EXECUTIVE SUMMARY

Demonstration and Validation of the Horizontal Reactive Media Treatment (HRX) Well for Managing Contaminant Plumes in Complex Geological Environments

ESTCP Project ER-201631

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TABLE OF CONTENTS

Page

1.0 INTRODUCTION 1
2.0 OBJECTIVES 1
3.0 TECHNOLOGY DESCRIPTION 1
4.0 PERFORMANCE ASSESSMENT 2
- 4.1 QUANTIFY HRX WELL CAPTURE WIDTH AND HYDRAULIC PERFORMANCE 3
- 4.2 DETERMINE REACTIVE MEDIA TREATMENT EFFICIENCY 6
- 4.3 QUANTIFY CONTAMINANT MASS DISCHARGE REDUCTION 6
- 4.4 DETERMINE PVP PERFORMANCE 6
- 4.5 IDENTIFY CHALLENGES AND LIMITATIONS OF HRX WELL INSTALLATION 6
- 4.6 COMPARE SUSTAINABILITY OF HRX WELL TREATMENT APPROACH WITH OTHERS 7
- 4.7 CHARACTERIZE LIFE CYCLE COSTS 7
- 4.8 FINALIZE AND VALIDATE THE HRX WELL DESIGN TOOL 7

5.0 COST ASSESSMENT 8
6.0 IMPLEMENTATION ISSUES 9

LIST OF FIGURES

Page

Figure ES-1. Illustration of the HRX Well Concept 2
Figure ES-2. HRX Well Field Testing Site 3
Figure ES-3. Interpreted Groundwater Flow Field 4
Figure ES-4. Updated Model Results Showing Predicted HRX Well Capture and Treatment Zones 4
Figure ES-5. TCE and Cis-1,2-DCE Concentration Trends at HRX Well Performance Monitoring Wells 5

LIST OF TABLES

Page

Table ES-1. Summary of Costs for Each Remedial Alternative 8

ACRONYMS AND ABBREVIATIONS

AFCEC	Air Force Center for Environmental Excellence
Cis-1,2-DCE	Cis-1,2-dichloroethene
DoD	U.S. Department of Defense
Ft	Feet
Ft/day	Feet per day
Ft^3/day	Cubic feet per day
G/day	Grams per day
GETS	Groundwater extraction and treatment system
HDPE	High-density polyethylene
PRB	Permeable reactive barrier
PVP	Point Velocity Probe
RWQCB	Regional Water Quality Control Board
SS003	Installation Restoration Program Site 003
TCE	Trichloroethene
µg/L	Micrograms per liter
VAFB	Vandenberg Air Force Base
ZVI	Zero valent iron

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1.0 INTRODUCTION

This project was completed to field-validate the horizontal reactive media treatment well (HRX Well®), a new *in situ* remediation approach offering distinct advantages over traditional approaches for managing dissolved contaminants from source zones in complex geological settings. The approach uses directionally drilled horizontal wells filled with granular reactive media (such as zero valent iron (ZVI) installed in the direction of groundwater flow. Groundwater is treated *in situ* as it flows through the HRX Well, similar to a permeable reactive barrier (PRB). Contaminant mass discharge from source zones can be significantly reduced, which can be cost-effectively sustained over many years. By greatly reducing or eliminating source zone discharge, downgradient plumes can be effectively treated, possibly even achieving low water quality standards in a relatively short period of time. For many U.S. Department of Defense (DoD) sites, it is increasingly recognized that contaminant mass flux and discharge may represent the most appropriate measure of plume strength and potential migration risk; therefore, remedial objectives and technologies focusing primarily on long-term mass discharge reduction will be increasingly favored. The HRX Well concept is particularly well-suited for sites where long-term mass discharge control is a primary performance objective.

2.0 OBJECTIVES

The objective of this project was to field-validate the HRX Well, a new *in situ* remediation approach offering distinct advantages over traditional approaches for managing dissolved contaminants from source zones in complex geological settings. This demonstration project was completed to: (1) apply the HRX Well technology to control mass discharge at an appropriate DoD field site; (2) measure the actual hydraulic capture, treatment efficiency, and mass discharge reduction and compare to model-predicted performance; (3) assess overall technical and sustainability performance of the HRX Well; and (4) develop a user-friendly design tool and guidance regarding technology applicability and limitations, anticipated performance, design and installation considerations, and costing.

3.0 TECHNOLOGY DESCRIPTION

The HRX Well (**Figure ES-1**) is a large diameter horizontal well that functions as an *in situ* reactive barrier and is a novel approach to managing long-term mass discharge within a contaminant plume. Typically, the HRX Well is oriented in the general direction of groundwater flow and is filled with a granular (i.e., solid phase) reactive media such as ZVI, activated carbon, zeolites, ion exchange resins, slow-release oxidants, or other sparingly soluble material. Under passive operation, groundwater flow-focusing occurs, which is a result of the high in-well hydraulic conductivity of the engineered reactive media relative to the aquifer hydraulic conductivity. The HRX Well therefore captures a proportionally large zone of impacted groundwater into the well through the screen at the upgradient portion of the well. Because the well is filled with a treatment media, impacted groundwater is treated *in situ* as it flows through the HRX Well. The treated groundwater then exits the well through the screen along the downgradient section. This concept is illustrated in **Figure ES-1**: impacted groundwater (red shading) is drawn into the well due to flow-focusing; is treated in-well; and clean groundwater (blue shading) exits the well on the downgradient portion of the well.

Therefore, the HRX Well controls contaminant mass discharge to downgradient aquifer zones, and these zones will clean up over time through flushing and contaminant elution. For some applications, the flow through the HRX Well and size of the capture zone can be increased through pumping, where the pump intake is placed in the upgradient screen and groundwater is pumped through a packer into the treatment media. In both the passive and active (pumping) configurations, no groundwater is brought to the surface for treatment.

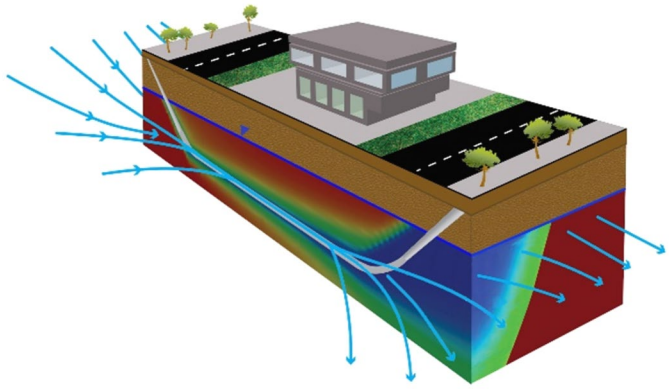

Figure ES-1. Illustration of the HRX Well Concept

4.0 PERFORMANCE ASSESSMENT

The HRX Well field demonstration occurred at Installation Restoration Program Site 003 (SS003) at the Vandenberg Air Force Base (VAFB) in Central California (Site; *see* **Figure ES-2**). The key criteria for site selection included: (1) a site where the objective is to significantly reduce mass discharge from a source or targeted plume zone to improve water quality in the downgradient plume; (2) a site where the geologic setting is appropriate and well understood; and (3) detailed lithologic, geochemical, and contaminant data are available. Some specific environmental and logistical conditions that made Site SS003 an ideal candidate include:

- The primary constituent of concern (trichloroethene (TCE)) can be treated with reactive media well-suited for an HRX Well (ZVI or other) and is consistently present at high concentrations, generally ranging from 30,000 to 50,000 micrograms per liter (µg/L) at the upgradient location of the HRX Well.
- The target treatment zone (Principal Zone aquifer) is at a relatively shallow depth and thickness, allowing for ease in HRX Well installation and easy identification of and performance monitoring for the treatment target zone.
- The lithologic materials observed within the Principal Zone consist of silts and silty sands, with moderate to low hydraulic conductivity values, maximizing the hydraulic conductivity contrast (and therefore HRX Well hydraulic performance under a passive configuration) relative to the hydraulic conductivity of the in-well reactive media (ZVI).
- Potential logistical issues associated with drilling, installation, and performance evaluation are minimal.

- Site remedial objectives are consistent with use of this technology (i.e., targeted long-term reduction of mass discharge from the source area).

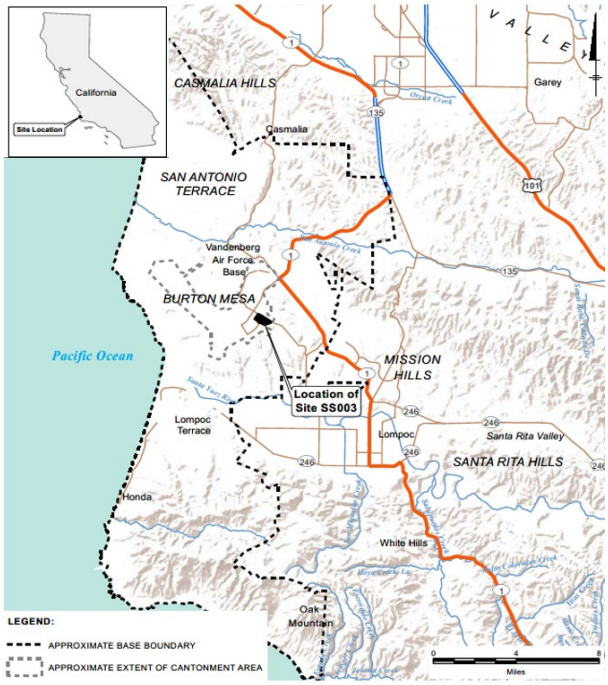

Figure ES-2. HRX Well Field Testing Site

Based on the additional site characterization, treatability testing, and design modeling completed in 2016 to 2018, the project team proceeded with the field demonstration. The HRX Well installation was completed on 1 August 2018 and subsequent performance monitoring and analyses were used to evaluate key performance objectives summarized below.

4.1 QUANTIFY HRX WELL CAPTURE WIDTH AND HYDRAULIC PERFORMANCE

As shown in **Figure ES-3**, groundwater levels near the HRX Well clearly show mounding and the effects of treated water discharge, and interpreted flowlines were qualitatively similar to model predictions. The average flow through the HRX Well predicted by the calibrated steady state-model was compared to estimates derived from the average hydraulic gradient and Darcy's Law calculations, Point Velocity Probe (PVP) tests using the measured velocity, and the results of the HRX Well tracer test. Based on these analyses, there is high confidence that the actual average HRX Well flow during the performance period was likely between 1.5 and two cubic feet per day (ft^3/day), which is consistent with the success criteria of this performance objective.

The capture zone width of the HRX Well predicted by the calibrated steady-state numerical flow model (**Figure ES-4**) was compared to estimates derived from the average hydraulic gradient and Darcy's law calculations, PVP tests using the measured velocity, and the results of the HRX Well tracer test. There is high confidence that the actual average HRX Well capture zone width during the performance period was between 45 and 67 feet (ft), which is consistent with the success criteria for this performance objective.

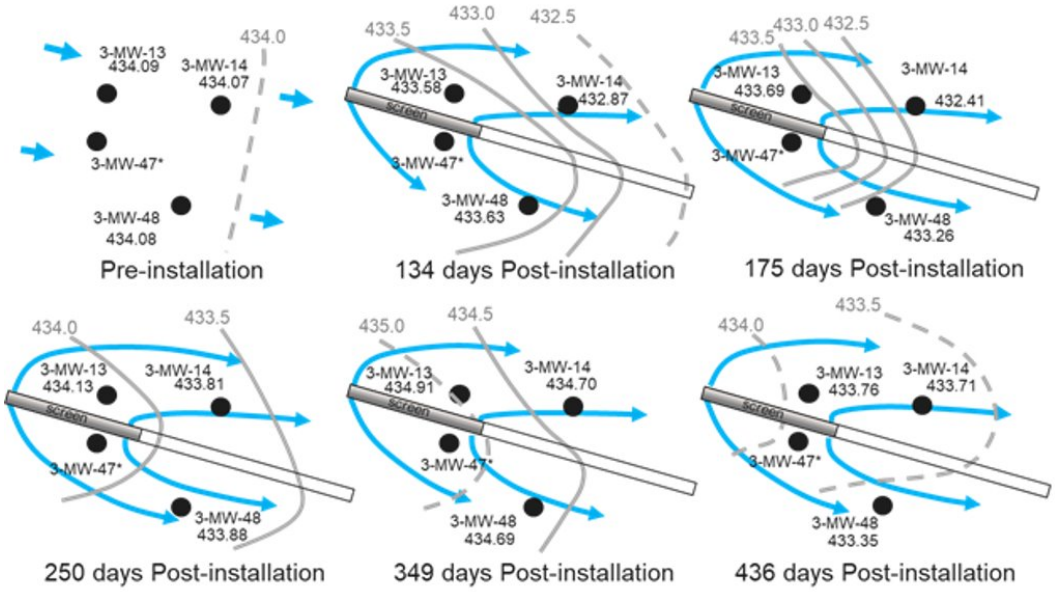

Figure ES-3. Interpreted Groundwater Flow Field

Depiction before and after HRX Well installation, showing hydraulic gradient and flushing zone consistent with model predictions

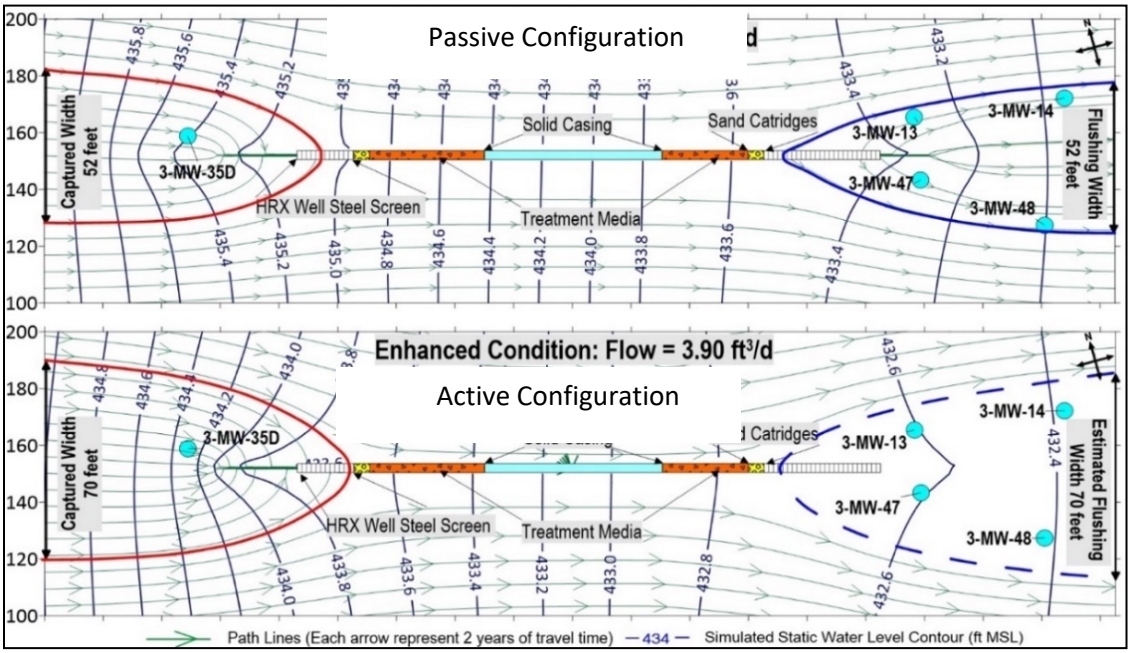

Figure ES-4. Updated Model Results Showing Predicted HRX Well Capture and Treatment Zones

Passive (top) and active (bottom) configurations

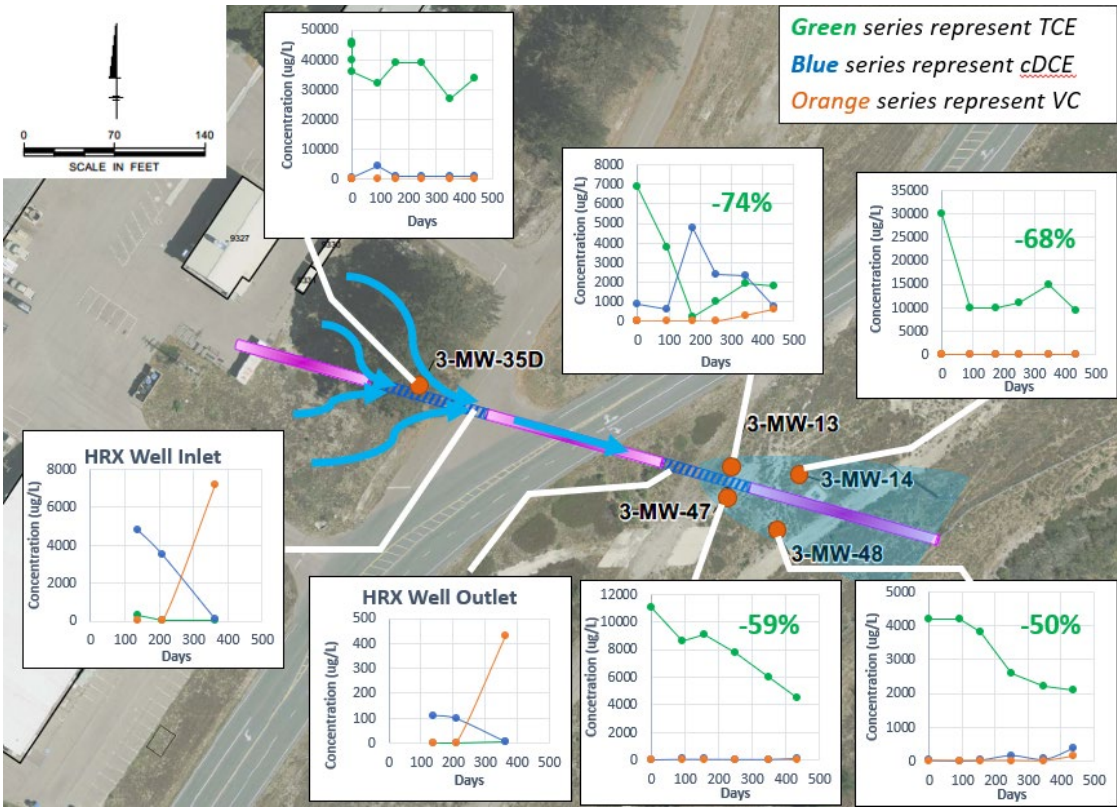

Figure ES-5. TCE and Cis-1,2-DCE Concentration Trends at HRX Well Performance Monitoring Wells

Data are plotted as elapsed time since HRX Well installation (the most recent data prior to installation was used for Day = 0). The distance between 3-MW-14 and 3-MW48 is 45 ft.

The HRX Well treatment zone that was achieved during the performance period was also assessed. **Figure ES-5** shows the TCE, cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride concentration trends at HRX Well performance monitoring wells (most other volatile organic compounds were detected only at low concentrations). TCE concentrations decreased at all four monitoring wells, from 50% to 74%. The Mann-Kendall and Sen's Slope trend tests were applied to evaluate performance monitoring data. Trend analysis results at downgradient monitoring wells 3-MW-13, 3-MW-47, and 3-MW-48 provide a strong line of evidence for HRX Well influence. The statistically significant increase in reductive dichlorination daughter products cis-1,2-DCE and vinyl chloride results suggest that there is some degree of biologically-mediated degradation in this area associated with the residual biopolymer drilling fluid, but that the overall effect of the drilling fluid induced degradation for downgradient wells was not significant over the HRX Well implementation period (treatment at these wells is primarily a result of clean water flushing). It is expected that drilling fluid will continue to be consumed over time and biologically-mediated reductive dichlorination rates will further decline. Multiple calculations supported by different data types and various tests and calculations confirm significant flow focusing and a resulting capture zone size that is generally consistent with model predictions and meets the success criteria of this performance objective.

4.2 DETERMINE REACTIVE MEDIA TREATMENT EFFICIENCY

TCE concentrations at the HRX Well Outlet ranged from non-detect (<2 µg/L) to 7.6 µg/L, lower than the performance goal of 50 µg/L throughout the performance period. The average TCE concentration reduction between upgradient well 3-MW-35D and the HRX Well Outlet was about 32,700 µg/L (>99.99%) and the initial TCE concentration reduction compared to the HRX Well Inlet was 310 µg/L (99.9%). There was a significant decrease in TCE concentration between upgradient well 3-MW-35D and the HRX Well Inlet, as a result of the enhanced biotransformation promoted by unrecovered residual biopolymer drilling fluid. Therefore, HRX Well outlet concentrations are compared to both upgradient well 3-MW-35D and the HRX Well inlet, which allows for the relative contribution of biotic and abiotic processes to be estimated.

Assuming an average flow velocity in the treatment media of 7.2 ft per day (ft/day), the calculated treatment media residence time is about eight to nine days, within the initial design goal of six to 20 days. The estimated TCE transformation rate (0.9 day^{-1}) is about 50% lower than the value assumed in the design based on previous treatability testing (1.8 day^{-1}), but greater than the estimated minimum rate (0.7 day^{-1}) needed to treat TCE from 35,000 µg/L to 50 µg/L. There was no evidence of a significant decrease in permeability due to media plugging or fouling during the performance period. Overall, performance data and analyses indicate the success criteria was met for reactive media treatment efficiency.

4.3 QUANTIFY CONTAMINANT MASS DISCHARGE REDUCTION

The contaminant mass discharge reduction was estimated to be between 1.1 and 2.2 grams per day (g/day) with a best estimate of 1.4 g/day. This represents >99.99% reduction in contaminant mass discharge across a transect defined by the capture width, and meets the performance objective success metric of mass discharge reduction of more than 90%.

4.4 DETERMINE PVP PERFORMANCE

The PVPs successfully and reliably measured flow velocities within the HRX Well and the average standard deviation of PVP measurements was 16%, which met the performance objective of less than 25%.

4.5 IDENTIFY CHALLENGES AND LIMITATIONS OF HRX WELL INSTALLATION

There are potential implementation challenges associated with the directional drilling methods used to install HRX Wells. These potential issues are not specific to HRX Wells and would be the same for a given site if directional drilling were used to install other types of horizontal remediation wells (e.g., horizontal groundwater extraction wells). Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. The HRX Well technology uses a combination of standard commercial off the shelf materials and custom-built prototypes. Standard materials include biopolymer drilling fluid, horizontal well screen and casing, and cement-bentonite grout for the annular grout seals. Custom build prototypes for this demonstration included the media and monitoring cartridges (using standard high-density polyethylene (HDPE) pipe and fittings) and the PVPs suited for horizontal orientation. Based on this demonstration, challenges and limitations associated with HRX Well installation

are well understood and can be readily mitigated or avoided with simple design changes; this understanding is considered sufficient to meet the success criteria for this performance objective.

4.6 COMPARE SUSTAINABILITY OF HRX WELL TREATMENT APPROACH WITH OTHERS

The sustainability impacts for three alternatives (HRX Well, groundwater extraction and treatment system (GETS), and PRB were measured by estimating a system design to address the same contaminant plume. The impacts were compared across four lifecycle phases where Phase 1 was materials transport and travel; Phase 2 was materials manufacture; Phase 3 was system installation; and Phase 4 was operation and maintenance. In each phase, the estimated energy used, the resulting carbon dioxide emissions equivalents, nitrogen oxides, sulfur oxide, and particulate matter 10 micrometers or less in diameter emissions were all determined. The sustainability analysis results indicated that the HRX Well sustainability performance objectives were met including that HRX Well compares favorably with the alternatives. The overall sustainability impacts were reflective of the materials or equipment used, particularly during system operation. The transportation impacts were greatest for the PRB because of the total mass of ZVI to be transported. The results were similar for materials manufacture where both PRB media placements involved a greater mass of ZVI than the HRX Well. The installation impacts for all systems were small compared to the impacts from materials manufacture or system operation. Phase 3 impacts were greatest for the GETS system due to nearly continuous equipment operation and regular media replacements. The PRB alternative does not require equipment use during operation; however, the initial and year 15 media replacement had substantial impacts in terms of energy use and emissions. The HRX Well performed favorably in comparison to GETS and the PRB because the HRX Well would not require equipment operation and the mass of media used throughout the lifecycle is a fraction of that required for the other alternatives.

4.7 CHARACTERIZE LIFE CYCLE COSTS

A feasibility evaluation was completed to compare the HRX Well technology to other appropriately scaled remedial technologies capable of achieving similar objectives. The HRX Well is a passive technology, appropriately suited for long-term plume treatment. Therefore, aggressive source removal/destruction technologies are not comparable, and the comparison focused on a GETS and a funnel and gate PRB. The remedial alternatives were evaluated by comparing six criteria, including life cycle cost. Lifecycle cost estimates included capital and operations costs. The results of this cost analysis confirm that the HRX Well costs compare favorably to appropriate comparable technologies and are considered sufficient to meet the success criteria for this performance objective.

4.8 FINALIZE AND VALIDATE THE HRX WELL DESIGN TOOL

In order to facilitate future efficient HRX Well designs, capture lessons learned, and promote technology transfer, an Excel-based HRX Well design, cost, and sustainability tool was developed. Many HRX Well configurations are possible, but the applicability of any design is subject to site-specific factors. The tool allows the user to optimize the design based on user-provided values. Supplemental literature values can also be used as inputs to support high-level estimations. To validate the reliability and usefulness of this tool, HRX Well designs were successfully evaluated for the VAFB site as well as two additional DoD sites.

5.0 COST ASSESSMENT

A feasibility evaluation was completed to compare the HRX Well technology to other appropriately scaled remedial technologies capable of achieving similar objectives. This feasibility cost evaluation is based on addressing the TCE groundwater plume (target plume width of 150 ft and depth of 25 ft) extending downgradient from the "hot spot" where the HRX Well was installed. The existing HRX Well has a capture width of 50 ft; therefore, two additional HRX Wells would be required to treat the full width of 150 ft. A typical remediation timeframe of 30 years was used for this cost comparison.

Therefore, the evaluated remedial technologies are:

- Alternative 1 – HRX Wells (Assumes three HRX Wells, each with a 50-ft capture width);
- Alternative 2 – GETS (Assumes 10 vertical extraction wells); and
- Alternative 3 – Funnel and Gate PRB (Assumes PRB 150 ft long and three ft wide).

Overall, this analysis found that the costs of the HRX Well technology compare favorably to other applicable technologies, as shown in the summary table below (**Table ES-1**). The HRX Well was a more cost-effective option than either GETS or PRB. The efficient use of media in the HRX Well combined with passive operation resulted in lower lifecycle costs compared to the other alternatives. The cost estimates include capital costs (costs associated with installation), operation, monitoring and maintenance costs (costs associated with ongoing operations necessary to operate the remedial alternative), and present worth cost (forecasted life-cycle costs accounting for both inflation and interest).

Table ES-1. Summary of Costs for Each Remedial Alternative

Cost Element	HRX Well (3 HRX Wells)	GETS (10 Vertical Extraction Wells)	PRB (150 Foot Long PRB)
Capital Costs			
Engineering & Design	$250,000	$200,000	$250,000
Treatability Study	$15,000	$0	$15,000
Baseline Characterization	$50,000	$50,000	$50,000
Installation & Materials	$1,175,000	$485,000	$1,050,000
Waste Disposal	$150,000	$30,000	$115,000
Total Capital Costs	$1.6 M	$0.8 M	$1.5 M
Operation, Maintenance, & Monitoring Costs			
Operation and Maintenance (30 years)	$82,500	$3,000,000	$1,050,000
Long-term Monitoring (30 years)	$900,000	$900,000	$900,000
30-Year Lifecycle Total	**$2.6 M**	**$4.7 M**	**$3.4 M**

Notes: Forecasted lifecycle costs account assume 4% interest and 3% inflation. Capital expenses were not depreciated, either at the onset or when incurred over the lifecycle.

6.0 IMPLEMENTATION ISSUES

There are potential generic implementation challenges associated with the directional drilling methods used to install HRX Wells. Examples include the potential for inadvertent drilling fluid returns to the ground surface along preferential pathways and electromagnetic interference with borehole navigation. Environmental regulations and necessary permits required for an HRX Well are expected to be consistent with those required for vertical well remediation projects and will vary by jurisdiction. Utility clearance will be required prior to drilling and many states require a licensed well driller for installation of remediation wells. Drilling waste will require characterization and disposal in accordance with local rules and regulations.

The HRX Well technology uses a combination of standard commercial off the shelf materials and custom-built prototypes. Standard materials include biopolymer drilling fluid, horizontal well screen and casing, and cement-bentonite grout for the annular grout seals. As noted in this demonstration, recovery of the biopolymer drilling fluid may be incomplete, and subsequent fermentation of this carbon source will affect local redox conditions and electron acceptor concentrations. For this demonstration, this effect resulted in beneficial complimentary biotic treatment processes; however, these geochemical conditions might not be desirable for some treatment strategies (e.g., slow-release chemical oxidation treatment media). The potential effects of residual drilling fluid should be considered in treatability studies and designs for future installations. Custom build prototypes for this project included the media and monitoring cartridges (using standard HDPE pipe and fittings) and the PVPs suited for horizontal orientation.