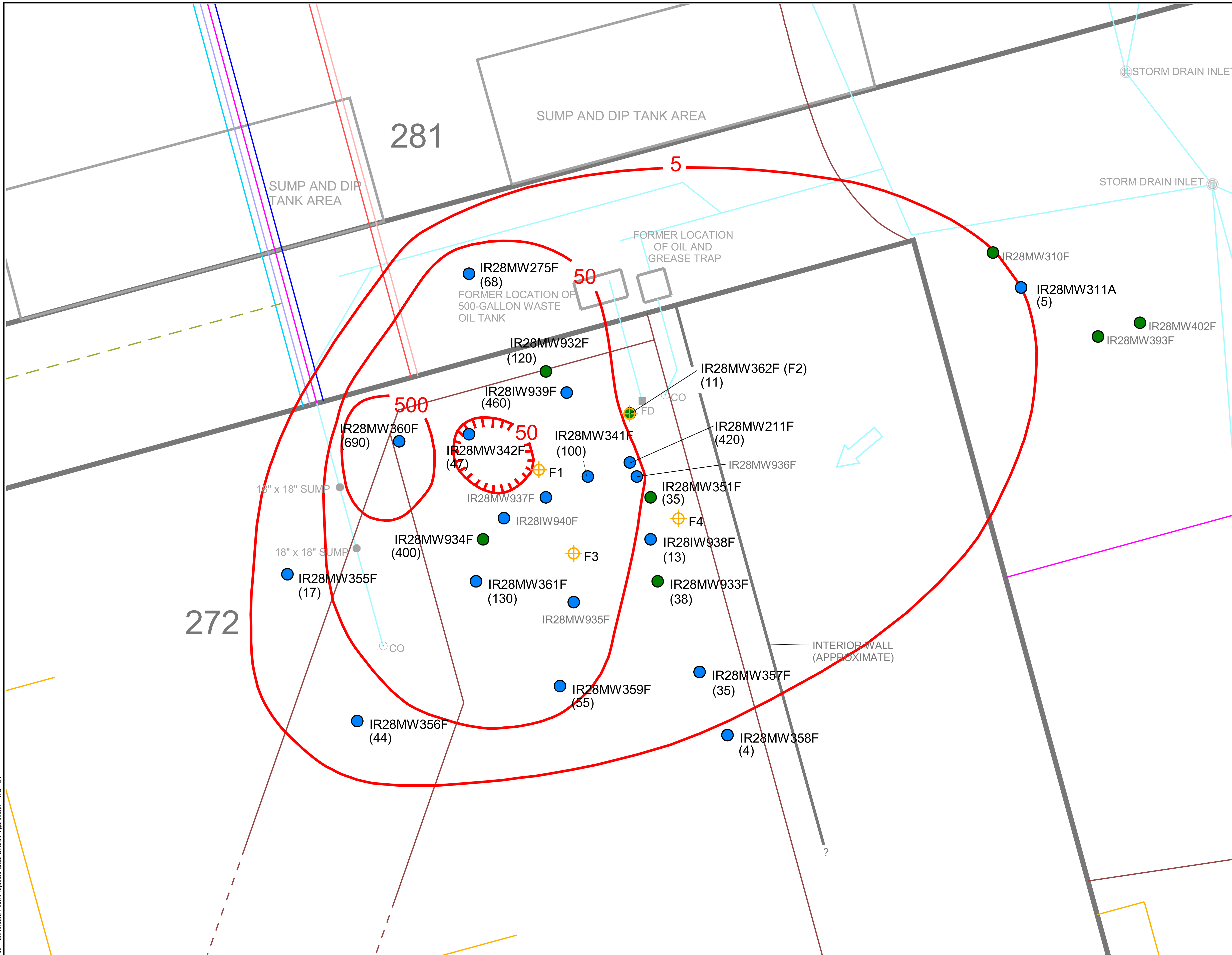
U.S. Navy Southwest Division, NAVFAC, San Diego

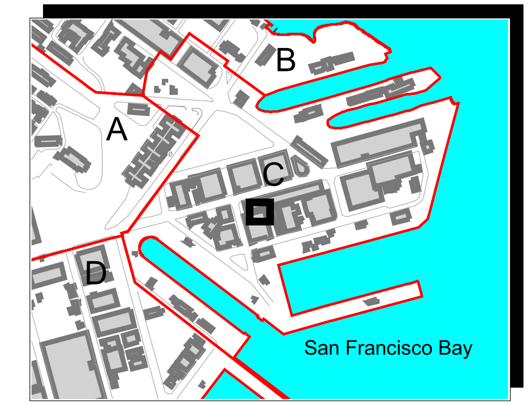
FIGURE 6

MEAN ORP, TCE, AND DISSOLVED GAS CONCENTRATIONS WITHIN TREATMENT ZONE

Final Cost and Performance Report

Ferox^{SM} Injection Technology Demonstration





Location Map

● (blue)	A-Aquifer Monitoring Well
● (green)	Bedrock Water-Bearing Zone Monitoring Well
IR28MW311A (5)	TCE Concentrations (micrograms per liter)
IR28MW351F	Well Not Sampled
	Injection Borehole
	TCE Isoconcentration Contour (micrograms per liter) (dashed where inferred)
CO	Clean Out
FD	Floor Drain
	Storm Drain Inlet
	Approximate Direction of Groundwater Flow
272	Building/Building Number
	Air not verified
	Electrical overhead not verified
	Electrical underground not verified
	Fresh water not verified
	Gas not verified
	Saltwater not verified
	Sanitary sewer not verified
	Steam condensate not verified
	Steam not verified
	Storm drain

Notes:

1. Utility locations taken from U.S. Navy drawing Quad. D-2, August 3, 1955 and Tetra Tech EM Inc., Hunters Point Shipyard Index Drawing No. 0712.
2. Utilities dashed where inferred

TCE Trichloroethene

? Not verified

N

12 0 12

Scale in Feet

Tetra Tech EM Inc.

Hunters Point Shipyard, San Francisco, California

U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 7
POST-INJECTION ROUND 1
TCE ISOCONCENTRATION CONTOURS

Final Cost and Performance Report
Ferox[SM] Injection Technology Demonstration

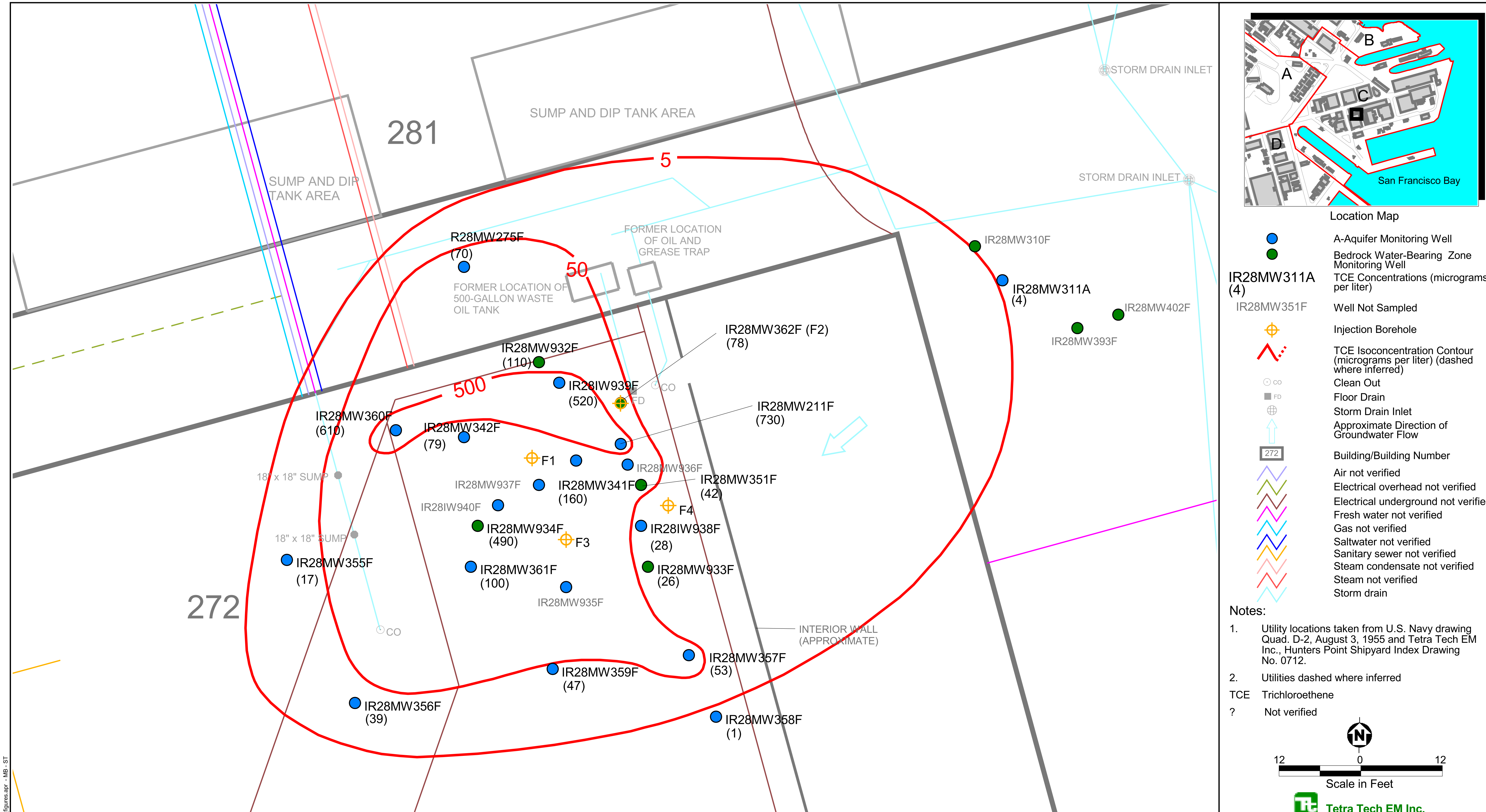


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FIGURE 8
POST-INJECTION ROUND 2
TCE ISOCONCENTRATION CONTOURS

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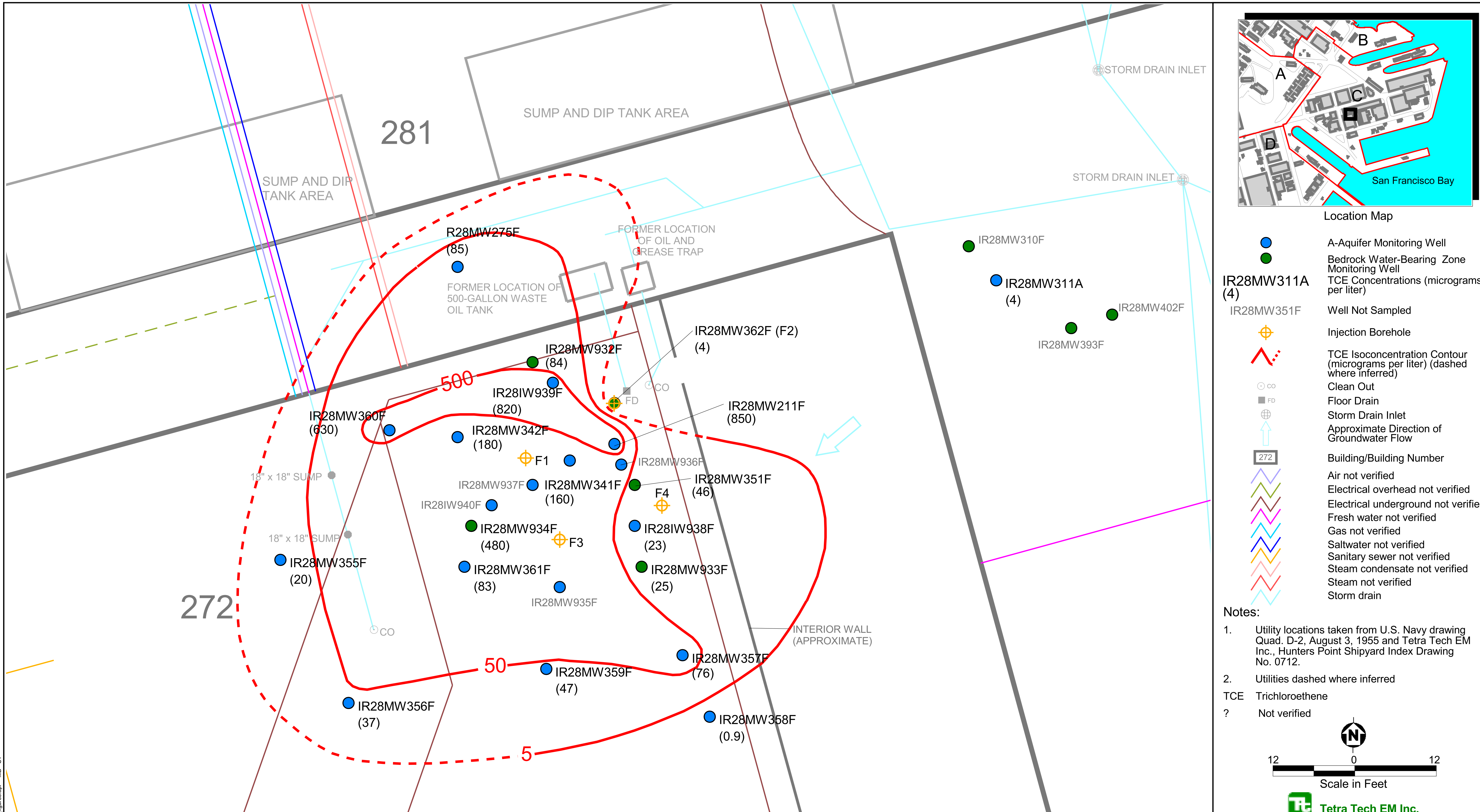
Ferox[SM] Injection Technology Demonstration



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U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 9
POST-INJECTION ROUND 3
TCE ISOCONCENTRATION CONTOURS

Final Cost and Performance Report
Ferox[SM] Injection Technology Demonstration

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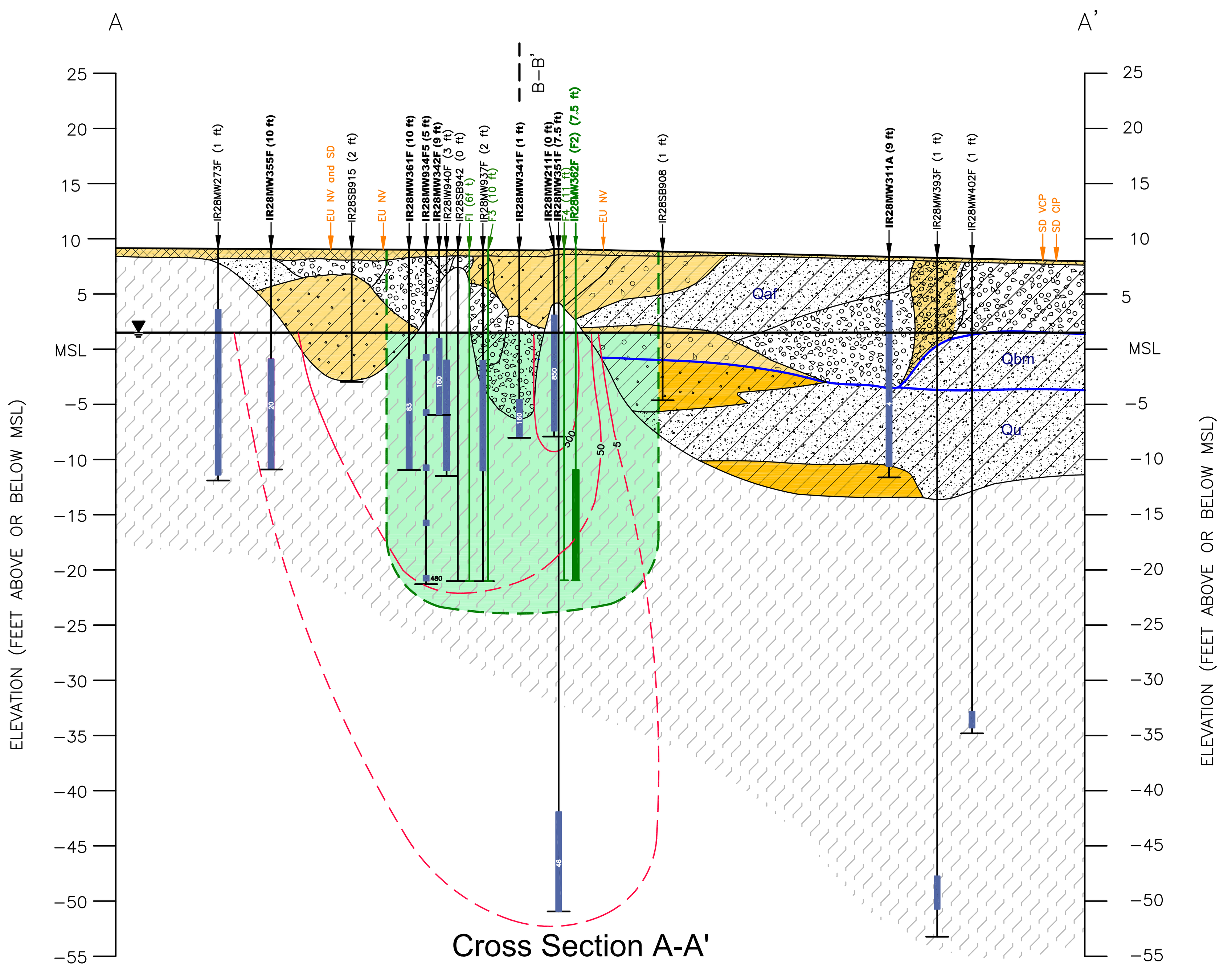
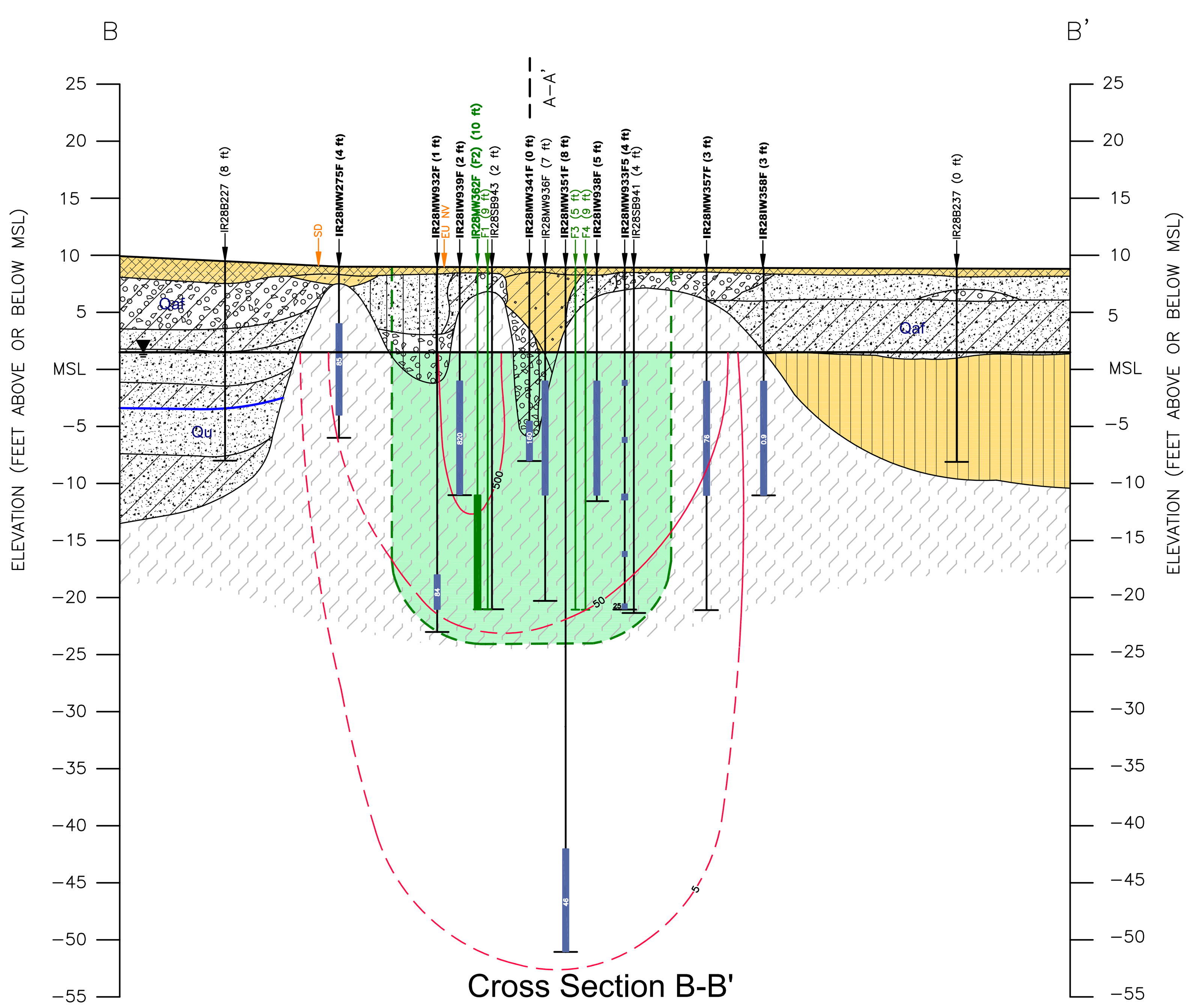
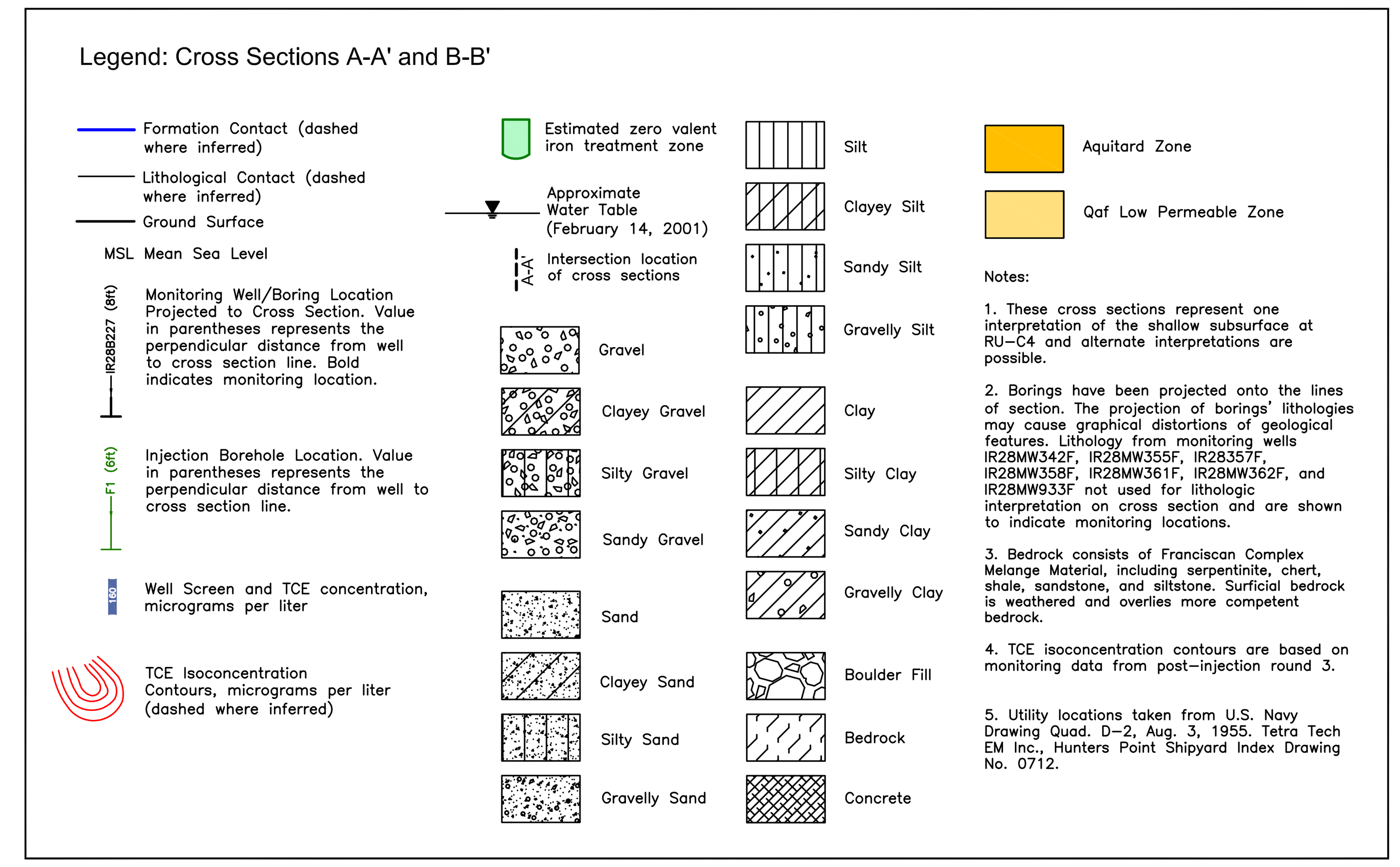


Cross Section A-A'



Cross Section B-B'



Notes:

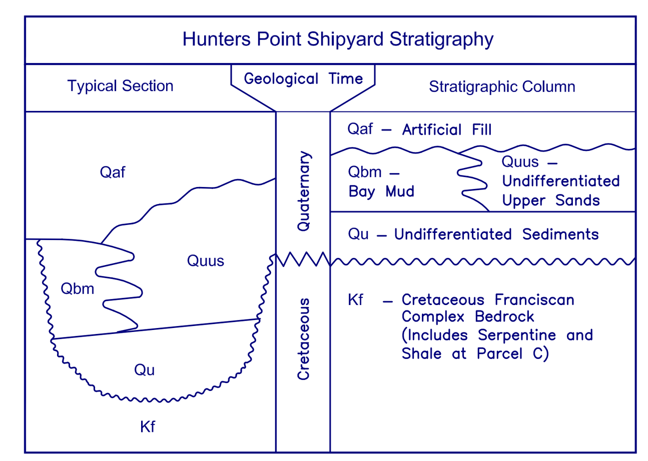
1. These cross sections represent one interpretation of the shallow subsurface at RU–C4 and alternate interpretations are possible.

2. Borings have been projected onto the lines of section. The projection of borings' lithologies may cause graphical distortions of geological features. Lithology from monitoring wells IR28MW342F, IR28MW355F, IR28357F, IR28MW358F, IR28MW361F, IR28MW362F, and IR28MW933F not used for lithologic interpretation on cross section and are shown to indicate monitoring locations.

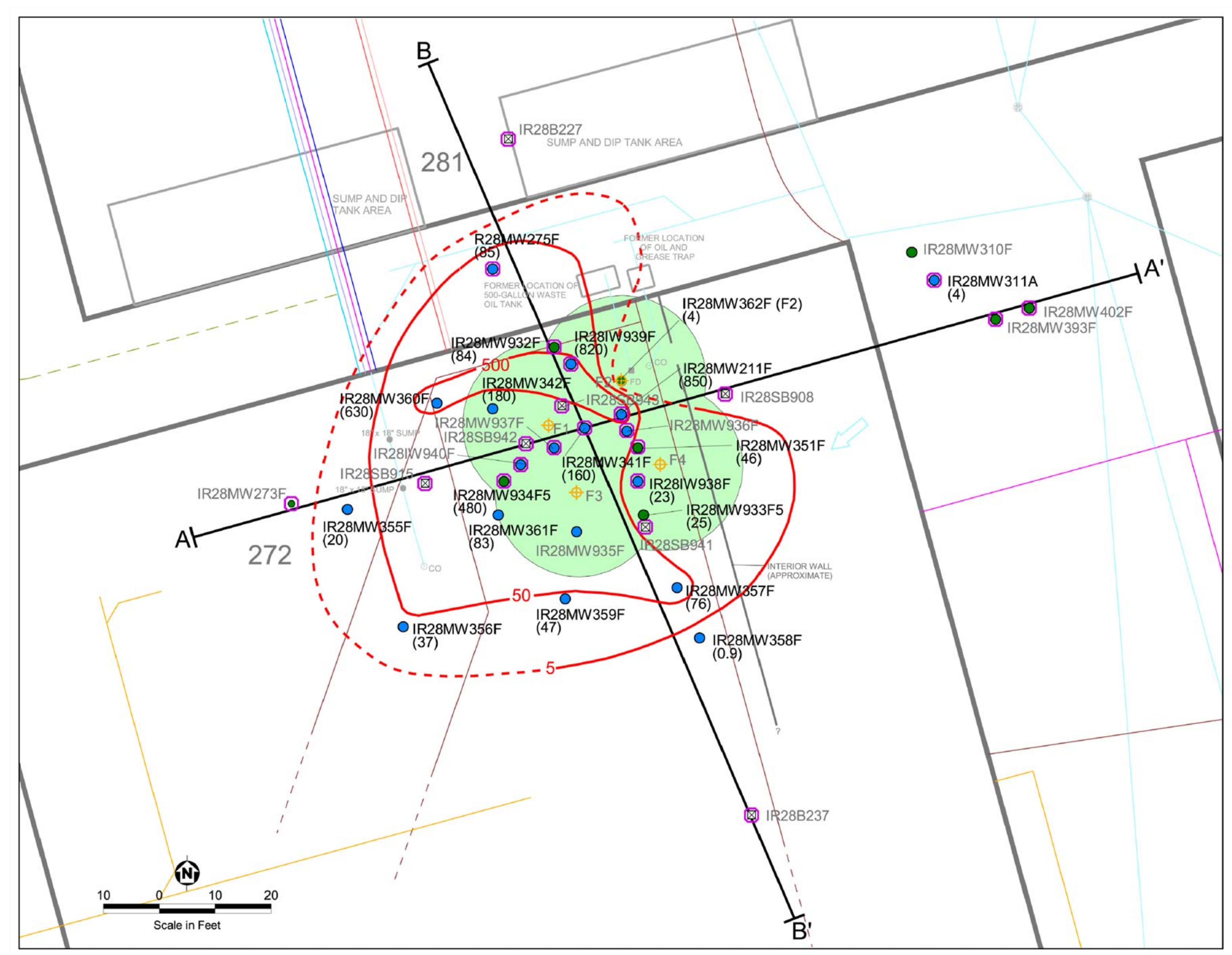
3. Bedrock consists of Franciscan Complex Melange Material, including serpentinite, chert, shale, sandstone, and siltstone. Surficial bedrock is weathered and overlies more competent bedrock.

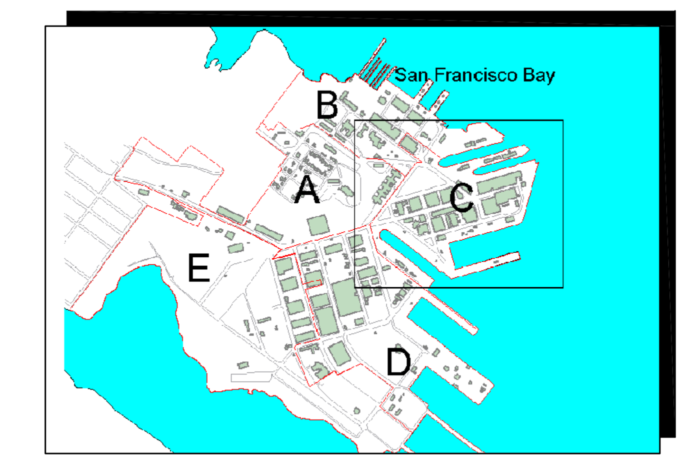
4. TCE isoconcentration contours are based on monitoring data from post–injection round 3.

5. Utility locations taken from U.S. Navy Drawing Quad. D–2, Aug. 3, 1955. Tetra Tech EM Inc., Hunters Point Shipyard Index Drawing No. 0712.

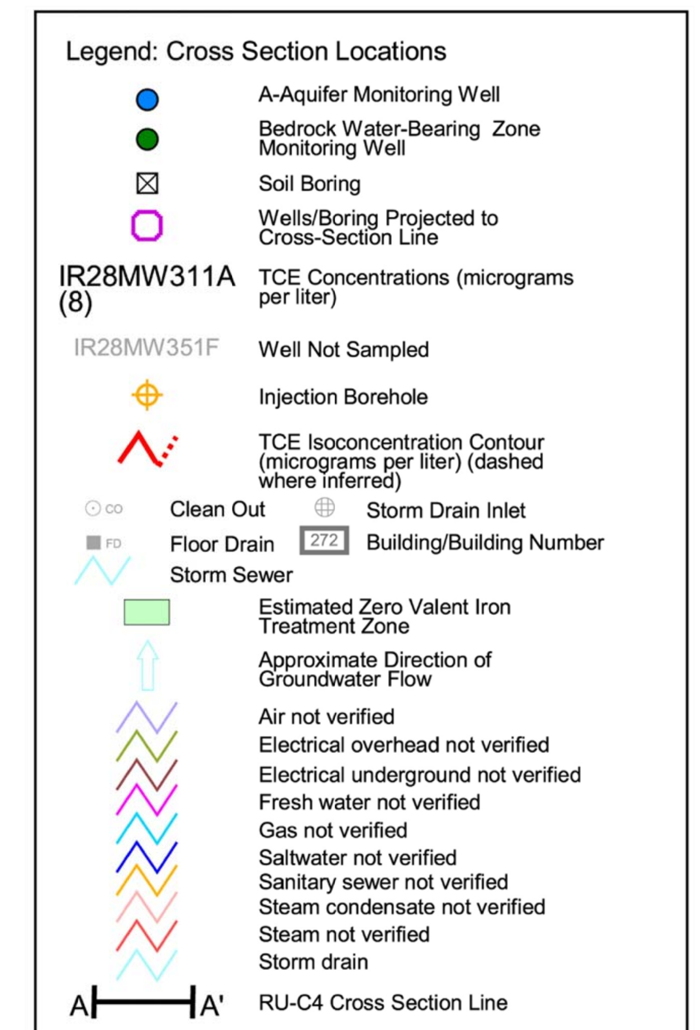


Cross Section Locations





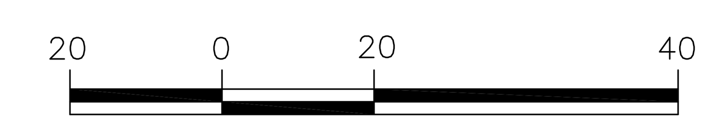
Location Map



Notes:

1. Utility locations taken from U.S. Navy drawing Quad. D-2, August 3, 1955 and Tetra Tech EM Inc., Hunters Point Shipyard Index Drawing No. 0712.
2. Post-inection concentrations are represented by mean of three post-injection sampling rounds.
3. Utilities dashed where inferred

RU-C4 Remedial Unit C-4
TCE Trichloroethene



HORIZONTAL SCALE IN FEET

VERTICAL EXAGGERATION = 2X

Tetra Tech EM Inc.

Hunters Point Shipyard, San Francisco, California

U.S. Navy Southwest Division, NAVFAC, San Diego

FIGURE 10

HYDROGEOLOGIC CROSS SECTION AND POST-INJECTION ROUND 3 TCE ISOCONCENTRATION CONTOURS

Final Cost and Performance Report
Ferox[SM] InjectionTechnology Demonstration

DATE: 07/09/03 DRIVE:\PATH GH SEATTLE, WASHINGTON

TABLES

TABLE 1: SUMMARY OF INJECTION PARAMETERS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Injection Borehole	Injection Interval (feet bgs)	Fracturing Pressure (psig)	Injection Pressure (psig)	Mass of Iron Injected (pounds)
F1	9 to 12	NA[a]	110 to 130[b]	805
	13 to 16	NA[a]	55 to 110	530
	16 to 19	NA[a]	110 to 125	795
	19 to 22	160	125 to 135	795
	24 to 27	NA[c]	~150	530
	27 to 30	145	140 to 155	530
F2	9 to 12	65	40 to 65	795
	12 to 15	90	55 to 65	805
	15 to 18	125	110 to 120	910
	18 to 21	105	110 to 180	635
	21 to 24	135	110 to 120	635
	24 to 27	170	145 to 160	635
	27 to 30	205	150 to 170	635
F3	10 to 13	120	100 to 120	740
	13 to 16	160	120 to 125	530
	16 to 19	125	120 to 130	805
	18 to 21	195	130 to 140	780
	24 to 27	100	140 to 150	530
	27 to 30	230	140 to 150	530
F4	8 to 11	55	70 to 95	795
	11 to 14	165	80 to 130	1,060
	21 to 24	85	80 to 135	530
	24 to 27	NA[c]	100 to 150	424
	27 to 30	190	160 to 165	530
Total	**NA**	**NA**	**NA**	**16,289**

Notes: Fracturing and injection pressures are approximate

a Formation was sufficiently loose so that pneumatic fracturing was not necessary at this interval

b Zero-valent iron slurry was hydraulically injected at this interval to minimize daylighting of nitrogen gas and displacement of potential contaminant vapors

c Pressure data for this injection interval were lost

bgs Below ground surface

NA Not applicable

psig Pounds per square inch gauge

Source: ARS Technologies, Inc. 2003. "Field Summary, Ferox[sm] Technology Demonstration, Parcel C, Remedial Unit 4, Hunters Point Shipyard, San Francisco, California." May 23.

TABLE 2: GROUNDWATER SAMPLING REQUIREMENTS

Final Cost and Performance Report, Ferox^{sm} Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Monitoring Well	Screen Interval (feet bgs)	ORP	pH	Dissolved Hydrogen	Ethane	Ethene	Chloride	Alkalinity	VOCs	Dissolved Arsenic	Dissolved Manganese	Dissolved Iron	Total Iron	Nitrate
IR28MW211F	6.0 to 16.5	X	X	X	X	X	X	X	X	--	--	X	X	--
IR28MW275F	7.0 to 12.0	X	X	X	X	X	X	X	X	--	--	X	X	--
IR28MW311A	4.0 to 19.0	X	X	X	X	X	X	X	X	--	--	X	X	--
IR28MW341F	13.5 to 17.0	X	X	X	X	X	X	X	X	--	--	X	X	X
IR28MW342F	8.0 to 15.0	X	X	X	X	X	X	X	X	--	--	X	X	--
IR28MW351F	51.0 to 59.0	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28MW355F	10.6 to 19.75	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28MW356F	10.6 to 19.75	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28MW357F	10.6 to 19.75	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28MW358F	10.6 to 19.75	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28MW359F	10.6 to 19.75	X	X	X	X	X	X	X	X	--	--	X	X	X
IR28MW360F	10.6 to 19.75	X	X	X	X	X	X	X	X	X	X	X	X	X
IR28MW361F	10.6 to 19.75	X	X	X	X	X	X	X	X	--	--	X	X	X
IR28MW362F (F2)	10.0 to 20.0	X	X	X	X	X	X	X	X	--	--	X	X	X
IR28MW932F	27.0 to 30.0	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28MW933F5	29.5 to 30.0	X	X	X	X	X	X	X	X	--	--	X	X	X
IR28MW934F5	29.5 to 30.0	X	X	X	X	X	X	X	X	--	--	X	X	--
IR28IW938F	10.4 to 20.4	X	X	X	X	X	X	X	X	X	X	X	X	--
IR28IW939F	10.5 to 20.5	X	X	X	X	X	X	X	X	X	X	X	X	--
	Total:	**19**	**19**	**19**	**19**	**19**	**19**	**19**	**19**	**9**	**9**	**19**	**19**	**6**

Notes: Field measurements for dissolved oxygen, ORP, pH, temperature, conductivity, and turbidity were collected using a YSI-556 water quality meter with flow-through cell.

The following analytical methods were used for the samples collected during this project:

- EPA Methods 8260B and SW-846 for VOCs
- EPA Methods 6010B and SW-846 for total and dissolved iron, dissolved arsenic, and dissolved manganese
- EPA Method 300.1 for chloride
- Standard Methods for the Examination of Water and Wastewater Method 2320 for alkalinity
- EPA RSK 175 for ethane and ethene
- EPA RSK 175 Modified for dissolved hydrogen

-- Analyte was not sampled for at this location
bgs Below ground surface
EPA U.S. Environmental Protection Agency
ORP Oxidation-reduction potential
VOC Volatile organic compound

TABLE 3: ORP RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection Point (feet)	Baseline (mV)	Post-Injection (mV)				Delta[a] (mV)
			Round 1	Round 2	Round 3	Mean	
IR28MW362F (F2)	0.0	88.5	-555	-436	-530	-507	-596
IR28IW938F	4.9	58.9	-578	-690	-622	-630	-689
IR28MW211F	6.0	166	-556	-447	-509	-504	-670
IR28MW341F	7.8	171	-351	-471	-566	-463	-634
IR28MW933F5	8.7	101	-318	-262	-231	-270	-371
IR28IW939F	9.0	38.8	-392	-427	-196	-338	-377
IR28MW342F	9.8	160	-324	-569	-427	-440	-600
IR28MW934F5	13.1	79.4	-2.0	138	139	92	12.6
IR28MW932F	13.3	-87.6	-428	-313	-179	-307	-219
IR28MW361F	15.0	97.6	-378	-448	-231	-353	-451
Mean Inside Treatment Zone:		**87.4**	**-388**	**-393**	**-335**	**-372**	**-460**
IR28MW351F[b]	4.8	82.3	0.4	61.5	50.1	37.3	-45.0
IR28MW359F	18.6	102	48.7	243	249	180	78
IR28MW360F	19.5	90.6	12.3	253	235	167	76.4
IR28MW357F	22.1	97.3	164	308	288	253	156
IR28MW275F	29.5	59.2	242	197	-41.5	133	73.8
IR28MW358F	31.7	85.5	210	231	86.1	176	90.5
IR28MW355F	38.7	98.1	45.5	154	249	150	51.9
IR28MW356F	39.4	116	182	150	282	205	89.0
IR28MW311A	58.0	125	61.3	137	150	116	-9.0
Mean Outside Treatment Zone:		**95.1**	**107**	**193**	**172**	**157**	**61.9**

Notes: Results less than 10 are reported to two significant figures; results greater than 10 are reported to three significant figures.

a The difference between the baseline and average post-injection results

b Monitoring well screened below the treatment zone

mV Millivolts

TABLE 4: pH RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection Point (feet)	Baseline	Post-Injection				Delta[a]
			Round 1	Round 2	Round 3	Mean	
IR28MW362F (F2)	0.0	7.3	8.2	8.3	8.4	8.3	**1.0**
IR28IW938F	4.9	6.6	8.4	8.9	9.0	8.8	**2.2**
IR28MW211F	6.0	6.9	8.5	7.9	8.1	8.2	**1.3**
IR28MW341F	7.8	6.9	7.9	8.5	8.4	8.3	**1.4**
IR28MW933F5	8.7	6.7	7.0	7.0	7.1	7.1	**0.4**
IR28IW939F	9.0	7.1	8.2	8.5	8.6	8.4	**1.3**
IR28MW342F	9.8	6.8	8.2	8.6	8.5	8.4	**1.6**
IR28MW934F5	13.1	6.8	6.7	6.8	6.8	6.8	**0.0**
IR28MW932F	13.3	7.1	8.2	8.3	8.1	8.2	**1.1**
IR28MW361F	15.0	6.8	7.5	8.0	8.0	7.8	**1.0**
Mean Inside Treatment Zone:		**6.9**	**7.9**	**8.1**	**8.1**	**8.0**	**1.1**
IR28MW351F[b]	4.8	7.1	7.2	7.0	7.0	7.1	**0.0**
IR28MW359F	18.6	6.9	7.0	7.3	7.3	7.2	**0.3**
IR28MW360F	19.5	6.9	7.1	7.2	7.2	7.2	**0.3**
IR28MW357F	22.1	6.8	7.3	7.2	7.3	7.3	**0.5**
IR28MW275F	29.5	6.9	7.0	7.0	6.9	7.0	**0.1**
IR28MW358F	31.7	7.3	7.2	7.4	7.3	7.3	**0.0**
IR28MW355F	38.7	7.2	7.6	7.8	7.9	7.8	**0.6**
IR28MW356F	39.4	6.6	7.3	7.3	7.5	7.4	**0.8**
IR28MW311A	58.0	6.7	6.8	6.9	6.8	6.8	**0.1**
Mean Outside Treatment Zone:		**6.9**	**7.2**	**7.2**	**7.3**	**7.2**	**0.3**

Notes: Results are reported to two significant figures.

a The difference between the baseline and average post-injection results

b Monitoring well screened below the treatment zone

TABLE 5: DISSOLVED GAS RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection Point (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Delta[a] (µg/L)
Ethane											
IR28MW362F (F2)	0.0	3		16		35		12		21	18
IR28IW938F	4.9	0.3	U	11		7		5		8	8
IR28MW211F	6.0	0.5	J	42		64		77		61	60
IR28MW341F	7.8	0.3	J	53		48		54		52	52
IR28MW933F5	8.7	0.3	U	2		4		6		4	2
IR28IW939F	9.0	0.4	J	50		83		74		69	65
IR28MW342F	9.8	0.3	U	55		64		45		55	53
IR28MW934F5	13.1	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW932F	13.3	0.6		33		54		89		59	58
IR28MW361F	15.0	0.3	U	2		4		6		4	4
Mean Inside Treatment Zone:		**1**		**26**		**36**		**37**		**33**	**32**
IR28MW351F[b]	4.8	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW359F	18.6	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW360F	19.5	0.3	J	4		18		4		9	8
IR28MW357F	22.1	0.3	U	0.4	J	0.6		0.5		0.5	0.4
IR28MW275F	29.5	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW358F	31.7	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW355F	38.7	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW356F	39.4	0.3	U	0.3	U	0.3	U	0.3	U	0.2	0.1
IR28MW311A	58.0	0.3	U	0.3	U	0.3	J	0.4	J	0.3	0.2
Mean Outside Treatment Zone:		**0.2**		**0.6**		**2**		**0.6**		**1**	**0.8**
Ethene											
IR28MW362F (F2)	0.0	3		3		36		5		15	12
IR28IW938F	4.9	0.4	U	2		4		3		3	3
IR28MW211F	6.0	0.4	U	11		48		52		37	37
IR28MW341F	7.8	0.4	U	9		20		19		16	16
IR28MW933F5	8.7	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28IW939F	9.0	0.4	U	31		49		44		41	41
IR28MW342F	9.8	0.4	U	10		21		17		16	16
IR28MW934F5	13.1	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW932F	13.3	1	J	31		34		49		38	37
IR28MW361F	15.0	0.4	U	0.4	U	2	J	2		1	1
Mean Inside Treatment Zone:		**0.1**		**10**		**21**		**19**		**17**	**17**
IR28MW351F[b]	4.8	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW359F	18.6	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW360F	19.5	0.7	J	3		2		0.4	U	2	1
IR28MW357F	22.1	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW275F	29.5	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW358F	31.7	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW355F	38.7	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW356F	39.4	0.4	U	0.4	U	0.4	U	0.4	U	0.2	0
IR28MW311A	58.0	0.4	U	0.4	U	0.4	U	0.4	J	0.3	0.1
Mean Outside Treatment Zone:		**0.3**		**0.5**		**0.4**		**0.2**		**0.4**	**0.1**

TABLE 5: DISSOLVED GAS RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection Point (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Delta[a] (µg/L)
Dissolved Hydrogen											
IR28MW362F (F2)	0.0	5	U	42		230		160		140	140
IR28IW938F	4.9	5	U	5	U	89		31		41	39
IR28MW211F	6.0	5	U	5	U	5	U	5	U	2.5	0
IR28MW341F	7.8	5	U	5	U	5	U	36		14	12
IR28MW933F5	8.7	5	U	5	U	5	U	5	U	2.5	0
IR28IW939F	9.0	5	U	5	U	5	U	5	U	2.5	0
IR28MW342F	9.8	5	U	5	U	5	U	5	U	2.5	0
IR28MW934F5	13.1	5	U	5	U	5	U	5	U	2.5	0
IR28MW932F	13.3	5	U	5	U	28		5	U	11	9
IR28MW361F	15.0	5	U	5	U	5	U	5	U	2.5	0
Mean Inside Treatment Zone:		**2.5**		**6**		**35**		**24**		**22**	**22**
IR28MW351F[b]	4.8	5	U	5	U	5	U	5	U	2.5	0
IR28MW359F	18.6	5	U	5	U	5	U	5	U	2.5	0
IR28MW360F	19.5	5	U	5	U	5	U	5	U	2.5	0
IR28MW357F	22.1	5	U	5	U	5	U	5	U	2.5	0
IR28MW275F	29.5	5	U	5	U	5	U	5	U	2.5	0
IR28MW358F	31.7	5	U	5	U	5	U	5	U	2.5	0
IR28MW355F	38.7	5	U	5	U	5	U	5	U	2.5	0
IR28MW356F	39.4	5	U	5	U	5	U	5	U	2.5	0
IR28MW311A	58.0	5	U	5	U	5	U	5	U	2.5	0
Mean Outside Treatment Zone:		**2.5**		**2.5**		**2.5**		**2.5**		**2.5**	**0**

Notes: Nondetected results are shown at the reporting limit; however, one-half of the reporting limit is used for calculations.
Results less than 10 are reported to one significant figure; results greater than 10 are reported to two significant figures.

a The difference between the baseline and average post-injection results
b Monitoring well screened below the treatment zone

µg/L Micrograms per liter
J Estimated result
U Nondetected result

TABLE 6: CHLORIDE RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection Point (feet)	Baseline (µg/L)	Post-Injection (µg/L)				Delta[a] (µg/L)
			Round 1	Round 2	Round 3	Mean	
IR28MW362F (F2)	0.0	110,000	120,000	140,000	130,000	130,000	20,000
IR28IW938F	4.9	170,000	110,000	120,000	110,000	110,000	-60,000
IR28MW211F	6.0	110,000	150,000	200,000	200,000	180,000	70,000
IR28MW341F	7.8	150,000	100,000	110,000	120,000	110,000	-40,000
IR28MW933F5	8.7	280,000	140,000	130,000	130,000	130,000	-150,000
IR28IW939F	9.0	190,000	140,000	140,000	150,000	140,000	-50,000
IR28MW342F	9.8	160,000	86,000	140,000	99,000	110,000	-50,000
IR28MW934F5	13.1	250,000	220,000	230,000	240,000	230,000	-20,000
IR28MW932F	13.3	120,000	92,000	110,000	110,000	100,000	-20,000
IR28MW361F	15.0	150,000	88,000	88,000	90,000	90,000	-60,000
Mean Inside Treatment Zone:		**170,000**	**125,000**	**140,000**	**140,000**	**140,000**	**-30,000**
IR28MW351F[b]	4.8	2,800,000	2,500,000	2,500,000	2,400,000	2,500,000	-300,000
IR28MW359F	18.6	72,000	66,000	73,000	68,000	70,000	-2,000
IR28MW360F	19.5	150,000	55,000	71,000	81,000	70,000	-80,000
IR28MW357F	22.1	68,000	72,000	71,000	67,000	70,000	2,000
IR28MW275F	29.5	13,000	13,000	12,000	13,000	13,000	0
IR28MW358F	31.7	58,000	54,000	50,000	48,000	51,000	-7,000
IR28MW355F	38.7	68,000	73,000	74,000	71,000	73,000	5,000
IR28MW356F	39.4	180,000	180,000	170,000	150,000	170,000	-10,000
IR28MW311A	58.0	15,000,000	15,000,000	14,000,000	14,000,000	14,000,000	-1,000,000
Mean Outside Treatment Zone:		**2,000,000**	**2,000,000**	**1,900,000**	**1,900,000**	**1,900,000**	**-100,000**

Notes: Results are reported to two significant figures.

a The difference between the baseline and average post-injection results

b Monitoring well screened below the treatment zone

µg/L Micrograms per liter

TABLE 7: ALKALINITY RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection Point (feet)	Baseline (µg/L)	Post-Injection (µg/L)				Delta[a] (µg/L)
			Round 1	Round 2	Round 3	Mean	
IR28MW362F (F2)	0.0	190,000	14,000	19,000	19,000	17,000	-170,000
IR28IW938F	4.9	140,000	190,000	94,000	38,000	110,000	-30,000
IR28MW211F	6.0	130,000	44,000	30,000	28,000	30,000	-100,000
IR28MW341F	7.8	140,000	22,000	21,000	23,000	22,000	-120,000
IR28MW933F5	8.7	110,000	55,000	49,000	54,000	53,000	-57,000
IR28IW939F	9.0	160,000	81,000	72,000	70,000	74,000	-86,000
IR28MW342F	9.8	130,000	53,000	52,000	70,000	58,000	-72,000
IR28MW934F5	13.1	110,000	100,000	100,000	100,000	100,000	-10,000
IR28MW932F	13.3	180,000	96,000	77,000	98,000	90,000	-90,000
IR28MW361F	15.0	120,000	110,000	120,000	120,000	120,000	0.0
Mean Inside Treatment Zone:		**140,000**	**77,000**	**63,000**	**62,000**	**67,000**	**-73,000**
IR28MW351F[b]	4.8	100,000	100,000	110,000	100,000	100,000	0.0
IR28MW359F	18.6	160,000	120,000	140,000	150,000	140,000	-20,000
IR28MW360F	19.5	160,000	80,000	88,000	85,000	84,000	-76,000
IR28MW357F	22.1	120,000	120,000	130,000	130,000	130,000	10,000
IR28MW275F	29.5	120,000	140,000	140,000	140,000	140,000	20,000
IR28MW358F	31.7	190,000	230,000	200,000	190,000	210,000	20,000
IR28MW355F	38.7	110,000	140,000	150,000	140,000	140,000	30,000
IR28MW356F	39.4	120,000	160,000	160,000	160,000	160,000	40,000
IR28MW311A	58.0	210,000	210,000	240,000	260,000	240,000	30,000
Mean Outside Treatment Zone:		**143,000**	**144,000**	**151,000**	**151,000**	**149,000**	**6,000**

Notes: Results are reported to two significant figures.

a The difference between the baseline and average post-injection results

b Monitoring well screened below the treatment zone

µg/L Micrograms per liter

TABLE 8: VOC RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1	Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
Trichloroethene											
IR28MW362F (F2)	0.0	88,000		11	78		4		31	99.96	-88,000
IR28IW938F	4.9	34,000		13	28		23		21	99.9	-34,000
IR28MW211F	6.0	76,000		420	730		850		670	99.1	-75,000
IR28MW341F	7.8	41,000	J	100	160	J	160		140	99.7	-41,000
IR28MW933F5	8.7	26		38	26		25		30	-15.4	4
IR28IW939F	9.0	15,000		460	520		820		600	96.0	-14,000
IR28MW342F	9.8	5,100	J	47	79		180		100	98.0	-5,000
IR28MW934F5	13.1	1,100		400	490		480		460	58.2	-640
IR28MW932F	13.3	5,300		120	110		84		100	98.1	-5,200
IR28MW361F	15.0	1		130	100		83		100	-9,900.0	99
Mean Inside Treatment Zone:		**27,000**		**170**	**230**		**270**		**220**	**99.2**	**-27,000**
IR28MW351F[b]	4.8	39		35	42		46		41	-5.1	2
IR28MW359F	18.6	1	U	55	47		47		50	-9,900.0	50
IR28MW360F	19.5	7,400		690	610		630		640	91.4	-6,800
IR28MW357F	22.1	6		35	53		76		55	-816.7	49
IR28MW275F	29.5	36		68	70		85		74	-105.6	38
IR28MW358F	31.7	0.3	J	4	1		0.9	J	2	-566.7	2
IR28MW355F	38.7	3		17	17		20		18	-500.0	15
IR28MW356F	39.4	71		44	39		37		40	43.7	-31
IR28MW311A	58.0	8		5	4		4		4	50.0	-4
Mean Outside Treatment Zone:		**840**		**110**	**98**		**110**		**100**	**88.1**	**-740**

TABLE 8: VOC RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
Tetrachloroethene												
IR28MW362F (F2)	0.0	250	U	1	U	1	U	1	U	0.5	99.6	-120
IR28IW938F	4.9	500	U	1	U	1	U	1	U	0.5	99.8	-250
IR28MW211F	6.0	1,000	U	4	U	0.3	J	0.5	J	0.9	99.8	-500
IR28MW341F	7.8	200	U	1	U	1	U	1	U	0.5	99.5	-100
IR28MW933F5	8.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28IW939F	9.0	130	J	1		1	J	3		2	98.5	-130
IR28MW342F	9.8	85	J	1		1		2		1	98.8	-84
IR28MW934F5	13.1	5	U	0.3	J	1	U	1	U	0.4	84.0	-2
IR28MW932F	13.3	89		2		1		1		1	98.9	-88
IR28MW361F	15.0	1	U	0.4	J	1	U	1	U	0.5	0.0	0
Mean Inside Treatment Zone:		**130**		**0.9**		**0.6**		**1**		**0.8**	**99.4**	**-130**
IR28MW351F[b]	4.8	0.3	J	0.3	J	0.4	J	0.5	J	0.4	-33.3	0.1
IR28MW359F	18.6	1	U	0.4	J	1	U	1	U	0.5	0.0	0
IR28MW360F	19.5	140		12		7		10		10	92.9	-130
IR28MW357F	22.1	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW275F	29.5	14		30		23		30		28	-100.0	14
IR28MW358F	31.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW355F	38.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW356F	39.4	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW311A	58.0	1	U	1	U	1	U	1	U	0.5	0.0	0
Mean Outside Treatment Zone:		**17**		**5**		**4**		**5**		**4.7**	**70.6**	**-12**

TABLE 8: VOC RESULTS (Continued)
Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
cis-1,2-Dichloroethene												
IR28MW362F (F2)	0.0	160	J	1	U	5		0.3	J	2	98.8	-160
IR28IW938F	4.9	500	U	1	U	1		0.9	J	0.8	99.7	-250
IR28MW211F	6.0	1,000	U	2	J	8		15		8	98.4	-490
IR28MW341F	7.8	200	U	0.4	J	2		4		2	98.0	-98
IR28MW933F5	8.7	2		1		0.6	J	0.6	J	0.7	65.0	-1
IR28IW939F	9.0	420	J	9		10		21		13	96.9	-410
IR28MW342F	9.8	17	J	1		3		8		4	76.5	-13
IR28MW934F5	13.1	37		54	J	41		41		45	-21.6	8
IR28MW932F	13.3	410		22		28		43		31	92.4	-380
IR28MW361F	15.0	0.6	J	3		2		2		2	-233.3	1
Mean Inside Treatment Zone:		**190**		**9**		**10**		**14**		**11**	**94.2**	**-180**
IR28MW351F[b]	4.8	4		4		5		6		5	-25.0	1
IR28MW359F	18.6	1	U	0.2	J	1	U	1	U	0.4	20.0	-0.1
IR28MW360F	19.5	320		18		12		11		14	95.6	-310
IR28MW357F	22.1	1	U	0.2	J	1	U	1	U	0.4	20.0	-0.1
IR28MW275F	29.5	2		5		3		3		4	-100.0	2
IR28MW358F	31.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW355F	38.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW356F	39.4	11		13	J	6		6		8	27.3	-3
IR28MW311A	58.0	2		3		2		2		2	0.0	0
Mean Outside Treatment Zone:		**38**		**5**		**3**		**3**		**4**	**89.5**	**-34**

TABLE 8: VOC RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
trans-1,2-Dichloroethene												
IR28MW362F (F2)	0.0	250	U	1	U	1	U	1	U	0.5	99.6	-120
IR28IW938F	4.9	500	U	1	U	1	U	1	U	0.5	99.8	-250
IR28MW211F	6.0	1,000	U	4	U	0.2	J	1	U	0.9	99.8	-500
IR28MW341F	7.8	200	U	1	U	1	U	1	U	0.5	99.5	-100
IR28MW933F5	8.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28IW939F	9.0	100	U	1	U	2	U	1	U	0.7	98.6	-49
IR28MW342F	9.8	50	U	1	U	1	U	1	U	0.5	98.0	-25
IR28MW934F5	13.1	5	U	0.3	J	1	U	0.3	J	0.4	84.0	-2
IR28MW932F	13.3	50	U	1	U	0.4	J	1	U	0.5	98.0	-25
IR28MW361F	15.0	1	U	1	U	1	U	1	U	0.5	0.0	0
Mean Inside Treatment Zone:		**110**		**0.6**		**0.5**		**0.5**		**0.5**	**99.5**	**-110**
IR28MW351F[b]	4.8	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW359F	18.6	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW360F	19.5	25	U	1	U	0.4	J	1	U	0.5	96.0	-12
IR28MW357F	22.1	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW275F	29.5	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW358F	31.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW355F	38.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW356F	39.4	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW311A	58.0	1	U	1	U	1	U	1	U	0.5	0.0	0
Mean Outside Treatment Zone:		**2**		**0.5**		**0.5**		**0.5**		**0.5**	**75.0**	**-2**

TABLE 8: VOC RESULTS (Continued)
Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
Vinyl Chloride												
IR28MW362F (F2)	0.0	250	U	1	U	0.4	J	1	U	0.5	99.6	-120
IR28IW938F	4.9	500	U	1	U	1	U	1	U	0.5	99.8	-250
IR28MW211F	6.0	1,000	U	4	U	0.7	J	0.8	J	1	99.8	-500
IR28MW341F	7.8	200	U	1	U	1	U	1	U	0.5	99.5	-100
IR28MW933F5	8.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28IW939F	9.0	100	U	0.7	J	2	U	2		1	98.0	-49
IR28MW342F	9.8	50	U	1	U	1	U	0.7	J	0.6	97.6	-24
IR28MW934F5	13.1	5	U	1	U	1	U	1	U	0.5	80.0	-2
IR28MW932F	13.3	50	U	0.8	J	1		4		2	92.0	-23
IR28MW361F	15.0	1	U	1	U	1	U	1	U	0.5	0.0	0
Mean Inside Treatment Zone:		**110**		**0.7**		**0.6**		**1**		**0.8**	**99.3**	**-110**
IR28MW351F[b]	4.8	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW359F	18.6	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW360F	19.5	25	U	0.8	J	1	U	1	U	0.6	95.2	-12
IR28MW357F	22.1	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW275F	29.5	1	U	0.5	J	1	U	1	U	0.5	0.0	0
IR28MW358F	31.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW355F	38.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW356F	39.4	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW311A	58.0	1	U	1	U	1	U	1	U	0.5	0.0	0
Mean Outside Treatment Zone:		**2**		**0.5**		**0.5**		**0.5**		**0.5**	**75.0**	**-2**

TABLE 8: VOC RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)	Post-Injection (µg/L) Round 1	Round 2	Round 3	Mean	Percent Reduction (%)	Delta[a] (µg/L)
Total Chlorinated Ethenes								
IR28MW362F (F2)	0.0	89,000	14	84	6	34	100.0	-88,000
IR28IW938F	4.9	36,000	16	31	26	23	99.9	-35,000
IR28MW211F	6.0	79,000	430	740	870	680	99.1	-77,000
IR28MW341F	7.8	42,000	100	160	170	140	99.7	-41,000
IR28MW933F5	8.7	30	41	29	28	31	-8.3	2
IR28IW939F	9.0	16,000	470	530	850	620	96.0	-15,000
IR28MW342F	9.8	5,700	50	84	190	110	97.9	-5,100
IR28MW934F5	13.1	1,100	460	530	520	500	56.0	-640
IR28MW932F	13.3	5,900	150	140	130	140	97.6	-5,700
IR28MW361F	15.0	4	130	100	87	110	-4,039.7	100
Mean Inside Treatment Zone:		**27,000**	**190**	**240**	**290**	**240**	**99.1**	**-27,000**
IR28MW351F[b]	4.8	44	40	48	54	47	-7.1	3
IR28MW359F	18.6	4	57	50	50	51	-2,451.7	49
IR28MW360F	19.5	7,900	720	630	650	670	91.5	-7,200
IR28MW357F	22.1	9	37	56	79	56	-647.6	49
IR28MW275F	29.5	53	100	97	120	110	-102.2	54
IR28MW358F	31.7	3	7	4	4	4	-92.6	2
IR28MW355F	38.7	6	20	20	23	20	-333.3	15
IR28MW356F	39.4	84	59	47	45	49	40.6	-34
IR28MW311A	58.0	12	10	8	8	8	30.3	-3
Mean Outside Treatment Zone:		**900**	**120**	**110**	**110**	**110**	**87.8**	**-790**

TABLE 8: VOC RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
Chloroform												
IR28MW362F (F2)	0.0	450		2	U	3		1	U	2	99.6	-450
IR28IW938F	4.9	500	U	1	U	1	U	1	U	0.5	99.8	-250
IR28MW211F	6.0	1,000	U	4	U	9		11		8	98.4	-490
IR28MW341F	7.8	230	U	3		6		5		5	95.7	-110
IR28MW933F5	8.7	12		6		3		3		4	66.7	-8
IR28IW939F	9.0	1100	J	57		48		83		63	94.3	-1,000
IR28MW342F	9.8	190	J	8		20		13		14	92.6	-180
IR28MW934F5	13.1	60		92	J	74		80		82	-36.7	22
IR28MW932F	13.3	420		64		30		34		43	89.8	-380
IR28MW361F	15.0	3		17		12		6		12	-300.0	9
Mean Inside Treatment Zone:		**310**		**25**		**21**		**24**		**23**	**92.6**	**-290**
IR28MW351F[b]	4.8	2		2	U	2	U	3		2	0.0	0
IR28MW359F	18.6	1	U	3		2		2		2	-300.0	2
IR28MW360F	19.5	420		44	J	24		25		31	92.6	-390
IR28MW357F	22.1	1	U	3		2	U	3		2	-300.0	2
IR28MW275F	29.5	1	U	2	U	1	U	2		2	-300.0	2
IR28MW358F	31.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW355F	38.7	0.2	J	1	U	1	U	1	U	0.7	-250.0	0.5
IR28MW356F	39.4	5		6	J	4	U	3		4	20.0	-1
IR28MW311A	58.0	1	U	1	U	1	U	1	U	0.4	20.0	-0.1
Mean Outside Treatment Zone:		**48**		**7**		**4**		**4**		**5**	**89.6**	**-43**

TABLE 8: VOC RESULTS (Continued)
Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Location	Distance From Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Percent Reduction (%)	Delta[a] (µg/L)
Carbon Tetrachloride												
IR28MW362F (F2)	0.0	250	U	1	U	1	U	1	U	0.5	99.6	-250
IR28IW938F	4.9	500	U	1	U	1	U	1	U	0.5	99.8	-250
IR28IW939F	9.0	77	J	1	U	2	U	1	U	0.7	99.1	-76
IR28MW211F	6.0	1,000	U	4	U	1	U	1	U	1	99.8	-500
IR28MW341F	7.8	67	J	1	U	1	U	1	U	0.5	99.3	-67
IR28MW342F	9.8	50	J	1	U	1	U	1	U	0.5	99.0	-50
IR28MW361F	15.0	0.6	J	5		0.8	J	1	U	2	-233.3	1
IR28MW932F	13.3	41	J	1	U	1	U	1	U	0.5	98.8	-41
IR28MW933F5	8.7	4		1		0.8	J	1		0.9	77.5	-3
IR28MW934F5	13.1	21		30		29		31		30	-42.9	9
Mean Inside Treatment Zone:		**110**		**4**		**3**		**4**		**4**	**96.4**	**-110**
IR28MW351F[b]	4.8	2		1		2		2		2	0	0
IR28MW359F	18.6	1	U	0.5	J	0.3	J	1	U	0.4	20	-0.1
IR28MW360F	19.5	82		4		2		3		3	96.3	-79
IR28MW357F	22.1	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW275F	29.5	1	U	0.3	J	1	U	1	U	0.4	20.0	-0.1
IR28MW358F	31.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW355F	38.7	1	U	1	U	1	U	1	U	0.5	0.0	0
IR28MW356F	39.4	12		11	J	5		5		7	41.7	-5
IR28MW311A	58.0	1	U	1	U	1	U	1	U	0.5	0.0	0
Mean Outside Treatment Zone:		**11**		**2**		**1**		**1**		**1**	**90.9**	**-10**

TABLE 8: VOC RESULTS (Continued)
Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Parcel C, Hunters Point Shipyard, San Francisco, California

Notes: Nondetected results are shown at the reporting limit; however, one-half of the reporting limit is used for calculations.
Results less than 10 are reported to one significant figure; results greater than 10 are reported to two significant figures.

a The difference between the baseline and average post-injection results
b Monitoring well screened below the treatment zone

µg/L Micrograms per liter
J Estimated result
U Nondetected result

TABLE 9: METALS RESULTS

Final Cost and Performance Report, Ferox^{sm} Injection Technology Demonstration, Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Delta[a] (µg/L)
Dissolved Arsenic											
IR28IW938F	4.9	5	U	1	U	1	U	1	U	0.5	-2
IR28IW939F	9.0	6	U	1	U	1	U	1	U	0.5	-3
IR28MW932F	13.3	8	U	3	U	1	U	1	U	0.8	-3
Mean Inside Treatment Zone:		**3**		**1**		**0.5**		**0.5**		**1**	**-2**
IR28MW351F[b]	4.8	1	U	1	U	1	U	2	U	0.7	0.2
IR28MW360F	19.5	3	U	3	J	3	J	3	J	3	2
IR28MW357F	22.1	3	U	2	J	4		3	U	3	2
IR28MW358F	31.7	4	U	4	J	4	J	5	U	4	2
IR28MW355F	38.7	4	U	6	J	7		8	J	7	5
IR28MW356F	39.4	2	U	1	J	3		3	U	2	1
Mean Outside Treatment Zone:		**1**		**3**		**4**		**3**		**3**	**2**
Dissolved Manganese											
IR28IW938F	4.9	110		190		140		860		400	290
IR28IW939F	9.0	390		1,100		670		980		920	530
IR28MW932F	13.3	1,900		1,200		720		680		870	-1,030
Mean Inside Treatment Zone:		**800**		**830**		**510**		**840**		**730**	**-70**
IR28MW351F[b]	4.8	200		250		190		170		200	0
IR28MW360F	19.5	7	J	74		71		51		65	58
IR28MW357F	22.1	10	J	110		86		39		78	68
IR28MW358F	31.7	4	J	3	J	4	J	2	J	3	-1
IR28MW355F	38.7	5	J	2	J	1	J	1	J	1	-4
IR28MW356F	39.4	23		5	J	1	U	1	U	2	-21
Mean Outside Treatment Zone:		**42**		**74**		**60**		**44**		**58**	**16**

TABLE 9: METALS RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration, Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Delta[a] (µg/L)
Dissolved Iron											
IR28MW362F (F2)	0.0	9	U	71	U	42	J	58	J	45	41
IR28IW938F	4.9	49	J	34	U	15	U	6,500		2,200	2,200
IR28MW211F	6.0	9	U	27	J	190		150		120	120
IR28MW341F	7.8	16	J	15	J	10	U	14	U	9	-7
IR28MW933F5	8.7	14	J	9	U	4	U	75	J	27	13
IR28IW939F	9.0	9	J	110		68	J	98	J	92	83
IR28MW342F	9.8	9	U	34	J	56	J	81	J	57	53
IR28MW934F5	13.1	9	U	9	U	4	U	6	U	3	-2
IR28MW932F	13.3	1,400		91	J	87	J	190		120	-1,300
IR28MW361F	15.0	10	J	9,200		4	U	63	J	3,100	3,100
Mean Inside Treatment Zone:		**150**		**950**		**46**		**720**		**570**	**420**
IR28MW351F[b]	4.8	12	J	100		20	U	63	J	58	46
IR28MW359F	18.6	46	J	10	J	4	U	8	U	5	-41
IR28MW360F	19.5	9	U	9	U	4	U	8	U	4	-1
IR28MW357F	22.1	9	U	9	U	4	U	13	U	4	-1
IR28MW275F	29.5	86	J	35	J	11	U	8	U	15	-71
IR28MW358F	31.7	9	U	9	U	4	U	7	U	3	-2
IR28MW355F	38.7	9	U	11	J	4	U	14	U	7	-3
IR28MW356F	39.4	17	J	14	J	4	U	6	U	6	-11
IR28MW311A	58.0	9	U	14	J	4	U	14	U	8	-4
Mean Outside Treatment Zone:		**20**		**22**		**3**		**11**		**12**	**-8**

TABLE 9: METALS RESULTS (Continued)

Draft Cost and Performance Report, Ferox^{sm} Injection Technology Demonstration, Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection (feet)	Baseline (µg/L)		Post-Injection (µg/L) Round 1		Round 2		Round 3		Mean	Delta[a] (µg/L)
Total Iron											
IR28MW362F (F2)	0.0	32,000		190	U	210		310		210	-32,000
IR28IW938F	4.9	140		180,000		93,000		30,000		100,000	100,000
IR28MW211F	6.0	26	J	2,100		480		460		1,000	980
IR28MW341F	7.8	11	J	1,700		630		570		970	960
IR28MW933F5	8.7	14	J	3,400		1,100		1,000		1,800	1,800
IR28IW939F	9.0	110		3,800		430		400		1,500	1,400
IR28MW342F	9.8	45	J	400		360		340		370	330
IR28MW934F5	13.1	9	U	960		230		240		480	480
IR28MW932F	13.3	1,300		400		470		470		450	-850
IR28MW361F	15.0	42	J	19,000		9,600		2,900		11,000	11,000
Mean Inside Treatment Zone:		**3,400**		**21,000**		**11,000**		**3,700**		**12,000**	**8,600**
IR28MW351F[a]	4.8	19	J	6,000		200		120		2,100	2,100
IR28MW359F	18.6	140		270		48	U	110		130	-10
IR28MW360F	19.5	38	J	720		310		190		410	370
IR28MW357F	22.1	180		1,300		1,100		230		880	700
IR28MW275F	29.5	120		590		76	J	60	J	240	120
IR28MW358F	31.7	27	J	570		110		130		270	240
IR28MW355F	38.7	140		49	J	38	J	42	J	43	-97
IR28MW356F	39.4	95	J	32	U	21	J	22	J	20	-75
IR28MW311A	58.0	9	U	42	U	68	J	51	J	47	42
Mean Outside Treatment Zone		**85**		**1,100**		**220**		**110**		**480**	**400**

TABLE 9: METALS RESULTS (Continued)

Draft Cost and Performance Report, Ferox[sm] Injection Technology Demonstration, Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Notes: Nondetected results are shown at the reporting limit; however, one-half of the reporting limit is used for calculations.
Results less than 10 are reported to one significant figure; results greater than 10 are reported to two significant figures.

a The difference between the baseline and average post-injection results

b Monitoring well screened below the treatment zone

µg/L Micrograms per liter

J Estimated result

U Nondetected result

TABLE 10: NITRATE RESULTS

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Location	Distance from Nearest Injection (feet)	Baseline (µg/L)	Post-Injection (µg/L)							Delta[a] (µg/L)
			Round 1		Round 2		Round 3		Mean	
IR28MW362F (F2)	0.0	1,200	80		15	U	16.0	U	32	-1,200
IR28MW341F	7.8	3,600	15	U	15	U	16	U	8	-3,600
IR28MW933F5	8.7	4,400	810		600		530		650	-3,800
IR28MW361F	15.0	4,400	660		50		16	U	240	-4,200
Mean Inside Treatment Zone:		**3,400**	**390**		**170**		**140**		**230**	**-3,200**
IR28MW359F	18.6	4,400	2,900		2,900		3,000		2,900	-1,500
IR28MW360F	19.5	730	3,500		1,600		1,900		2,300	1,600
Mean Outside Treatment Zone:		**2,600**	**3,200**		**2,300**		**2,500**		**2,600**	**0.0**

Notes: Nondetected results are shown at the reporting limit; however, one-half of the reporting limit is used for calculations. Results less than 10 are reported to one significant figure; results greater than 10 are reported to two significant figures.

a The difference between the baseline and average post-injection results

µg/L Micrograms per liter
U Nondetected result

TABLE 11: COST SUMMARY

Final Cost and Performance Report, Ferox[sm] Injection Technology Demonstration
Remedial Unit C4, Hunters Point Shipyard, San Francisco, California

Category/Item	Itemized	Cost	Cost per Cubic Yards of Treatment Zone	Percent (%) of Total Cost
Mobilization and Demobilization for Injection		**$31,170**	**$18.52**	**10.8**
Equipment Transport	$13,400			
Personnel	$7,036			
Travel	$10,734			
Equipment and Supplies for Injection		**$99,919**	**$59.37**	**34.5**
Consumables (parts, etc.)	$4,800			
Health and Safety Materials	$940			
Zero-Valent Iron (including delivery)	$32,500			
Nitrogen	$27,639			
Pneumatic Fracturing Module	$10,500			
Dual System Ferox[sm] Trailer	$9,500			
Injection Nozzles and Packer Assemblies	$5,800			
Survey Equipment	$330			
Water Pumps	$330			
Generator	$980			
Hoist Truck	$750			
Support Truck	$2,300			
Miscellaneous Rental	$1,050			
Fork Lift	$2,500			
Labor for Injection		**$38,936**	**$23.13**	**13.5%**
Drilling Services for Injection		**$22,800**	**$13.55**	**7.9%**
Other – New Jersey Institute of Technology Patent Royalty		**$3,840**	**$2.28**	**1.3%**
SUBTOTAL – Injection		**$196,665**	**$116.85**	**68.0%**
Sampling and Analysis		**$85,412**	**$50.74**	**29.5%**
Labor	$25,805			
Equipment and Supplies	$14,343			
Laboratory	$41,017			
Data Validation	$4,247			
Demonstration-Derived Waste Disposal		**$7,197**	**$4.28**	**2.5%**
Waste Analysis (soil)	$480			
Waste Disposal (soil)	$1,782			
Waste Analysis (water)	$971			
Waste Disposal (water)	$3,964			
SUBTOTAL – Sampling and Analysis, and Derived Waste Disposal		**$92,609**	**$55.02**	**32.0%**
GRAND TOTAL:		**$289,274**	**$171.85**	**100.0%**