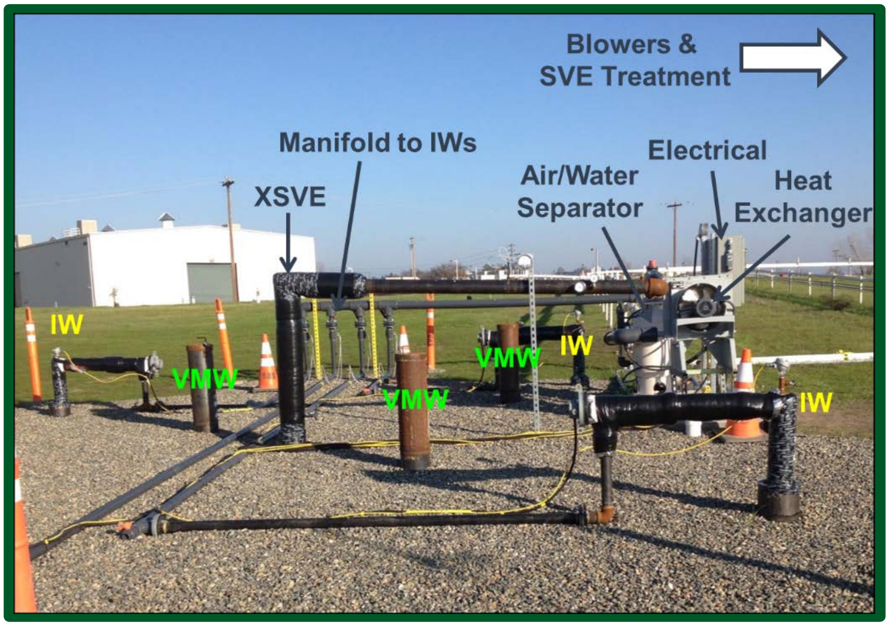
ESTCP
Cost and Performance Report

(ER-201326)



1,4-Dioxane Remediation by Extreme Soil Vapor Extraction (XSVE)

October 2017

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10/30/2017

2. REPORT TYPE
Cost & Performance Report

3. DATES COVERED *(From - To)*
8/8/2013 - 8/8/2018

4. TITLE AND SUBTITLE
1,4-Dioxane Remediation by Extreme Soil Vapor Extraction (XSVE)

5a. CONTRACT NUMBER
Contract: 13-C-0059

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
ER-201326

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Integrated Science & Technology, Inc.
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Panacea, FL 32346

8. PERFORMING ORGANIZATION REPORT NUMBER
ER-201326

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 17D03
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ER-201326

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A; unlimited public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

1,4-Dioxane, a cyclic diether and an additive in the chlorinated solvent 1,1,1-trichloroethane, has proven to be a persistent groundwater contaminant. Conventional soil vapor extraction (SVE) can remove some 1,4-dioxane, but a substantial residual source is left behind causing long-term groundwater contamination. Although 1,4-dioxane's vapor pressure in the range of trichloroethylene or benzene, it is totally miscible in water soluble. As a result, 1,4-dioxane becomes sequestered in vadose zone pore water which serves as a long-term source of groundwater contamination. Extreme soil vapor extraction (XSVE), an enhancement of SVE, specifically addresses 1,4-dioxane-contaminated soil by incorporating enhancements such as decreased infiltration, increased air flow, focused vapor extraction, and injection of heated air.

15. SUBJECT TERMS

air-water separator, 1,4-Dioxane Remediation, Extreme Soil Vapor Extraction (XSVE), non-aqueous phase liquid, 1,1,1-trichloroethane (TCA), volatile organic compounds

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Rob Hinchee
					19b. TELEPHONE NUMBER *(Include area code)*
UNCLASS	UNCLASS	UNCLASS	UNCLASS	61	850-984-4460

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COST & PERFORMANCE REPORT
Project: ER-201326

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ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AWS	air-water separator
bgs	below ground surface
COC	contaminant of concern
$C_{soil,14D}$	treatment zone 1,4-dioxane soil concentration
cm	centimeter
CY	cubic yards
DoD	Department of Defense
DoE	Department of Energy
ESTCP	Environmental Security Technology Certification Program
ft	feet
IDW	investigation-derived waste
ITRC	Interstate Technology and Regulatory Council
L	liter
m	meter
mg	milligram
n	soil porosity
NAPL	non-aqueous phase liquid
PCE	tetrachloroethylene (IUPAC); perchloroethylene (common)
PI	principal investigator
POC	point of contact
ppb_v	parts per billion by volume (vapor concentration unit)
ppm_v	parts per million by volume (vapor concentration unit)
PRG	preliminary remediation goal
RH	relative humidity
scfm	standard cubic feet per minute
SHSO	site health and safety officer
SVE	soil vapor extraction
T	temperature
T_{start}	initial soil temperature
$T_{ambient}$	ambient air temperature

T_{in}	injection air temperature
TCA	1,1,1-trichloroethane
TCE	trichloroethene (IUPAC); trichloroethylene (common)
TLA	three letter acronym
TO-15	Toxic Organics-15 (USEPA analytical method)
$Q_{air,STP}$	extraction flow rate
USEPA	United States Environmental Protection Agency
VMW	Vapor Monitoring Well
VOCs	volatile organic compounds
V_{soil}	treatment zone soil volume
XSVE	extreme soil vapor extraction
Θ_m	soil moisture content
ρ_{soil}	soil bulk mass density
$\%RH_{ambient}$	ambient air relative humidity

ACKNOWLEDGEMENTS

The authors would like to thank Hunter Anderson, Ph.D., of the Air Force Civil Engineering Center, for greatly facilitating the demonstration site search process. We also extend our appreciation to the Groundwater and SVE Program Manager, Kenneth Smarkel, Ph.D., P.E., of the McClellan facility for his assistance facilitating this project. Successful field implementation of this project was largely accomplished by AECOM with Kimiye Touchi, P.E., as the project manager and Paul Graff, P.E., as oversight lead and, especially, AECOM field personnel.

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EXECUTIVE SUMMARY

1,4-Dioxane, a cyclic diether and an additive in the chlorinated solvent 1,1,1-trichloroethane, has proven to be a persistent groundwater contaminant. Conventional soil vapor extraction (SVE) can remove some 1,4-dioxane, but a substantial residual source is left behind causing long-term groundwater contamination. Although 1,4-dioxane's vapor pressure in the range of trichloroethylene or benzene, it is totally miscible in water soluble. As a result, 1,4-dioxane becomes sequestered in vadose zone pore water which serves as a long-term source of groundwater contamination. Extreme soil vapor extraction (XSVE), an enhancement of SVE, specifically addresses 1,4-dioxane-contaminated soil by incorporating enhancements such as decreased infiltration, increased air flow, focused vapor extraction, and injection of heated air.

The XSVE field demonstration site was at the former McClellan AFB near Sacramento, California, adjacent to an SVE well with high 1,4-dioxane concentrations. Pneulog® was used to determine vertical profiles of 1,4-dioxane vapor concentrations and effective permeabilities in the SVE well. Field analysis of soil boring samples for 1,4-dioxane during drilling operations was conducted to insure suitable placement of injection and extraction wells for the demonstration. The XSVE system consists of four two-inch steel-cased injection wells forming a 20-foot square with a central four-inch steel-cased extraction well (38–68 ft below ground surface (bgs) screened interval each). The treatment zone and soil beneath were instrumented with thermocouples, soil moisture sensors, and soil vapor monitoring probes. 1,4-Dioxane and soil moisture distributions prior to XSVE were determined using five soil borings. The system operated for approximately 13 months with about 98% uptime. Injection temperatures were maintained in the 100–130˚C range (mid-screen) for the bulk of system operation, with flow rates generally in the 70–90 standard cubic feet per minute (scfm) range for each injection well. Extraction well flow rate was generally in the 70–110 scfm range. Observed treatment zone temperatures reached as high as 90˚C near the injection wells, however extraction well temperatures did not exceed 40˚C. Soil heating costs were approximately $25 per cubic yard (CY) for this demonstration. Soil moisture readings decreased significantly in the sensors closest to the injection wells, whereas those near the extraction well generally remained stable. Because elevated temperature soil gas could potentially condense water vapor in ambient temperature vapor sampling canisters and water condensation has the potential to removing 1,4-dioxane from the vapor, 1,4-dioxane vapor concentrations in the treatment zone and extraction well were determined using a vapor/condensate sampling apparatus. Through this method, approximately 13 kg of 1,4-dioxane were removed from the treatment zone over the course of the demonstration.

Five soil borings collected post-demonstration soil samples. 1,4-Dioxane in the treatment zone decreased by approximately 94% and soil moisture decreased by approximately 45%. Downward migration of 1,4-dioxane due to condensation was not observed. A screening-level mass and energy balance model, HyperVentilate (HypeVent) XSVE, was developed to simulate the remediation of 1,4-dioxane by XSVE. HypeVent XSVE adequately simulated 1,4-dioxane removal, soil moisture, and soil temperatures observed during the demonstration—proving itself a useful feasibility assessment and design tool for XSVE of 1,4-dioxane. Sensitivity analyses showed that 1,4-dioxane removal benefited considerably from heated air injection. XSVE has been demonstrated to be a cost-effective remediation approach for vadose zone 1,4-dioxane.

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1.0 INTRODUCTION

Soil Vapor Extraction (SVE) has long been an accepted and widely used technology for remediation of vadose zones contaminated by volatile organic compounds (VOCs). As a result most sites with vadose zone VOC contamination either have been subject to SVE or are likely candidates for SVE treatment. Unfortunately, conventional SVE does not readily treat 1,4-dioxane, a common VOC co-contaminant. Enhanced or extreme soil vapor extraction (XSVE) is a form of SVE designed specifically to address 1,4-dioxane contaminated soil by incorporating enhancements such as increased air flow, increased temperature, and focused vapor extraction.

1.1 BACKGROUND

1,4-Dioxane contamination has been an emerging problem. The compound has historically been a stabilizer additive to chlorinated solvents, particularly 1,1,1-trichloroethane (TCA) (Mohr, 2010). 1,4-Dioxane is relatively volatile (38 mm Hg vapor pressure; i.e., 0.05 atmospheres), completely miscible in water, and tends to be resistant to degradation. This combination of characteristics has resulted in extensive 1,4-dioxane groundwater plumes. Residual vadose zone 1,4-dioxane can leach to groundwater, thus creating a long-term source area and prolonging the need for groundwater remediation efforts.

There is currently no demonstrated approach for *in situ* remediation of vadose zone 1,4-dioxane. Excavation is an option where feasible. Other technologies such as *in situ* oxidation or bioremediation, though possible, are unproven. Conventional SVE designed to remove volatiles such as trichloroethylene (TCE) or TCA often leaves substantial 1,4-dioxane behind that serves as a continued source of groundwater contamination. TCE and TCA have Henry's Law constants orders of magnitude higher than that of 1,4-dioxane and are removed much more quickly than 1,4-dioxane.

Increased soil temperatures enhances 1,4-dioxane removal by SVE. The temperature-dependent 1,4-dioxane Henry's Law constant is nonlinear and favors higher 1,4-dioxane concentrations in the vapor phase as temperature increases (Figure 1.1.1).

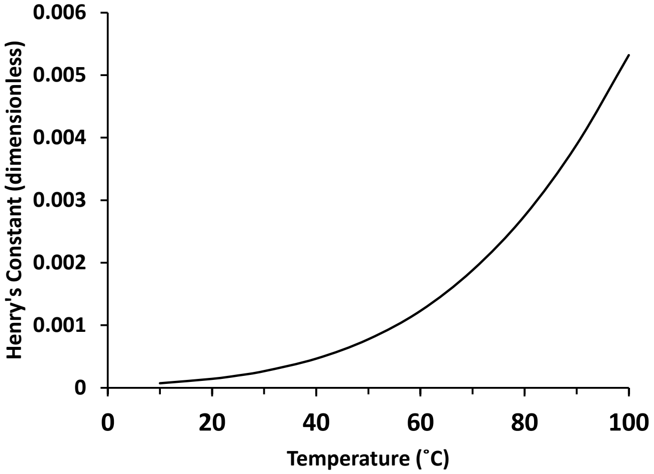

Figure 1.1.1. 1,4-Dioxane Henry's Law Constant (dimensionless; vapor/aqueous) as a function of temperature (Ondo and Dohnal, 2007).

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objective of this project is to provide The Department of Defense (DoD) and its contractors with the tools and information necessary to remediate 1,4-dioxane-contaminated vadose soils. This project evaluated and demonstrated the efficacy of XSVE to remove 1,4-dioxane from the vadose zone, thus reducing the need for long-term groundwater remediation. The project also aimed to provide a useful feasibility assessment and design tool for XSVE of 1,4-dioxane and to facilitate the implementation of the XSVE technology by updating HyperVentilate (HypeVent) SVE guidance software (e.g., USEPA, 1993).

1.3 REGULATORY DRIVERS

1,4-Dioxane is an emerging contaminant of concern (COC) for which cleanup standards are only now being set. USEPA Region 9 (USEPA, 2015a & b) screening levels are 0.094 µg/kg for soil to groundwater and 0.46 µg/L for drinking water (tap water). California has adopted a drinking water notification level for 1,4-dioxane of 1 µg/L (CA State Water Resources Control Board, 2015), and regulators have been requiring groundwater remediation with 1,4-dioxane contamination.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

XSVE extends SVE to specifically address soil contaminated by 1,4-dioxane. Conventional SVE is often the remediation technology of choice for the chlorinated solvents typically found with 1,4-dioxane. While known to remove some 1,4-dioxane, SVE usually leaves behind substantial residual levels of this COC because, although 1,4-dioxane has a vapor pressure in the same range as TCE or benzene, its higher water solubility results in preferential partitioning into pore water rather than vapor. Because conventional SVE focuses on high vapor pressure/low solubility VOCs, existing site data show incomplete 1,4-dioxane removal occurring during conventional SVE cleanup.

XSVE solves this problem through a combination of focused vapor extraction, increased air flow, increased temperature, and decreased infiltration. These enhancements, which focus on the removal of vadose 1,4-dioxane, may not all be required at every site. Conventional SVE typically requires extraction of between 200 and 5,000 pore volumes over two to four years of operation (Army CoE, 2002). Without the XSVE enhancements, substantially more pore volumes would be required to remove significant 1,4-dioxane mass. Injection of heated air near the extraction point reduces required pore volumes to achieve cleanup.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

XSVE extends SVE, a widely used, well-understood, and effective remedial technology for VOCs, through the addition of enhancements such as hot air injection. Various technologies for hot air injection are available, and models such as HypeVent can aid in the design and operation of SVE systems.

XSVE’s focused extraction can only be accomplished if the location of 1,4-dioxane in the vadose zone is known. Adequately locating the 1,4-dioxane source within the vadose zone presents a challenge and potential disadvantage to this method, as experience has shown that the distribution of 1,4-dioxane can be much more confined than that of the chlorinated solvents because it tends to stay close to the release location. If there are multiple unknown chlorinated solvent release locations, it may be difficult to cost-effectively determine the locations of 1,4-dioxane in the vadose zone to the degree necessary for effective focused extraction.

The dynamics of heating soil with injected air introduces the potential for condensation and downward migration of 1,4-dioxane. This demonstration and the HypeVent XSVE model (Section 5.8) provides insights as to potential difficulties due to condensation.

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3.0 PERFORMANCE OBJECTIVES

The quantitative and qualitative performance objectives for this technology demonstration are given in Tables 3.1 and 3.2, respectively.

Table 3.1. Quantitative Performance Objective

Performance Objective	Data Requirements	Success Criteria
Reduction in soil 1,4-dioxane	Soil 1,4-dioxane concentrations in soil borings within treatment zone prior to and after XSVE operation	> 90% Reduction in the average treatment zone soil 1,4-dioxane concentration
Minimization of 1,4-dioxane downward migration	Soil 1,4-dioxane concentrations in soil borings below treatment zone prior to and after XSVE operation	< 20% Increase in average soil 1,4-dioxane soil concentration beneath treatment zone

Table 3.2. Qualitative Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Adequate soil gas 1,4-dioxane measurements at elevated temperatures	Accurate sampling and analysis of soil gas 1,4-dioxane concentrations before and during XSVE operation	Meaningful, comparable 1,4-dioxane soil gas data for process control over wide temperature range
Ease XSVE system installation and startup	Input from field Project Team, including onsite contractor AECOM	Moderate complexity compared to traditional SVE system installation and startup
Ease XSVE system operation and monitoring	Input from field Project Team, including onsite contractor AECOM	Moderate complexity compared to traditional SVE system operation and monitoring
Update HypeVent to be a useful tool in XSVE system design and implementation	Input from Project Team members	Updated version implemented as a valuable tool in XSVE system design and implementation

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4.0 SITE DESCRIPTION

4.1 SITE SELECTION

BRAC (Base Realignment and Closure) Former McClellan Air Force Base (AFB) (hereinafter, McClellan), California, was selected as the test site for this technology demonstration. The study site is within the Operable Unit (OU) D landfill near SVE well VES-105 (Figure 4.2.1).

4.2 SITE LOCATION AND HISTORY

Approximately seven miles northwest of Sacramento, California, McClellan was an active industrial facility since 1939, used for the maintenance of bombers during World War II and the Korean conflict, for jet aircraft in the 1960s, and later for maintenance and repair of electronics and communications equipment. The BRAC Commission recommended the base for closure in 1995, and in 2001 McClellan was closed as an active military base (Former McClellan AFB Air Force Real Property Agency, 2007). Historical operations released contaminants into the soil and groundwater at McClellan.

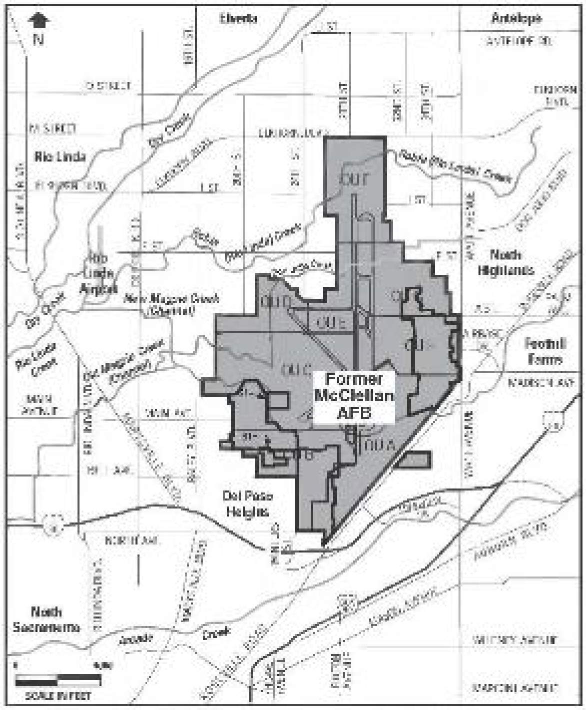

Figure 4.2.1. Former McClellan AFB, located near Sacramento, California (Former McClellan AFB Air Force Real Property Agency, 2007). OU-D is located in the northwest part of installation.

The study site at McClellan is located within the OU-D landfill in the northwest quadrant of the facility, where chlorinated solvents (including TCA) are the main COCs. Groundwater extraction and SVE systems were installed, and in 1995, a double-liner cap and drainage system was installed over the OU-D landfill (URS, 2013). The disposal pits were excavated prior to installation of the landfill cap. The OU-D SVE system has been operated consistently since 1996.

4.3 SITE GEOLOGY/HYDROGEOLOGY

A complex series of alluvial and fluvial deposits that were deposited, eroded, and redeposited characterizes the geology of the OU-D area. The subsurface geologic environment consists of transitional alluvial system alternating between braided streams and meandering streams/flood plains. This geologic environment has resulted in little lithologic continuity, making correlation between similar lithologies difficult (CH2M Hill, 1992). These observations are consistent with the boring logs obtained during this project. Groundwater flow direction is generally to the west in the vicinity of VES-105, and water-bearing sands are generally encountered close to 100 ft bgs.

4.4 CONTAMINANT DISTRIBUTION

The 2004 distribution of VOCs in groundwater and soil gas at McClellan are shown in Figure 4.4.1. SVE systems have been located in various portions of the facility, including OU-D. The system consists of 31 SVE wells and 80 soil vapor monitoring wells (URS, 2014). Only 5 to 10 SVE wells operate at any given time.

The 1,4-dioxane soil gas concentrations in 2013 in the OU-D study area are shown in Figure 4.4.2. The highest concentration observed was in a historical disposal area, VES-105 (screened 38–100 ft bgs). PneuLog® profiling (Praxis Environmental Technologies, Inc., Burlingame, California) was performed in VES-105 and determined that 1,4-dioxane was primarily in the 38–68 ft bgs interval (confirmed by soil borings). A 1,4-dioxane groundwater plume was associated with this area of soil contamination. Historical site characterizations and Pneulog results indicated that VES-105 would be the preferable study site location for this project.

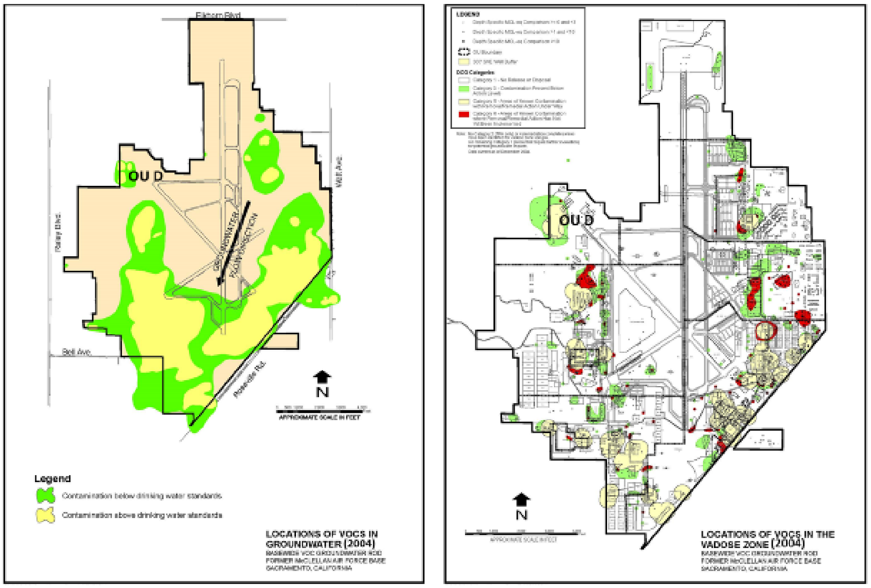

Figure 4.4.1. 2004 Facility-wide VOC Distributions in Groundwater (left) and Soil Vapor (right) (Former McClellan AFB Air Force Real Property Agency, 2007). OU-D location Indicated.

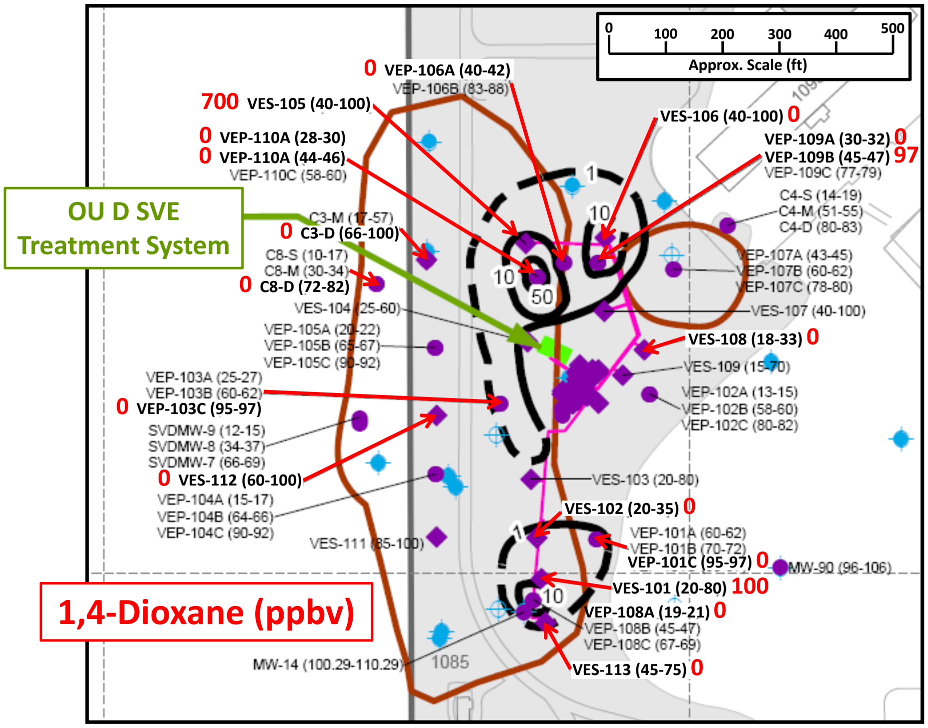

Figure 4.4.2. OU-D 1,4-dioxane Soil Gas Concentrations Observed in 2013 Prior to This Demonstration Project (data obtained from Ken Smarkel, Noblis Inc., Former McClellan AFB). Base map black isopleths are soil vapor total VOCs (ppm$_v$) and brown isopleth is groundwater VOC Maximum Contaminant Level (URS, 2014).

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

Field observations at various sites have shown that although some 1,4-dioxane removal occurs during conventional SVE, cleanup is incomplete. The case at McClellan was consistent with these observations. XSVE addresses this problem through a combination of increased air flow, increased temperature, decreased infiltration, and focused air extraction. The site was capped so infiltration was limited. The demonstration injection and extraction wells were screened approximately 38–68 ft bgs to focus air extraction and increase extraction flow rates in the region where 1,4-dioxane was observed. Injection air would be heated to at least 90ºC to increase soil temperature.

VES-105 well construction and materials were not compatible with focused flow and elevated temperatures needed for XSVE. Shifting the demonstration area slightly to the north within the disposal trench provided conditions similar to VES-105, and field determinations of soil 1,4-dioxane concentrations ensured proper placement.

The general layout of the XSVE system is shown in Figure 5.1.1. The four injection wells formed a 20 ft square pattern around a central vapor extraction well. Preliminary screening-level modeling indicated a combined injection flow rate up to approximately 400 standard cubic feet per minute (scfm) (100 scfm per injection well) and the satisfactory extraction flow rate of approximately 100 scfm. Geometry dictates that a fourth of the injected air should flow into the target treatment zone and ultimately to the extraction well—necessary since the OU-D SVE system continued to operate. Conditions within and below the treatment zone were assessed at four locations by vapor monitoring probes (within treatment zone only) and temperature and soil moisture sensors. Injection flow was distributed equally between the four wells. The XSVE extracted air was merged into the existing SVE system air for treatment. The injection air was to be heated by in-line heaters at each wellhead.

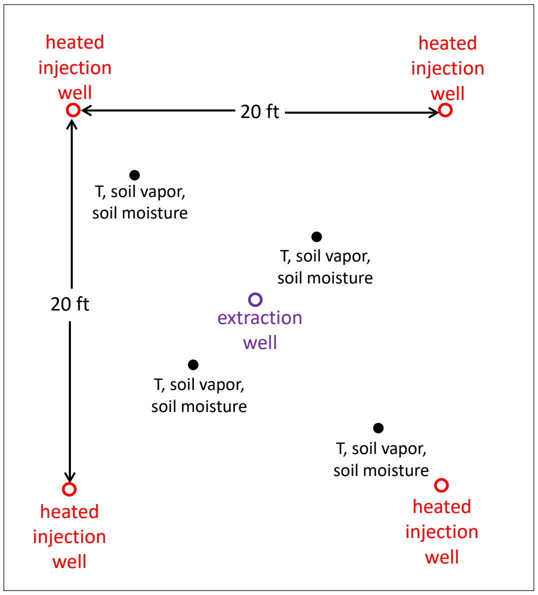

Figure 5.1.1. Plan View Schematic of Conceptual XSVE Demonstration Layout.

Soil borings from the installation of the four monitoring locations and the extraction well soil boring provided samples to determine initial 1,4-dioxane soil concentration and soil moisture content. Samples from comparable soil borings (Figure 5.1.2) were used to determine the final 1,4-dioxane soil concentration at the completion of XSVE. Also shown are the incremental sampling methodology sampling zones (ITRC, 2012; Outer Ring, Inner Ring, and Center.).

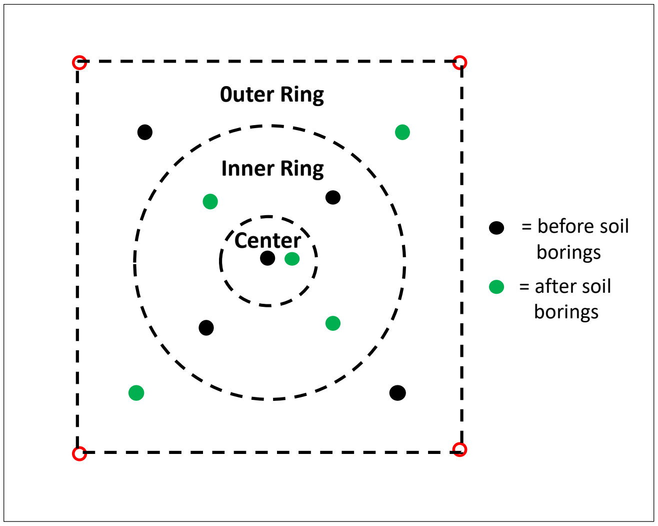

Figure 5.1.2. Plan View Conceptual Schematic of Soil Borings to be Taken before and after XSVE Demonstration Showing the Three Zones Used for Incremental Sampling (outer, inner, and center).

XSVE process monitoring included periodic sampling of the multi-level samplers for 1,4-dioxane in soil gas, *in situ* soil moisture content, and temperature. The extraction well effluent were periodically sampled for 1,4-dioxane soil gas concentrations.

5.2 BASELINE CHARACTERIZATION ACTIVITIES

Drilling and well installation was conducted in September 2014, and baseline site characterization was conducted during site instrumentation activities (installation of injection and extraction wells and vapor monitoring well (VMW) locations). The site layout is shown in Figure 5.2.1. VES-105 was grouted to prevent it from being a conduit for vapor flow. As soil borings were advanced, soil samples were characterized to generate boring logs. The XSVE treatment zone is characterized by layers comprised primarily of sand mixed with some silt, others primarily silt mixed with some sand, with some layers composed of just sand or silt.

Prior to drilling it was not known whether the site layout would contain a treatment zone with sufficient 1,4-dioxane for the demonstration project. Triad Environmental Solutions, Inc. (Durham, North Carolina) conducted field analysis of 1,4-dioxane soil concentrations to confirm the presence of sufficient contamination.

Laboratory analytical results of soil 1,4-dioxane and moisture content prior to XSVE operation are shown in Figure 5.2.2.

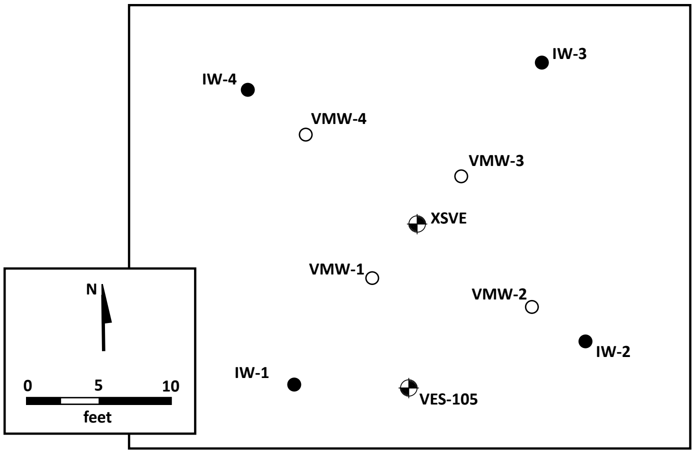

Figure 5.2.1. Extraction, Injection and Vapor Monitor Well Locations Relative to VES-105.

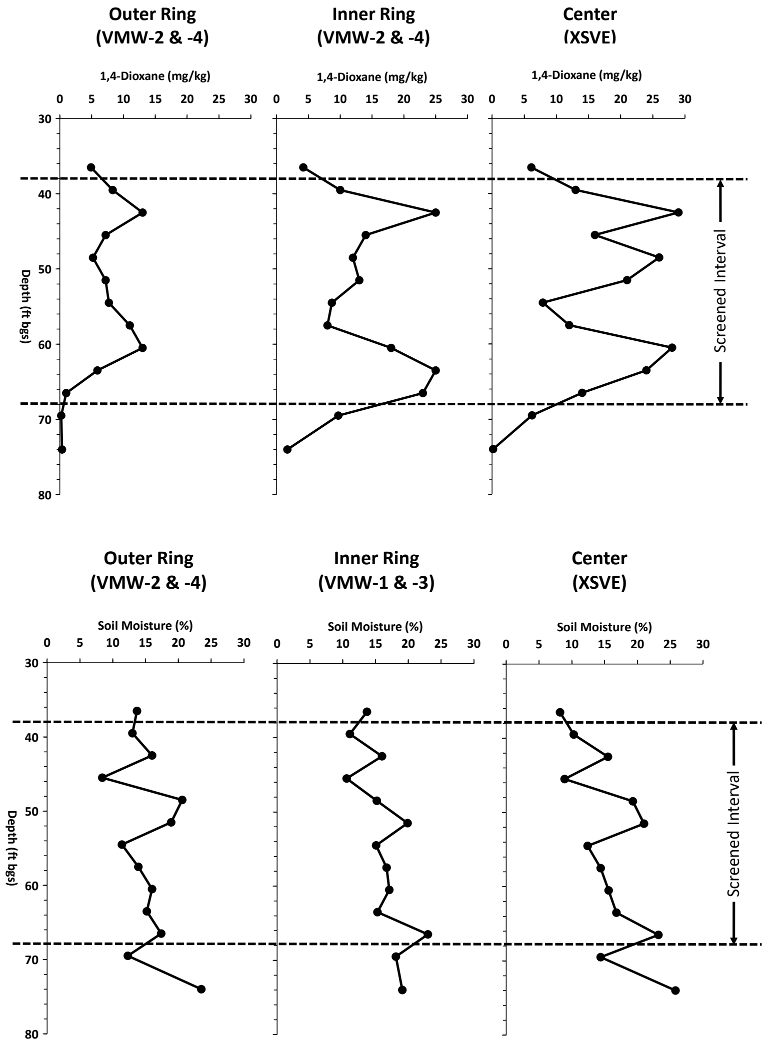

Figure 5.2.2. 1,4-Dioxane (mg/kg) and Soil Moisture (%) Concentrations prior to XSVE.

5.3 1,4-DIOXANE SOIL VAPOR SAMPLING AT ELEVATED TEMPERATURES

When sampling soil vapor at elevated temperatures using an evacuated vapor sampling canister (e.g., Summa canister) at ambient temperature, condensation of water vapor occurs within the canister. 1,4-Dioxane could partition into that condensate and lower the measured vapor concentration. Laboratory experiments were conducted to evaluate whether this phenomenon could potentially be a problem in field sampling of 1,4-dioxane at ambient and elevated temperatures using an alternative sampling method to account for potential losses due to condensation. The results (Figure 5.3.1) showed that a substantial amount of 1,4-dioxane could reside in condensate when sampling moist air at elevated temperatures.

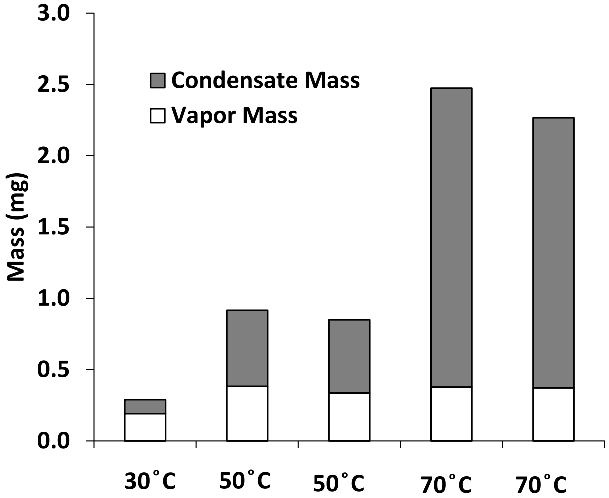

Figure 5.3.1. 1,4-Dioxane Mass for Condensate and Vapor Phases per Hour in Vapor Generator (18.5 mg/L 1,4-dioxane sparged at 1.0 L/min) Using Vapor/Condensate Sampling Apparatus.

A vapor/condensate sampling apparatus was designed to sample both the vapor and condensate phases (Figure 5.3.2). Effective vapor phase concentrations at elevated temperatures could then be determined by dividing the combined 1,4-dioxane mass (vapor and condensate from sampling apparatus) and total vapor volume to obtain the condensate sample. The vapor/condensate sampling apparatus was used throughout the XSVE demonstration to alleviate potential concerns of possible low sampling bias due to condensation.

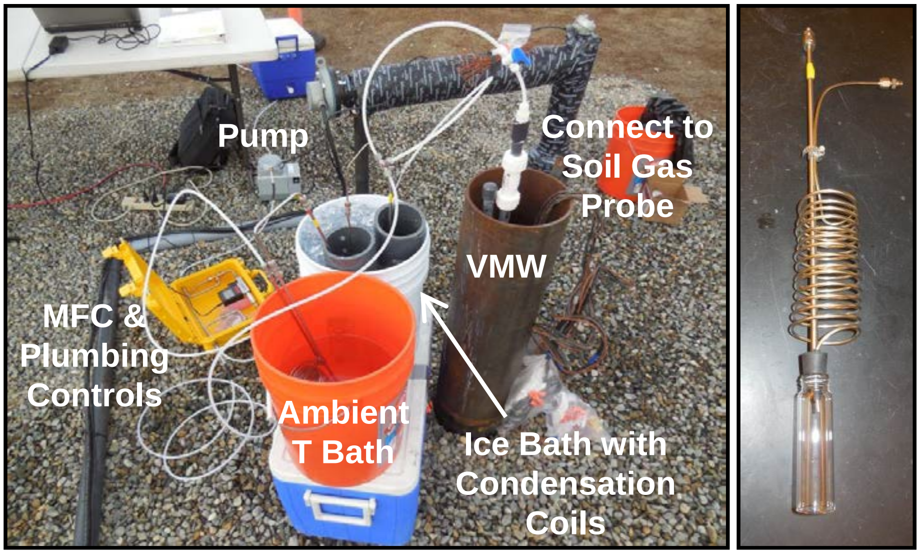

Figure 5.3.2. Vapor/Condensate Sampling Apparatus as Used in the Field (left). Ice Bath Condensate Coil Mockup with Stopper and VOA Condensate Collection Vessel is Shown on Right.

5.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The XSVE treatment zone consisted of one extraction well surrounded by four injection wells, all screened in the 38–68 ft bgs interval. Well construction and layout are shown in Figures 5.4.1 and 5.4.2. Thermocouples were placed within the top of the extraction and injection well casings, as well as at the centers of the well screens within the injection well casings, to monitor the temperature of the injected and extracted air. There were four locations (designated VMW) for monitoring conditions within the treatment zone. Each VMW contained two soil vapor monitoring probes, one in each the upper and lower portion of the treatment zone. Each VMW also contained three sets of temperature and soil moisture sensors, one in each in the upper and lower treatment zone and one below the treatment zone.

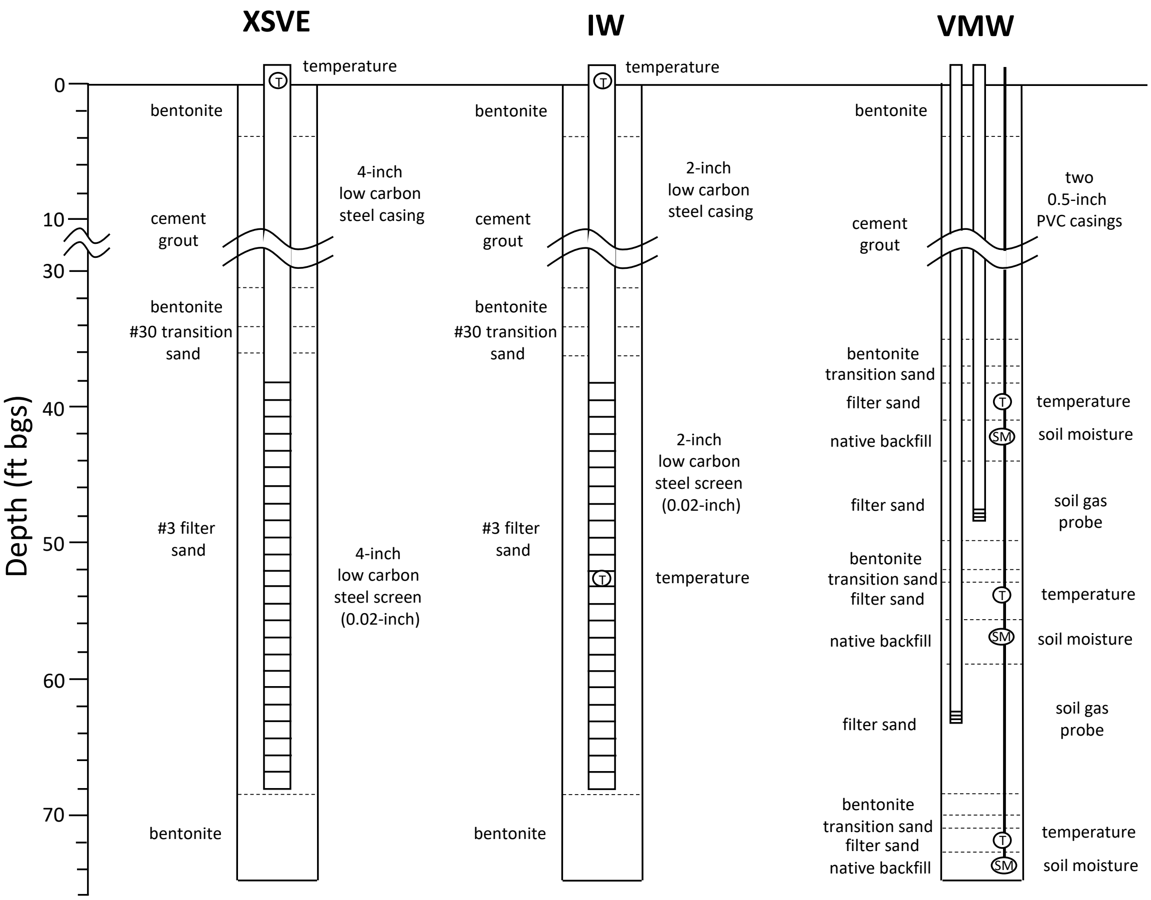

Figure 5.4.1. Well Construction and Instrumentation Details for XSVE Demonstration.

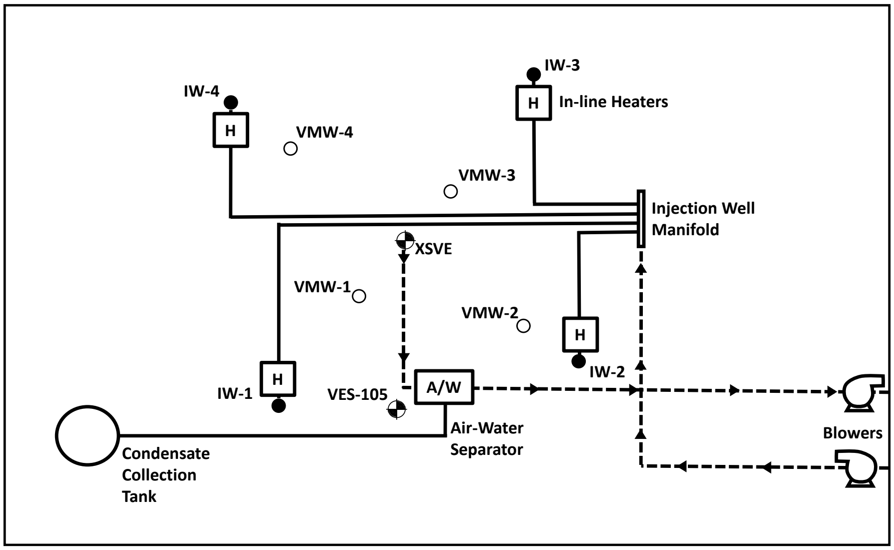

Figure 5.4.2. Schematic of XSVE Demonstration System Design.

Injection well piping came from a rotary-positive displacement blower to a manifold that distributed flow to each of the four injection wells. The manifold contains valves to control and balance the flow distribution. An in-line heater at each of the injection wellheads (Figure 5.3.3). was configured to cycle off at a specified temperature and cycle on when below that temperature. The extraction well piping was connected to an air-water separator (AWS) and a blower. The condensate of the AWS discharged to a storage tank, the contents of which were periodically trucked to the facility waste water treatment plant for disposal. Figure 5.4.4 shows an annotated photograph of the XSVE demonstration site layout.

Figure 5.4.3. Injection Wellheads

Top Left – Prior to insulation and in-line heater. Right – In-line heater. Bottom Left – Finished with insulation, heater, plumbing, thermocouple access, and pressure sensor access. Note: Piping along ground surface was changed from PVC to steel.

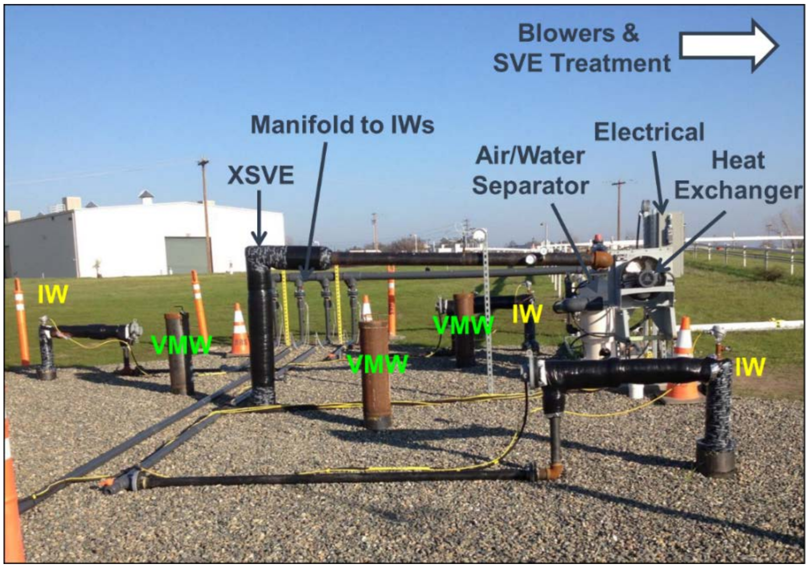

Figure 5.4.4. Layout of XSVE Demonstration Site.

5.5 FIELD TESTING

After construction of the XSVE system, injection and extraction well flows were established. The injection well flows were adjusted and balanced using valves on the injection well manifold. The in-line heaters were turned on (November 19, 2014) and monitored. PVC piping leading towards the in-line heaters melted and was replaced with steel piping. The extraction well flow was limited by the narrow piping of the heat exchanger/AWS setup, which was replaced with a larger AWS that accommodated larger piping. Emergency stop testing was conducted to ensure the system would shut down if blowers turned off and/or temperatures got too high. Injection well temperatures (top of casing) were held at around 100˚C for the first 1.5 months then were increased to as high as 160˚C. Generally, as the injection temperature at mid-screen increased (i.e., temperature entering treatment zone) the injection temperature at the top of casing was allowed to decrease.

The XSVE system had minimal downtime (approximately 99% uptime after the first two weeks of operation). Temperatures, flow rates, and pressures were measured and recorded on a weekly basis. Treatment zone conditions (e.g., VMW locations, temperature, pressure, soil moisture) were measured and recorded on a biweekly basis. Soil vapor samples (VMW locations and extraction well) were taken and analyzed on a two- to three-month basis. The XSVE system was operated for 54 weeks.

After system shutdown, all above ground components of the XSVE were removed from the site. The casings for the wells were cut off at ground level to allow drill rig access during the final soil sampling. After drilling operations, the landfill cap liner was repaired.

5.6 SAMPLING METHODS

There were three phases of this field demonstration: 1) pre-XSVE; 2) XSVE process monitoring; and 3) post-XSVE. Table 5.1 details the types and approximate numbers of samples analyzed.

Incremental sampling approach (ITRC, 2012) was used to reduce the number of soil samples taken. Soil samples were shipped to the laboratory in glass sample jars and analyzed for 1,4-dioxane by EPA Method 8270 (GC/MS) and for moisture content by EPA Method 160.3. Soil gas samples were taken using evacuated, cleaned one-liter vapor sampling canisters and analyzed by EPA Method TO-15 (GC/MS). Condensate water samples were shipped to the laboratory in 40-mL VOA vials and analyzed for 1,4-dioxane by EPA Method 8270. Temperature readings were made using thermocouples. Pressure measurements were made using Pitot tubes. *In situ* soil moisture measurements were made using time domain reflectometry-based sensors.

Soil borings were obtained at the beginning and end of the demonstration using hollow-stem augur drilling rigs. The split spoons were placed on clean paper sheeting where the soil boring depths could be marked. Sampled soil (either three-foot composite or grab) was place in a cleaned stainless-steel bowl, crushed, and mixed. The three-foot composites from the same depths for the inner and outer rings were combined into a single composite; soil from the first boring was stored in a zip-lock bag until it could be mixed with the soil from the second boring and put into a glass jar and labelled for laboratory analysis. Split spoons in the post-demonstration soil sampling of elevated temperature were cooled prior to sampling.

During the first vapor sampling event prior to heated air injection, vapor samples were obtained by direct canister sampling. The VMW vapor probes were purged prior to sampling. All other sampling events used the vapor/condensate sampling methodology.

Table 5.1. Approximate Total Number and Types of Samples Collected.

<table>
<tr><th colspan="4">Pre-XSVE</th></tr>
<tr><th>Location</th><th>Matrix</th><th>Analyte/Parameter</th><th># of Samples</th></tr>
<tr><td>Soil borings (VMWs and extraction well)</td><td>Soil</td><td>1,4-dioxane, soil moisture content</td><td>44</td></tr>
<tr><td>Soil vapor probes and extraction well</td><td>Soil gas, lab</td><td>1,4-dioxane</td><td>9</td></tr>
<tr><td>VMWs</td><td>Soil (<i>in situ</i>), field</td><td>temperature, soil moisture, pressure</td><td>12</td></tr>
<tr><td>Injection wells and extraction well</td><td>Vapor, field</td><td>temperature, pressure</td><td>6</td></tr>
<tr><th colspan="4">XSVE Process Monitoring</th></tr>
<tr><th>Location</th><th>Matrix</th><th>Analyte/Parameter</th><th># of Samples</th></tr>
<tr><td>Soil vapor probes and extraction well</td><td>Soil gas, lab</td><td>1,4-dioxane</td><td>64</td></tr>
<tr><td>Soil vapor probes and extraction well</td><td>Water (soil gas condensate), lab</td><td>1,4-dioxane</td><td>64</td></tr>
<tr><td>VMWs</td><td>Soil (<i>in situ</i>), field</td><td>temperature, soil moisture, pressure</td><td>336</td></tr>
<tr><td>Injection wells and extraction well</td><td>Vapor, field</td><td>temperature, pressure</td><td>342</td></tr>
<tr><th colspan="4">Post-XSVE</th></tr>
<tr><th>Location</th><th>Matrix</th><th>Analyte/Parameter</th><th># of Samples</th></tr>
<tr><td>Soil borings (VMWs and extraction well)</td><td>Soil</td><td>1,4-dioxane, soil moisture</td><td>53</td></tr>
</table>

5.7 SAMPLING RESULTS

5.7.1 XSVE SYSTEM MONITORING

Injection well flow rates and pressures during XSVE operation are shown in Figure 5.7.1. Flow rates were generally between 70–90 scfm—slightly lower than the design flow rate of 100 scfm each. Since the injection wells provide an excess of air flow needed for the treatment zone, this reduction is not significant. Extraction well flow rates and pressures during XSVE operation are shown in Figure 5.7.2. Extraction well flowrates were generally in the 80 to 120 scfm range. Injection well temperatures at the wellhead and mid-screen during XSVE operation are shown in Figure 5.7.3. There was a temperature loss from the wellheads to the mid-screen depths. The mid-screen temperatures reflect the temperatures entering the treatment zone, generally in the 100–120˚C range and allowed to rise above 120˚C toward the end of operation. These injection temperatures were not difficult to maintain.

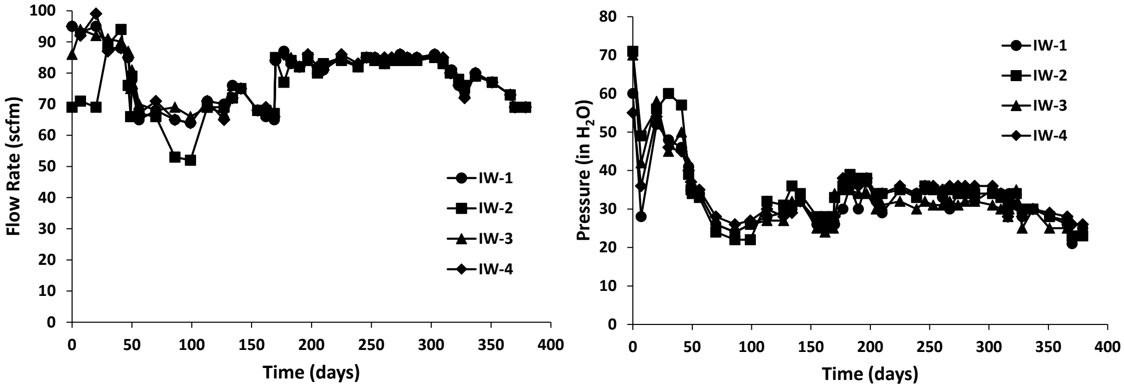

Figure 5.7.1. Injection Well Flow Rates and Pressures during XSVE Operation.

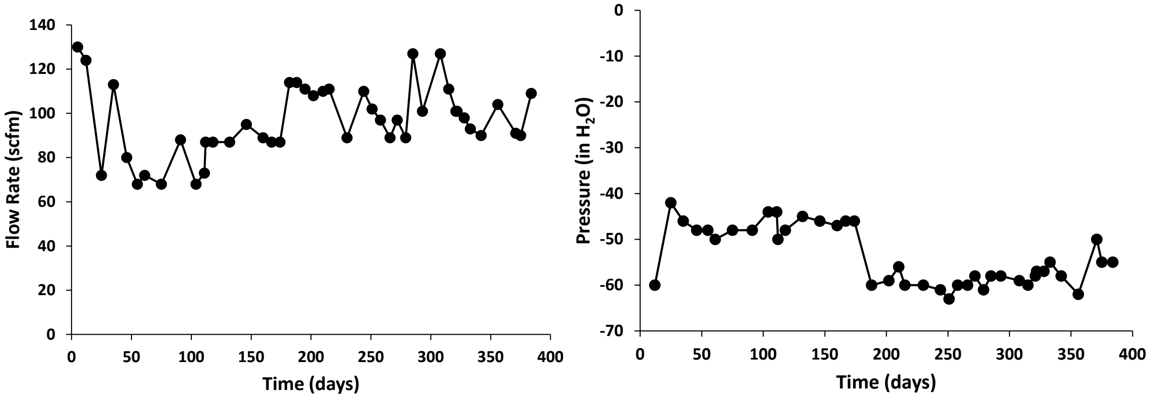

Figure 5.7.2. Extraction Well Flow Rates and Pressures (after AWS) during XSVE Operation.

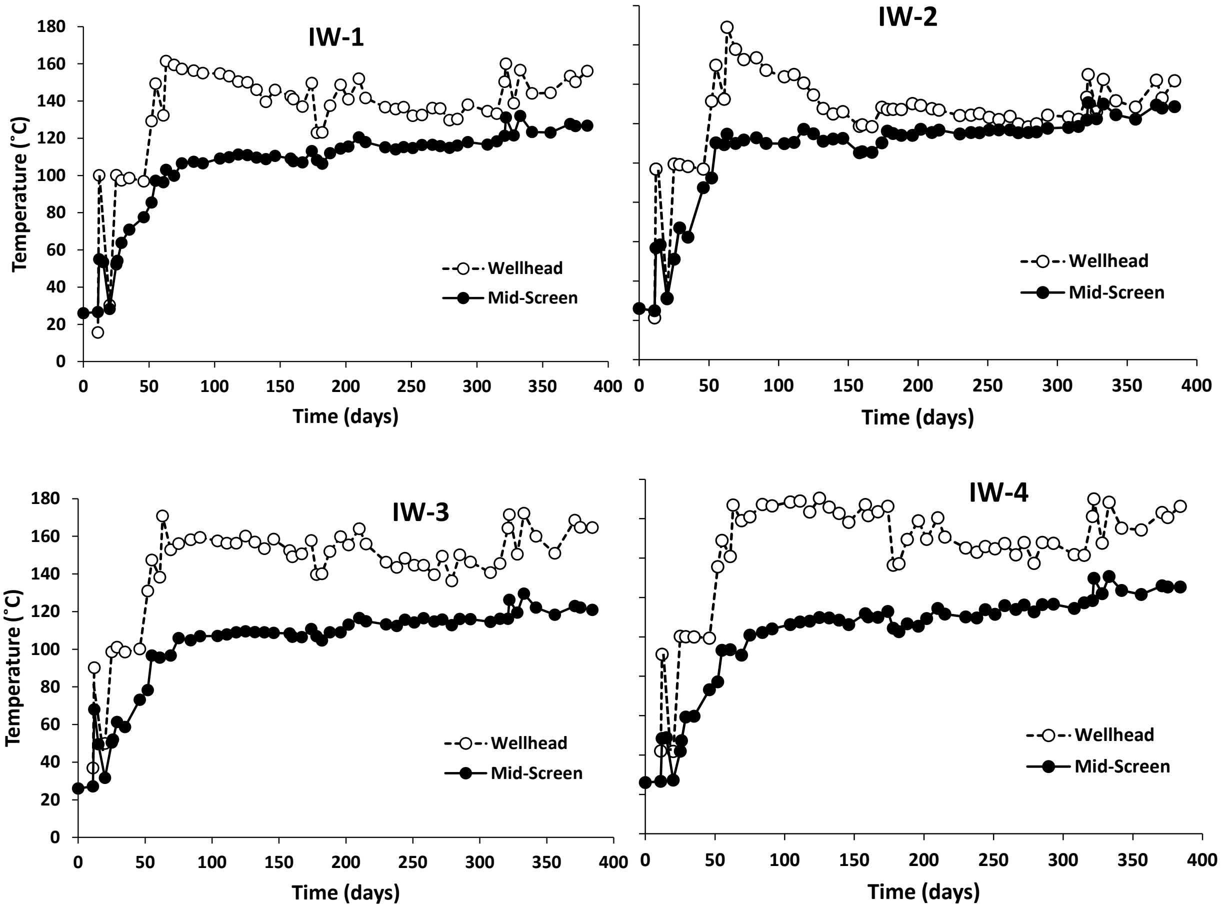

Figure 5.7.3. Injection Well Temperatures at the Wellhead and Mid-screen during XSVE Operation.

Treatment zone temperatures for the VMW locations during XSVE operation are given in Figure 5.7.4. The outer ring (VMWs 2 and 4) temperatures were higher due to their proximity to the injection wells. Temperatures reached as high as 90˚C in the treatment zone. The upper portion of the outer ring reached higher temperatures than the lower portion. The inner ring treatment zone temperatures reached as high as 40–45˚C, with the upper and lower zones being relatively similar. The temperature rose below the treatment zone at each location. The extraction well temperatures during XSVE operation (Figure 5.7.5) reached the 35–40˚C range.

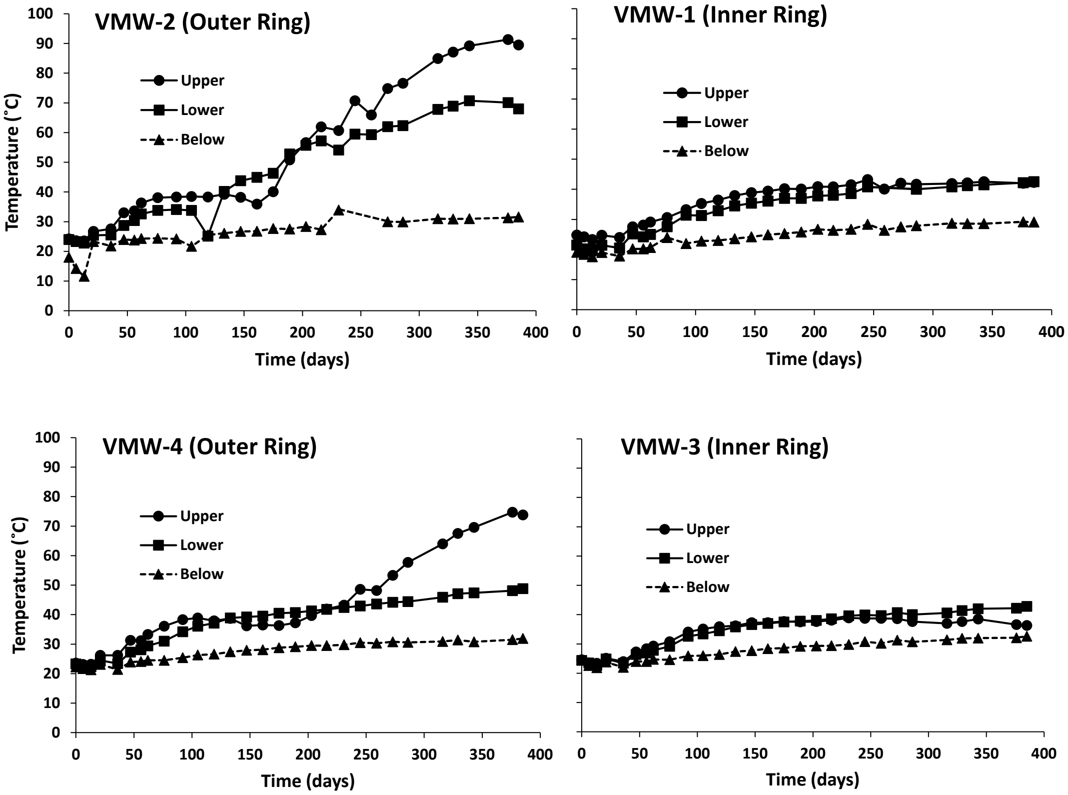

Figure 5.7.4. Treatment Zone Temperatures for During XSVE Operation.

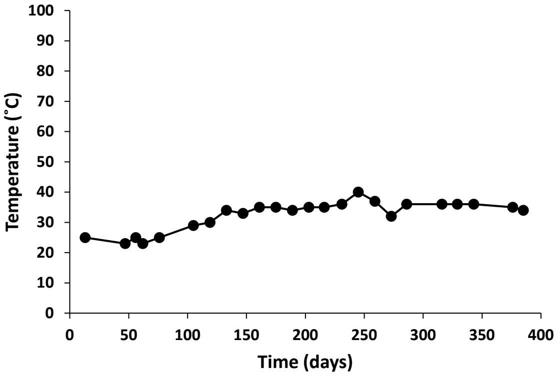

Figure 5.7.5. Extraction Well Temperatures during XSVE Operation.

Treatment zone soil moisture contents during the XSVE operation are given in Figure 5.7.6. All four outer ring soil moisture sensors reached or approached zero during XSVE operation, indicating that the soil moisture content in the outer ring was substantially reduced. Only one of the four inner ring locations showed a decrease in soil moisture content before the end of operation.

The soil moisture content below the treatment zone appeared to increase over operation of XSVE but did not exceed 16%, indicating that substantial condensation and downward migration did not occur.

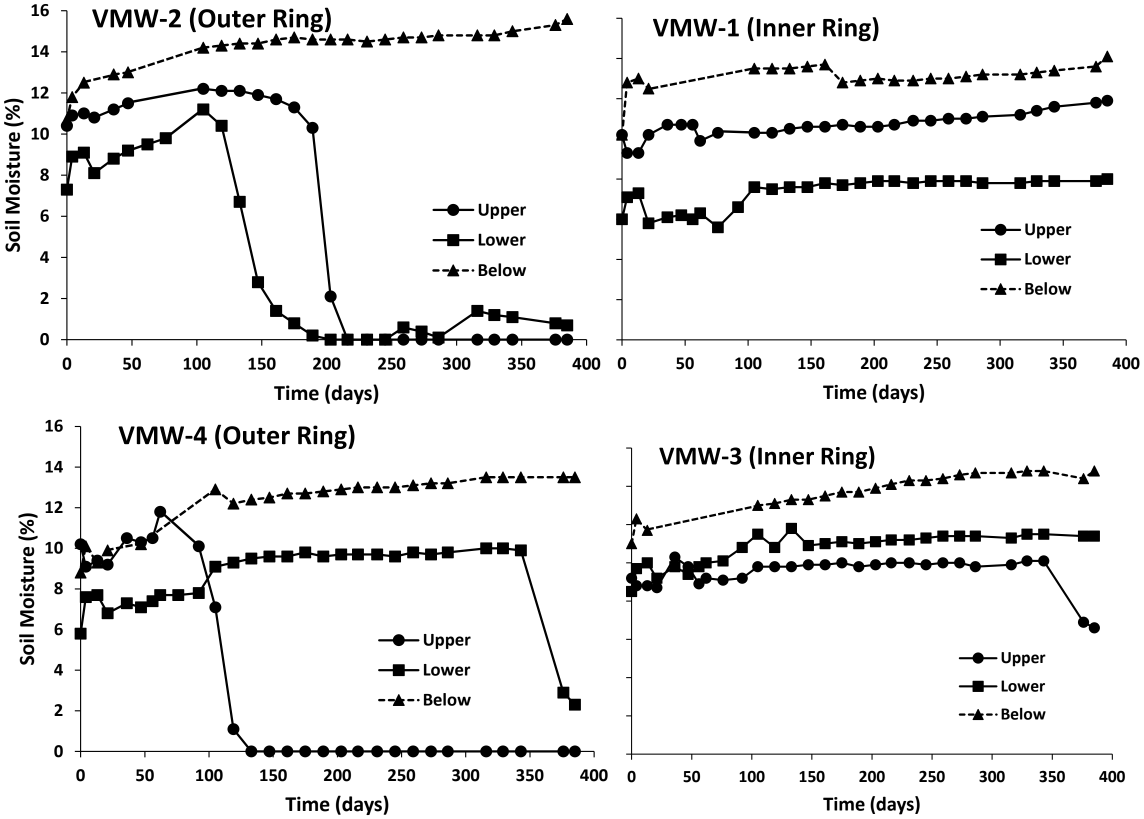

Figure 5.7.6. Treatment Zone Soil Moisture Contents (%) for during XSVE Operation.

Extracted soil vapor 1,4-dioxane concentrations are given Figure 5.7.7; levels as high as 21 mg/m^3 were observed. Treatment zone 1,4-dioxane soil vapor concentrations during XSVE operation are given in Figure 5.7.8. The bulk of 1,4-dioxane in the soil vapor was in the inner ring, especially in VMW-3 where concentrations as high as 47 mg/m^3 were observed. These results indicate a heterogeneous distribution of 1,4-dioxane in the treatment zone. Figure 5.7.9 shows the 1,4-dioxane mass removal rates and cumulative mass removed during XSVE operation. The bulk of 1,4-dioxane was removed during the first half of XSVE operation. Estimated power consumption is given in Figure 5.7.10.

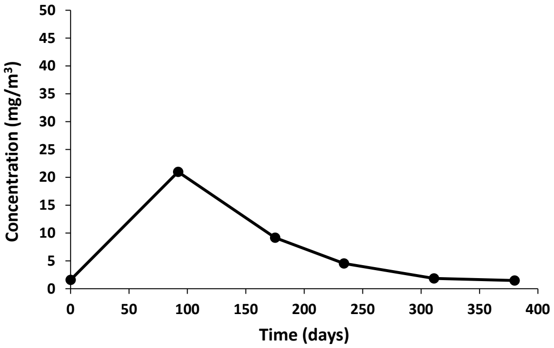

Figure 5.7.7 Extraction Well 1,4-dioxane Soil Vapor Concentrations during XSVE Operation.

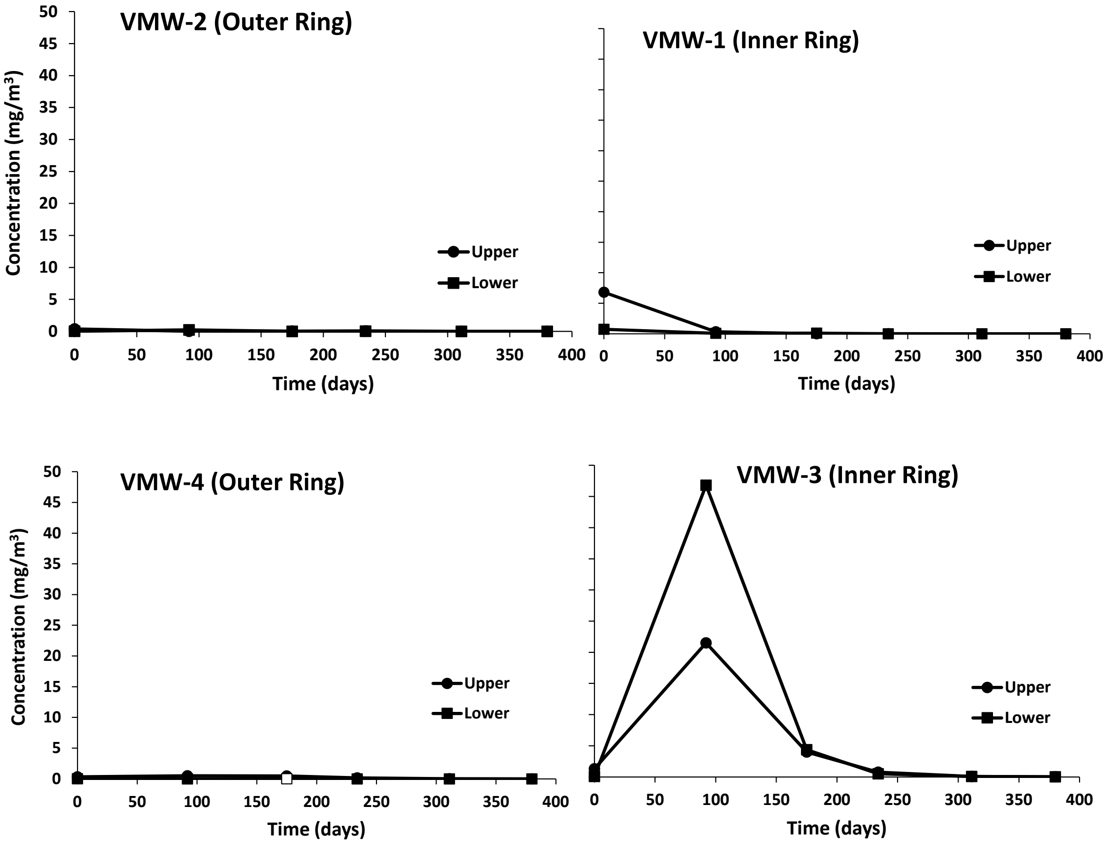

Figure 5.7.8 Treatment Zone 1,4-dioxane Concentrations (mg/m^3) in Soil Gas during XSVE (open symbols are non-detects).

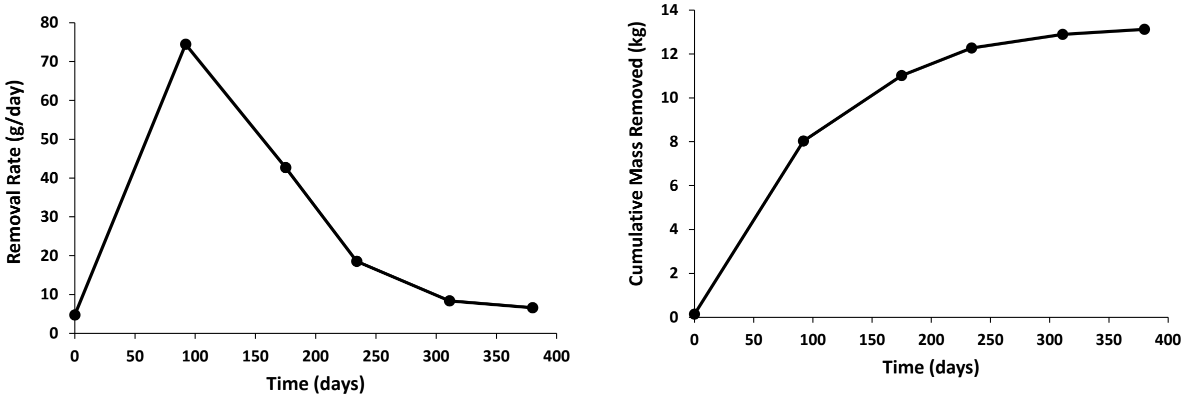

Figure 5.7.9. 1,4-Dioxane Mass Removal Rates and Cumulative Mass Removed During XSVE.

Cumulative mass removed (13 kg 1,4-dioxane) corresponds to approximately 94% removal.

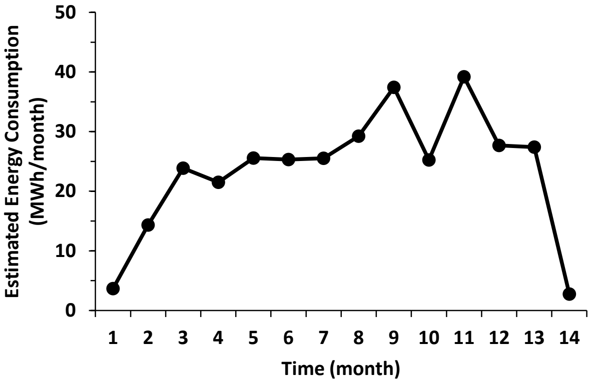

Figure 5.7.10. Estimated Power Consumption During XSVE Operation.

5.7.2 POST-DEMONSTRATION SOIL SAMPLING

Post-demonstration drilling and soil sampling was performed a week after XSVE shut-down. Figure 5.7.11 shows locations of the post-demonstration soil borings. The treatment zone soils reached temperatures as high as 90˚C, so the hollow stem auger split spoons were cooled down before the spoons were opened for soil sampling. 1,4-Dioxane soil concentrations for the pre- and post-demonstration soil borings, indicating screened interval (i.e., treatment zone), are given in Figure 5.7.12. A substantial reduction of up to 94% in 1,4-dioxane concentrations occurred throughout the treatment zone. Soil moisture content for the pre- and post-demonstration soil borings are shown in Figure 5.7.13. A reduction in soil moisture is apparent in the outer ring soil borings, while the center remained essentially unchanged. There was an approximate 45% reduction in soil moisture content in the treatment zone.

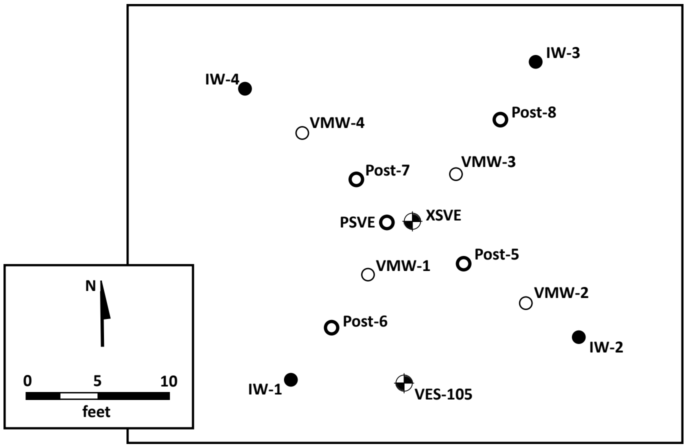

Figure 5.7.11. Locations of Post-demonstration Soil Borings.

Center: PSVE; Inner Ring; Post-5 and Post-7; Outer Ring; Post-6 and Post-8.

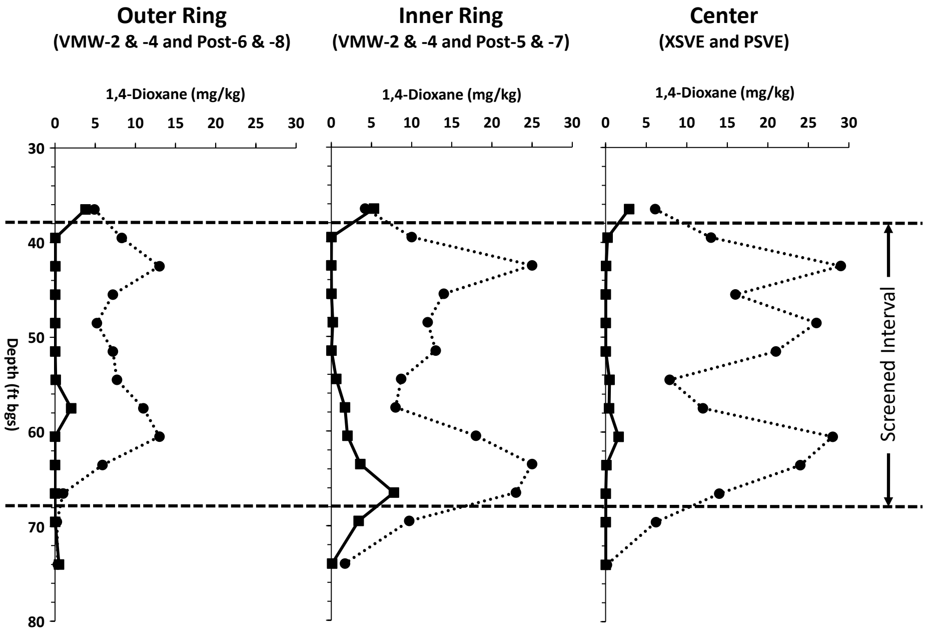

Figure 5.7.12. 1,4-Dioxane Soil Concentrations (mg/kg) Before (dotted) and After (solid) XSVE.

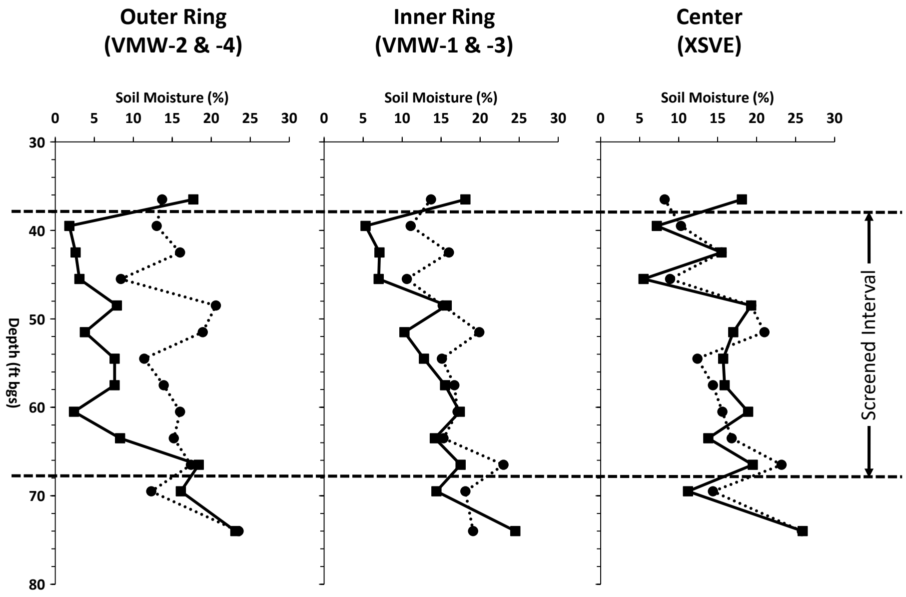

Figure 5.7.13. Soil Moisture Concentrations (%) Before (dotted) and After (solid) XSVE.

5.8 HYPEVENT XSVE FOR 1,4-DIOXANE

HypeVent XSVE for 1,4-dioxane (HypeVent XSVE) is a spreadsheet-based tool that runs in Microsoft Excel®. This screening-level feasibility assessment and design tool for XSVE facilitates quick exploration of best-case performance for 1,4-dioxane removal from soils using the XSVE technology demonstrated in this project. Equations embedded in HypeVent XSVE assume an idealized process involving the following:

- An isolated treatment zone with no exchange of 1,4-dioxane, water, air, or energy between soils inside and outside the treatment zone
- Uniform concentrations of 1,4-dioxane and water, and uniform temperature within the treatment zone
- 1,4-Dioxane dissolved in the soil moisture without sorption to soil surfaces, given its high-water solubility and low sorption potential
- Equilibrium partitioning between 1,4-dioxane dissolved in soil moisture and in soil vapor, and 100% relative humidity in the soil gas, as long as liquid water is present in the soil
- Temperature-dependent 1,4-dioxane Henry's Law Constant and vapor pressure of water; constant (independent of temperature) soil, water, and air heat capacities; and enthalpy of vaporization for water

Actual XSVE applications will involve heat loss to soils outside the treatment zone, flow of some unheated ambient air pulled into the treatment zone, non-uniform temperature and moisture fronts that move outward from the heated air injection points, and non-equilibrium partitioning. Thus, the HypeVent XSVE predictions should be considered upper-bound, best-case performance estimates when using them in decision-making.

Users enter the target treatment zone size, initial 1,4-dioxane and soil moisture concentrations, ambient site conditions, and operating conditions and can then assess the potential for XSVE to achieve their remediation goals (cleanup level, remediation time, etc.) under ideal conditions. The primary operating inputs are the vapor flow rate through the target treatment zone and temperature that ambient air will be heated to prior to injection. HypeVent XSVE predicts treatment zone temperatures, 1,4-dioxane and moisture removal rates, and concentration changes for the idealized conditions. It also projects the corresponding changes in 1,4-dioxane vadose water and soil vapor concentrations as remediation progresses.

Along with the observed demonstration results, Figures 5.8.1 to 5.8.3 show HypeVent XSVE results for the XSVE demonstration site conditions [V_{soil} = 340 m^3 (20 ft x 20 ft x 30 ft); $C_{soil,14D}$ = 20 mg/kg; Θ_m = 0.15 g-H_2O/g-soil; n = 0.4 L-pores/L-soil; ρ_{soil} = 1.7 kg-soil/L-soil; T_{start} = 20 ˚C; $T_{ambient}$ = 17˚C; $\%RH_{ambient}$ = 58%; $Q_{air,STP}$ = 2,264 standard L/min (80 ft^3/min); T_{in} = 120˚C]. Considering the idealized nature of HypeVent XSVE, the model results compare well with those observed from the field.

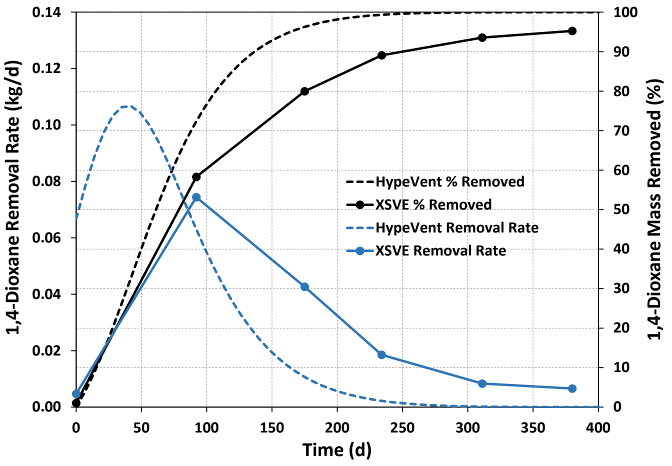

Figure 5.8.1. 1,4-Dioxane Removal Results for HypeVent XSVE and Actual Demonstration.

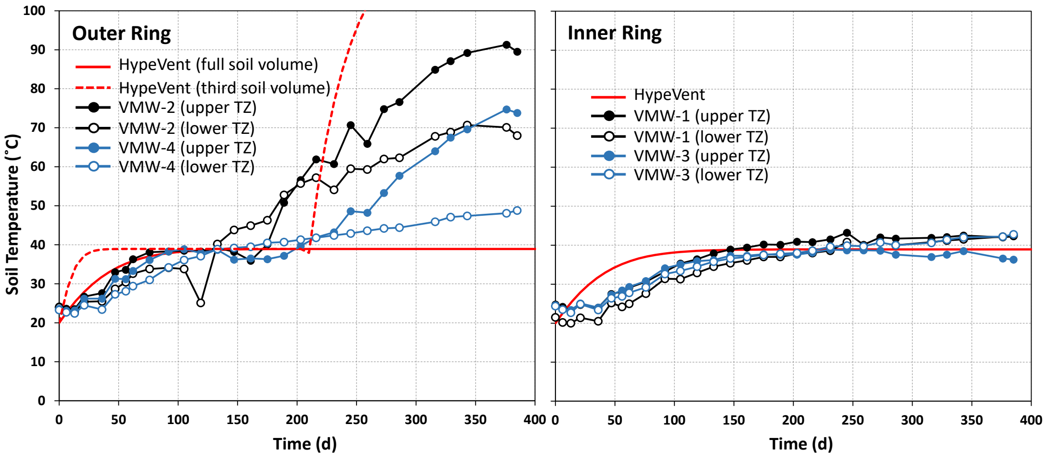

Figure 5.8.2. Soil Temperature Results for HypeVent XSVE and Actual Demonstration.

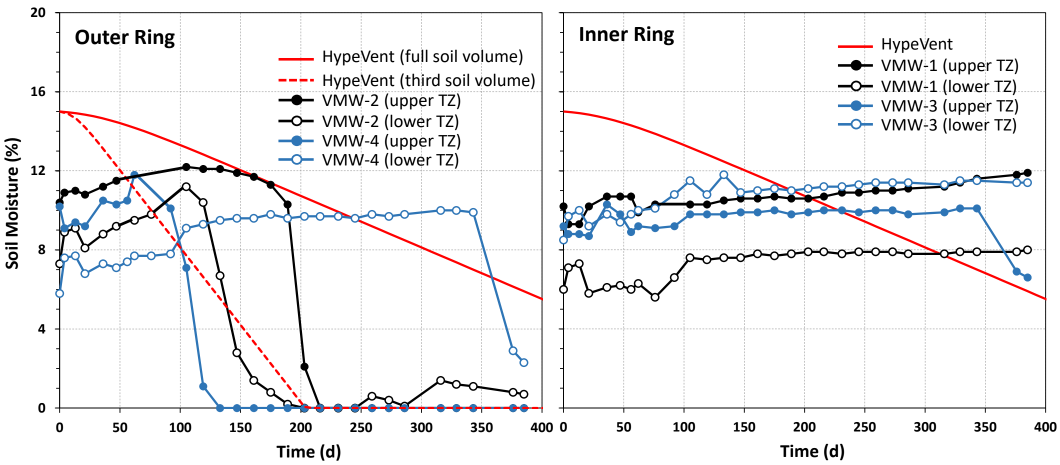

Figure 5.8.3. Soil Moisture Results for HypeVent XSVE and Actual Demonstration.

A series of HypeVent XSVE sensitivity analyses were conducted to examine the effect that different injection temperatures, soil moisture contents, and injection air relative humidities had on XSVE remediation performance. These sensitivity analyses were conducted using the demonstration site conditions except for the variables being examined.

The injection temperature sensitivity analyses used 17°C, 120°C, and 200°C injection temperatures. The first represents conventional SVE conditions with no heating, the second is the demonstration test condition, and the third is treatment with a more elevated injection temperature. Results are presented in Figure 5.8.4. Heated air injection accelerates remediation. For example, the demonstration test condition (120°C) achieves 80% 1,4-dioxane removal in about one-fourth the time as SVE with focused extraction (112 days (d) for XSVE vs. 400 d for SVE) under ideal conditions. Increasing the injection temperature to 200°C decreases that time by about another 50% relative to 120°C air injection.

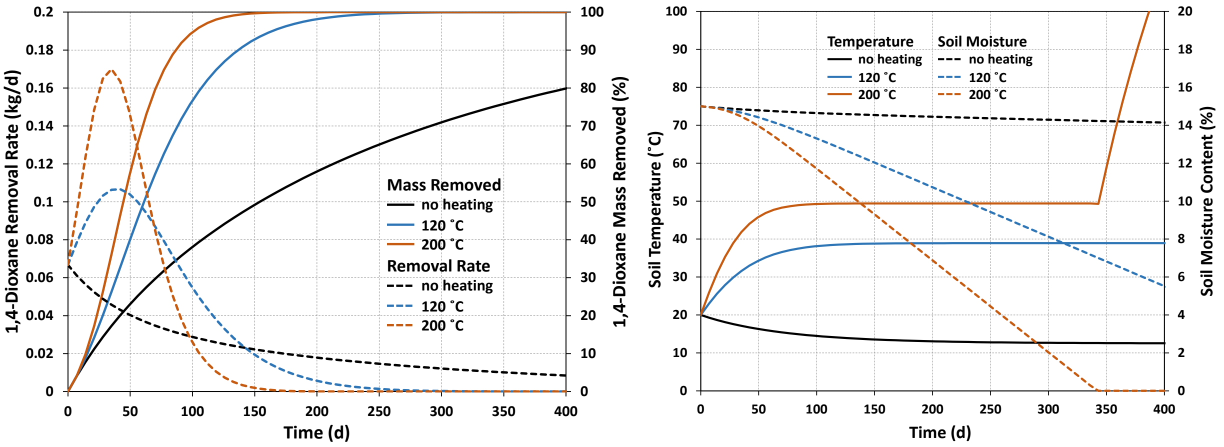

Figure 5.8.4. HypeVent XSVE 1,4-dioxane, soil temperature and soil moisture removal output for the demonstration site conditions for three different heating scenarios (17, 120, and 200°C).

Soil moisture sensitivity analyses, the results of which are shown in Figure 5.8.5, used demonstration conditions for soil moisture contents of 1, 5, 10, and 15%. 1,4-Dioxane removal was significantly improved with lower soil moistures, primarily due to higher 1,4-dioxane aqueous concentrations in the presence of lower soil moisture and because low soil moisture levels also significantly increase the rate at which the soils dry out.

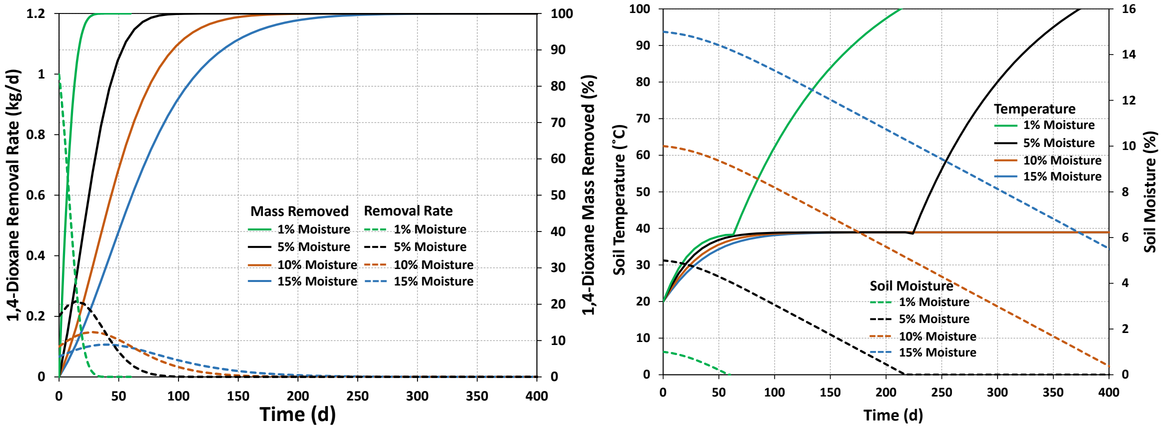

Figure 5.8.5. HypeVent XSVE 1,4-dioxane Removal, Soil Temperature, and Soil Moisture Output for the Demonstration Site Conditions for Four Different Soil Moisture Scenarios (1, 5, 10, and 15%).

HypeVent XSVE sensitivy analyses for demonstration conditions using different injection temperatures (20, 40, 60, and 80°C) each with 100% relative humidity (RH) are shown in Figure 5.8.6. The results show significant improvements in 1,4-dioxane removal— the highest rates of all of the sensitivity analyses—as temperature increases. Soil temperatures reach the injection temperatures relatively quickly since there is no evaporative cooling because the injection air is already at 100% RH. As long as soil temperature is below the injection air temperature there is some condensation and soil moisture increases, which may be problematic if it causes downward migration of 1,4-dioxane in the condensate. Thus, caution should be used when applying increased temperatures.

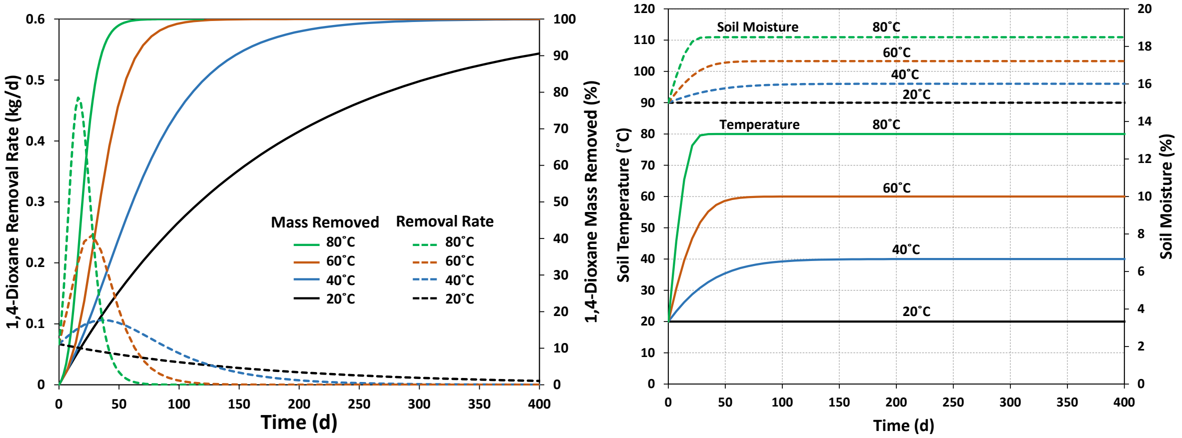

Figure 5.8.6. HypeVent XSVE 1,4-dioxane Removal, Soil Temperature, and Soil Moisture Output for the Demonstration Site Conditions for Four Different Injection Temperatures (20, 40, 60, and 80°C) at 100% RH.

6.0 PERFORMANCE ASSESSMENT

REDUCTION IN SOIL 1,4-DIOXANE: The primary performance metric for this project was sufficient 1,4-dioxane removal from the vadose zone so that it no longer served as a source of groundwater contamination. The performance goal for this metric was to remove at least 90% of the 1,4-dioxane present in the treatment zone. The pre- and post-demonstration soil results showed a reduction of up to 94% in 1,4-dioxane, so this performance metric was reached. The approximate 6% remaining in the soil should result in a substantially reduced flux of 1,4-dioxane to groundwater.

A relevant question is whether heating was required to remove 1,4-dioxane or whether it would have been removed using focused SVE alone. The HypeVent XSVE model results shown in Figure 5.8.10 examine this question and show that heated air injection significantly decreases remediation time compared to focused SVE alone (ambient temperature injection).

MINIMIZATION OF 1,4-DIOXANE DOWNWARD MIGRATION: Injection of heated air helps to volatilize water so that it can be removed, but before it reaches the extraction well, water vapor can be re-condensed and 1,4-dioxane could also be present in the re-condensed water. If sufficient volume of water was re-condensed, it could saturate the vadose zone and migrate downward below the treatment zone and continue to serve as a source of groundwater contamination. The performance goal for this metric was for 1,4-dioxane concentrations beneath the treatment zone to not increase more than 20% over initial conditions. The pre- and post-demonstration soil results showed a decrease in 1,4-dioxane concentrations beneath the treatment zone, so this performance metric was reached. The soil moisture results suggest that some condensation did occur in the inner ring, however it does not appear to have caused any increase in 1,4-dioxane beneath the treatment zone.

ADEQUATE SOIL GAS 1,4-DIOXANE MEASUREMENTS AT ELEVATED TEMPERATURES: The vapor/condensate sampling apparatus and the resulting analyses of the vapor and condensate phases provided dependable soil gas 1,4-dioxane measurements at elevated temperatures. The use of the vapor/condensate sampling apparatus provided a more reliable measure of 1,4-dioxane in soil gas at elevated temperatures than direct vapor canister sampling. At times, direct vapor canister sampling at the extraction wellhead resulted in low values for unknown reasons. Direct vapor canister sampling after AWS provided values that were reasonably consistent with those obtained with the vapor/condensate apparatus.

EASE XSVE SYSTEM INSTALLATION AND STARTUP: The XSVE system was only moderately more complex to install than a traditional SVE system. While most SVE systems do not use injection wells, the wells are not complicated to install. The in-line heaters and materials used to construct the system were the main concerns during the design stage. The only difficulty encountered was the melting of PVC piping adjacent to the in-line heater. After replacement steel piping was installed just before the in-line heaters, there were no further difficulties.

EASE XSVE SYSTEM OPERATION AND MONITORING: Operation of the XSVE system was robust with approximately 99% uptime after the first two weeks of operation. System monitoring was generally no more complex than done for most SVE operations where flows and pressures are routinely monitored. Temperature measurements are straightforward.

HYPEVENT XSVE AS A USEFUL TOOL IN SYSTEM DESIGN: HypeVent XSVE, a screening-level tool created to assist in system design and data reduction, anticipates how XSVE operating conditions affect XSVE performance (e.g., cleanup level, remediation time, etc.). Its energy and mass balance (water and 1,4-dioxane) model assumes well-mixed conditions. Although it simplifies assumptions, HypeVent XSVE was able to adequately anticipate the field demonstration results. It was used to predict XSVE system performance under differing conditions of air injection temperature, injection relative humidity, and soil moisture. The HypeVent XSVE results for elevated temperature injections at 100% relative humidity were confirmed with laboratory column experiments. HypeVent XSVE proved to be a useful tool for XSVE system design and implementation.

7.0 COST ASSESSMENT

7.1 COST MODEL

Table 7.1 summarizes the various cost elements and total cost for a routine application of XSVE using the demonstration site as an example. The estimated cost to have implemented this technology on a more routine basis at this same scale on this same site is $450,000. Though the actual cost of routine implementation will vary considerably from site to site, the unit cost in terms of cubic meters treated will go down on most sites, as this demonstration was relatively small in scale.

Table 7.1. Cost Model for XSVE.

Element	Routine Application, estimated
Capital Costs	
System Design	$84,000
Well Installation	$94,000
System Installation	$101,000
Subtotal	*$279,000*
Operation and Maintenance Costs	
Power	$18,000
Labor and Travel	$87,000
Materials	$12,000
Analytical Cost	$16,000
Subtotal	*$133,000*
Other Costs	
Well destruction and liner repair	$18,000
Final Report	$20,000
Subtotal	*$38,000*
Total	**$450,000**

7.1.1 Capital Costs

Capital costs (primarily system design and installation) accounted for $279,000, or about 62% of the total cost. For future applications, the HypeVent XSVE model can aid in making design calculations, and highly instrumented VMW monitoring wells may not be unnecessary. Additionally, though not reflected here, well spacing could likely be wider, lowering unit costs by allowing treatment of a greater volume of soil.

7.1.2 Operations and Maintenance Costs

Operations and maintenance (O&M) accounted for $133,000, or about 30% of the total cost. Compared to the demonstration, power costs should be lower as excess heated air was injected during the demonstration to insure all capture air had been heated. The largest O&M savings future applications would realize would be lower labor and travel costs, since local labor can be used. Substantially less monitoring and system optimization should be required.

7.1.3 Demonstration-Specific Costs

In addition to the specialized demonstration costs described above, other costs associated with an ESTCP project would not be expected to be incurred in a routine application. Soil sampling would be at a much lower density, and there would be no need for the laboratory testing, HypeVent XSVE model development, technology transfer, or other ESTCP-related costs.

7.2 COST DRIVERS

7.2.1 General Considerations

Many factors will impact the potential cost of XSVE implementation and its cost relative to competing technologies. These cost drivers are detailed in Table 7.2. Note that comparisons to conventional SVE are made as it is a well-developed and understood technology closely related to XSVE. Existing or planned conventional SVE would likely exist at most sites where XSVE could be applicable.

Table 7.2. Cost Drivers to Consider for XSVE.

Cost Drivers	Considerations
Volume of Soil to be Treated	• Depth, surface area, concentrations; generally, larger volumes have lower unit cost, and deeper treatments are more cost competitive than shallow ones
Preexisting SVE Infrastructure	• Because SVE infrastructure to treat VOCs would be common at most XSVE candidate sites, usable infrastructure in good condition will lower XSVE costs
Site Geology	• Because large volumes of air must be moved for effective XSVE, the technology will be more cost effective at higher permeability sites • Application in dryer vadose zone conditions will also lower cost
Presence of Other Contaminants	• Most common VOCs will also be extracted, potentially increasing treatment costs
Site Characterization	• Site characterization may be costlier than for conventional SVE; due to the high number of pore volumes of soil requiring extraction by XSVE, more precise identification of source zone soils is required
Installation	• Similar to SVE, except well materials and construction must account for the increased temperature if heated air injection is used
Operation and Maintenance Costs	• Similar to SVE, except for heated air injection, which will require energy costs and may increase the need for site security and oversight • XSVE air treatment of 1,4-dioxane (if required) can be accomplished with conventional SVE equipment such as activated carbon or thermal treatment • Analysis costs similar to SVE

7.2.2 Competing Treatment Technologies

At present, there are few competing technologies for 1,4-dioxane treatment in vadose zone soils. The authors are aware of no full-scale treatments to date. It may be possible to treat 1,4-dioxane contaminated vadose zone soil *in situ* using bioremediation, chemical oxidation, or soil flushing. To our knowledge, these technologies have not yet been attempted and there are technical challenges to overcome before they could be applied. As excavation is the only developed, proven competitor to XSVE, two excavation approaches will be compared to XSVE.

7.3 COST ANALYSIS

XSVE is compared with traditional and large diameter auger excavations. A hypothetical site (Section 7.3.1 Base Case) with characteristics similar to the XSVE demonstration site is used. Cost estimates for the XSVE technology are based on this demonstration. Cost estimates for the excavation technologies are based on USEPA (2000) guidance for traditional excavation and DOE (2009) for the large diameter auger excavation. Table 7.3 presents the cost comparisons.

For the hypothetical site situation and assumptions described below, XSVE appears to be the most cost-effective approach. As we expect actual costs will vary considerably from site to site, it cannot be assumed that XSVE will always be the most cost-effective. However, XSVE will likely be a competitive technology in terms of cost, efficiency, and remediation timeframe at many sites.

Table 7.3. Cost Comparison Between XSVE and Competing Technologies.

Technology	Cost	Treatment Efficiency	Timeframe
XSVE	$450,000	95%	18 months
Traditional Excavation	$3,400,000	100%	12 months
Excavation using Large Diameter Auger	$760,000	75%	12 months

A comparison to conventional SVE is not presented as we do not believe conventionally operated SVE without heating to be a practical process for 1,4-dioxane removal. The HypeVent simulation presented in Figure 5.8.4 shows that removal without heating would result in substantially lower rates of 1,4-dioxane removal. After removal of about 10,000 pore volumes of air—far more than are typically removed by conventional SVE—only 80% removal is predicted (in practice this would likely be less). Air injection without heating or humidification lowers soil temperatures due to evaporative cooling, resulting in a lower Henry's constant and slower 1,4-dioxane removal. The McClellan site where the demonstration was performed clearly evidences the inefficiency of conventional SVE for 1,4-dioxane removal. The site had been subject to conventional SVE for about 20 years before the demonstration, and yet significant 1,4-dioxane remained in the soil. XSVE removed about 95% of this 1,4-dioxane in a single year.

7.3.1 Base Case

The hypothetical base case for this analysis is based on the field demonstration and has the following characteristics:

- 20 x 20 ft area requiring treatment

- 38–68 ft bgs, overlain by capped sanitary landfill
- Silty/clayey sand with 10% soil moisture
- Operating SVE system exists; costs are incremental cost of XSVE application
- For XSVE, five new wells will be installed and connected: four injection wells plus one extraction well.

It is important to note that XSVE for 1,4-dioxane will typically involve smaller soil volumes than for VOC remediation due to greater spreading of VOCs. 1,4-Dioxane-contaminated vadose zone soil volume is typically limited to areas of initial direct non-aqueous phase liquid (NAPL) contact, where 1,4-dioxane partitions into vadose pore water. The estimated XSVE cost for the base case is $450,000 (Table 7.3) for an estimated duration of 18 months and treatment efficiency of approximately 95% based on the demonstration project experience.

7.3.2 Excavation Using Traditional Methods

Excavation using traditional methods means excavation with earth moving equipment and shoring as necessary to remove all of the target soils. Table 7.4 breaks down the cost details for traditional excavation. The assumptions used for this cost estimate are:

- 20 x 20 ft area requiring treatment
- 38–68 ft bgs, overlain by caped sanitary landfill
- Silty/clayey sand with 10% soil moisture (unsaturated)
- 250 ft ramp required to excavate to the 68 ft depth
- Landfill cap and liner are at approximately three-foot depth; municipal and mixed waste to a depth of 38 ft
- Clean soil cap can be removed and put aside to access the landfill liner
- Sheet pile will be necessary to avoid ramping all four sides of the excavation pit
- Excavated soil and waste disposed at nonhazardous landfill; replaced with clean fill

Table 7.4. Cost Detail for Traditional Excavation.

Cost Element	Quantity	Unit	Unit Price	Cost
Pre-Engineering Geotechnical Investigation	1	Lump Sum	$50,000	**$50,000**
Excavation and Stockpile Top Cover of Liner	2,450	yd^3	$11.00	**$26,950**
Install Sheet Wall on 3 Sides of Area	66,375	ft^2	$8.80	**$519,200**
Build Ramp Down to 68 ft depth	18,229	yd^3	$16.50	**$300,781**
Excavate Waste and Contaminated Soil	18,729	yd^3	$16.50	**$309,031**
Nonhazardous Waste Transport & Disposal	18,729	yd^3	$55.00	**$1,030,104**
Clean Fill Placed in Excavation	18,729	yd^3	$22.00	**$412,042**
Replace Liner and Cover; Site Restoration	22,050	ft^2	$1.10	**$24,255**
Subtotal				**$2,672,363**
Engineering Design		% of subtotal	8%	**$213,789**
Project Management		% of subtotal	5%	**$133,618**
Construction Management		% of subtotal	6%	**$160,342**
Mobilize Equipment & Personnel to Site		% of subtotal	5%	**$133,618**
Demobilize Equipment & Personnel		% of subtotal	5%	**$133,618**
Total				$3,447,348

Traditional excavation is estimated to cost $3,400,000 and requires about 12 months. Significant cost drivers for conventional excavation is the need to shore excavation on 3 sides with sheet pile, construction of ramp on the remaining side for access, landfill and clean fill costs. This approach results in excavation of more soils and waste than need treatment. Traditional excavation however will remove all of the contaminated soil within the target volume, resulting in 100% treatment.

7.3.3 Excavation Using Large Diameter Augers

An alternative approach to excavation which would result in lower cost is the use of large diameter augers. Casing would be driven in advance of the auger followed by auguring inside of the casing with waste or soil removal, then the boring is filled with flowable (cement) fill. Cement is allowed to set before drilling of each adjacent hole. Cementitious fill is necessary for geotechnical stability; however, it prohibits overlap between holes. The result is that only about 75% of the contaminated soil in the target zone would be removed. Table 7.5 breaks down the cost details for excavation by large diameter auger. The assumptions make to cost this approach include:

- 20 ft x 20 ft area requiring treatment
- 38 ft to 68 ft below land surface, overlain by caped sanitary landfill
- Silty/Clayey sand with 10% soil moisture (unsaturated)
- 3 ft diameter auger capable of penetration and excavation to full 68 ft depth
- Flowable concrete fill will be used to allow for hole stabilization; approximately 75% of soil removal
- The landfill cap and liner at about 3 ft depth; municipal and mixed waste to a depth of 38 ft
- Clean soil cap can be removed and put aside to access the landfill liner
- No sheet pile will be necessary
- All excavated soil and waste disposed at nonhazardous landfill; replaced with clean fill

Table 7.5. Cost Detail for Excavation by Large Diameter Auger.

Cost Element	Quantity	Unit	Unit Price	Cost
Excavation and Stockpile Top Cover of Liner	113	yd^3	$11.00	**$1,238**
Large Diameter Auger Excavation	1,083	yd^3	$220.00	**$238,333**
Backfill each Casing with Flowable Fill (concrete)	1,083	yd^3	$110.00	**$119,167**
Onsite Loader to Move and Stockpile Material	1,463	yd^3	$11.00	**$16,088**
Nonhazardous Waste Disposal (includes transportation)	1463	yd^3	$55.00	**$80,438**
Replace Liner and Cover; Site Restoration		Lump Sum		**$10,000**
Subtotal				**$465,264**
Engineering Design		% of total	15%	**$85,658**
Project Management		% of total	8%	**$45,684**
Construction Management		% of total	10%	**$50,526**
Mobilize Equipment & Personnel to Site		% of total	15%	**$75,789**
Site Preparation		% of total	10%	**$40,000**
Demobilize Equipment & Personnel		% of total	5%	**$25,263**
Total				**$758,380**

Large diameter auger excavation is estimated to cost about $760,000 and requires about 12 months of project time. While this cost is closer to the cost of XSVE than is conventional excavation, the treatment efficiency of 75% would be lower than for XSVE and may not achieve remediation goals.

8.0 IMPLEMENTATION ISSUES

Implementation issues for XSVE are similar to those for the well-developed and well-understood SVE technology (e.g., Army CoE, 2002; Truex et al., 2013; AFCEE, 2001; USEPA, 1995). Sites must have sufficient permeability for the high vapor flow rates required for XSVE. Well construction materials and piping need to be able to withstand injection well temperatures reached with heated air injection. Heated injection will require additional energy and may require additional safety measures to prevent contact with heating elements and hot piping. If high relative humidity injection air is used, caution must be exercised to ensure that downward migration of 1,4-dioxane does not occur due to condensation. The authors are not aware of any unique procurement issues associated with XSVE implementation. The equipment necessary is available off-the-shelf, and to our knowledge there are no patents that would prevent or limit XSVE implementation.

8.1 APPLICABLE REGULATIONS

There is nothing unique to the regulation of XSVE as opposed to SVE. While the demonstration took place using existing, already permitted SVE infrastructure, no special permits or approvals were required for heated air injection or otherwise for this demonstration. The authors note, however, that some regulatory jurisdictions require permitting for air injection.

8.2 END USERS

The demonstration was designed to help end users more effectively understand the costs of XSVE, its implementability, and its potential effectiveness. XSVE requires a realistic 1,4-dioxane source zone characterization for proper placement of injection and extraction wells—ensuring cost-effective implementation by decreasing system size and increasing removal efficiency. The demonstration showed that removal of up to 94% of 1,4-dioxane from the vadose zone is feasible, and HypeVent XSVE can assist users in evaluating XSVE performance under different site and operation conditions. This report and the HypeVent XSVE model allow end users to readily implement the XSVE technology.

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