Final

FEASIBILITY STUDY FOR SS-28

PERFORMANCE-BASED RESTORATION
JOINT BASE ANDREWS NAVAL AIR FACILITY WASHINGTON
CAMP SPRINGS, MARYLAND

Contract W9128F-13-D-0002, DO #0003
August 2017
VERSION: 00

Prepared for:

U.S. Air Force
Civil Engineer Center (AFCEC)
3466 North Carolina Avenue
Joint Base Andrews, MD 20762-4803

U.S. Army Corps of Engineers
Omaha District
1616 Capitol Avenue
Omaha, NE 68102-4901

Prepared by:

Weston Solutions, Inc.
1400 Weston Way
West Chester, Pennsylvania 19380
(610) 701-3500

and

Bay West LLC
5 Empire Drive
St. Paul, Minnesota 55103
(651) 291-0456

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Prepared for:

U.S. Air Force
AFCEC-CZOE
1602 California Avenue, Suite 239
Joint Base Andrews, Maryland 20762-6441

U.S. Army Corps of Engineers,
Omaha District
1616 Capitol Avenue
Omaha, Nebraska 68102-4901

Prepared by:

Weston Solutions, Inc.
1400 Weston Way
West Chester, Pennsylvania 19380
(610) 701-3500

Bay West LLC
5 Empire Drive
St. Paul, Minnesota 55103
(651) 291-0456

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LIST OF ACRONYMS

%	percent
°F	degrees Fahrenheit
µg/L	microgram per liter
µg/m^3	micrograms per cubic meter
1,2-DCA	1,2-dichloroethane
A	applicable
ADAF	age-dependent adjustment factor
Adventus	Adventus Group
AFCEC	Air Force Civil Engineer Center (former Air Force Center for Engineering and the Environment)
AFCEE	Air Force Center for Engineering and the Environment (former Air Force Center for Environmental Excellence)
AMEC	AMEC Environment & Infrastructure, Inc.
amsl	above mean sea level
ANG	Air National Guard
ARAR	applicable or relevant and appropriate requirement
AST	aboveground storage tank
Bay West	Bay West LLC
BGP	Base General Plan
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylene
CAA	Clean Air Act
cells/mL	cells per milliliter
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cis-1,2-DCE	cis-1,2-dichloroethene
COC	contaminant of concern
COMAR	Code of Maryland Regulations
COPC	contaminant of potential concern
CTC	carbon tetrachloride
CTE	central tendency exposure
DCA	dichloroethane
DHC	Dehalococcoides spp.
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen

LIST OF ACRONYMS (CONTINUED)

DoD	Department of Defense
DP	direct push
DPT	direct push technology
DRO	diesel range organic
ECD	electron capture detection
Eh	reduction potential
EHC®	reduction potential compound
EIAP	Environmental Impact Analysis Process
EOS™	edible oil substrate
ERP	Environmental Restoration Program
ESTCP	Environmental Security Technology Certification Program
EVO	emulsified vegetable oil
FAA	Federal Aviation Administration
FFA	Federal Facility Agreement
FS	Feasibility Study
ft/day	feet per day
ft/yr	feet per year
FY	fiscal year
GAC	granular activated carbon
GDP	General Discharge Permit
GRO	gasoline range organic
HDPE	high-density polyethylene
HGL	HydroGeoLogic, Inc.
HHRA	human health risk assessment
HI	hazard index
HRC®	Hydrogen Release Compound
IC	institutional control
ISB	in situ biodegradation
ISCO	in situ chemical oxidation
ISCR	in situ chemical reduction
IT	IT Corporation
ITRC	Interstate Technology and Regulatory Council
JBA	Joint Base Andrews Naval Air Facility Washington
LATA	Los Alamos Technical Associates, Inc.

LIST OF ACRONYMS (CONTINUED)

LUC	Land Use Control
MCL	maximum contaminant level
MDE	Maryland Department of the Environment
mg/kg	milligram per kilogram
mg/L	milligram per liter
MIP	membrane interface probe
MNA	monitored natural attenuation
MTBE	methyl tert-butyl ether
mV	millivolt
MW	monitoring well
NA	not available
NAPL	non-aqueous phase liquid
NCP	National Contingency Plan or National Oil and Hazardous Substances Pollution Contingency Plan
NEPA	National Environmental Policy Act
NPDES	National Pollutant Discharge Elimination System
NPW	net present worth
NS	not sampled
O&M	operation and maintenance
OMB	United States Office of Management and Budget
ORP	oxidation-reduction potential
OSWER	Office of Solid Waste and Emergency Response
OWS	oil/water separator
PA/SI	Preliminary Assessment/Site Investigation
PAG	Presidential Air Group
PBTZ	permeable biostimulation treatment zone
PCB	polychlorinated biphenyl
PCE	tetrachloroethene
PID	photoionization detector
POTW	publicly owned treatment works
PP	Proposed Plan
ppbv	parts per billion volume
PVC	polyvinyl chloride
RA	Relevant and Appropriate

LIST OF ACRONYMS (CONTINUED)

RACR	remedial action completion report
RAO	remedial action objective
RBC	risk-based concentration
RBSL	risk-based screening level
RC	Response Complete
RCRA	Resource Conservation and Recovery Act
RI	remedial investigation
RME	reasonable maximum exposure
RNA	Relevant but Not Appropriate
ROD	Record of Decision
ROI	radius of influence
SARA	Superfund Amendments and Reauthorization Act of 1986
SRG	site remediation goal
SRS®-SD	slow-release substrate - small droplet size
SSL	soil screening level
SVE	soil vapor extraction
SVOC	semivolatile organic compound
SWMU	Solid Waste Management Unit
SWPPP	stormwater pollution prevention plan
TACW	Temporary Airfield Construction Waiver
TBC	to be considered
TCE	trichloroethene
TMV	toxicity, mobility, or volume
TOC	total organic carbon
TPH	total petroleum hydrocarbon – diesel range organic
TSCA	Toxic Substances Control Act
UFC	Unified Facilities Criteria
URS	URS Group, Inc.
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
UST	underground storage tank
UV	ultraviolet

LIST OF ACRONYMS (CONTINUED)

VI	vapor intrusion
VOC	volatile organic compound
WESTON®	Weston Solutions, Inc.
ZVI	zero-valent iron

EXECUTIVE SUMMARY

This feasibility study (FS) for the Environmental Restoration Program (ERP) Site SS-28 at Joint Base Andrews Naval Air Facility Washington (JBA) identifies and evaluates potential remedial options for contaminated groundwater at the site. The remedial investigation (RI) data were collected by URS Corporation, Inc. (URS) from June 2009 through July 2012 and presented in a report dated June 2013.

Site SS-28 is located in the western portion of JBA and extends approximately 3,700 feet to the southeast and 3,000 feet to the east-southeast from the location of Building 1217 across the concrete aircraft taxiways and parking aprons utilized by the Presidential Air Group (PAG) out to the grassy airfield. The structures encompassed within the site area include Buildings 1201, 1202, 1206, 1207, 1217, 1285, 1287, 1288, 1290, 1291, and 1292, a basketball court, two sanitary sewage pump stations, and an open-air fire station storage pavilion. Site access requires significant advanced coordination and logistics because of the highly active and secure nature of the airfield. The ground surface at Site SS-28 generally slopes towards the southeast and is currently covered by concrete, asphalt, or grass. Activities at or near the SS-28 site are known to have generated petroleum and solvent waste, due to the number of underground storage tanks (USTs), hydraulic lifts, a waste oil aboveground storage tank (AST), and two solid waste management units (SWMUs) that did not have a secondary containment setup situated around Building 1206. All site runoff from the concrete areas discharges into the stormwater sewer system. There are no surface water bodies within the site boundaries.

Based on the human health risk assessment (HHRA) conducted as a part of the RI and a weight-of- evidence evaluation of the Contaminants of Potential Concern (COPCs) versus drinking water standards, frequency of detection, cancer risk, and non-cancer hazard, the contaminants of concern (COCs) for SS-28 are benzene, carbon tetrachloride (CTC), chloroform, 1,2-dichloroethane (1,2-DCA), trichloroethene (TCE), and tetrachloroethene (PCE). There are documented historical fuel oil releases at the site, but there are no documented solvent releases. Groundwater concentrations were not indicative of dense non-aqueous phase liquids (DNAPLs) in the subsurface soil below the site.

Available historical information does not document specific evidence of chemical releases to the ground surface within the site. The RI data collected at SS-28 suggest that there are four potential release areas that have contributed to the overall contamination at the site: one to the east of Building 1217, two located around Building 1206, and one located between Taxiways W2 and W3 in a grassy area (**Figure ES-1**). The bulk of the volatile organic compound (VOC) mass dissolved in the groundwater is located southeast of these buildings parallel with the groundwater flow vector as shown in the groundwater contour maps. The RI concluded that there was little-to-no evidence of soil contamination within 5 feet of the ground surface, and any VOC detections in the soil were observed at depths that were consistent with the top of the groundwater table. No soil or indoor air COCs were identified in the RI during the HHRA.

Although CTC degradation has occurred, as evidenced by the presence of degradation daughter product, chloroform, the current subsurface system is not optimal for sustainable VOC degradation by microbial reductive dehalogenation because of the low observed populations of dehalococcoides (DHCs) microorganisms (less than 50 cells per milliliter [cells/mL]) and less than favorable water quality conditions (pH and oxidation-reduction potential [ORP]) for anaerobic biodegradation. However, each of these conditions can be improved, as needed, during the remedial action.

The following remedial action objectives (RAOs) were determined for the FS:

- Protect potential future human receptors from exposure to contaminated groundwater by dermal contact or inhalation and to vapor emanating from the contaminated groundwater above unacceptable risk levels.
- Reduce groundwater concentrations of the following compounds to their respective site remediation goals (SRGs):
  - Benzene: 5 micrograms per liter (µg/L).
  - CTC: 5 µg/L.
  - Chloroform: 80 µg/L.
  - 1,2-DCA: 5 µg/L.
  - TCE: 5 µg/L.
  - PCE: 5 µg/L.
- Monitor the groundwater during the remedial action to ensure that the potential degradation products of the COCs do not exceed their respective United States Environmental

Protection Agency (USEPA) Maximum Contaminant Levels (MCLs) or MDE groundwater cleanup standard:

- Chloromethane: 19 µg/L
- Methylene chloride: 5 µg/L
- cis 1,2-Dichloroethene: 70 µg/L
- Vinyl chloride: 2 µg/L

Restrict the use of groundwater so that it is not used for drinking water or showering purposes until the SRGs for benzene, CTC, chloroform, 1,2-DCA, TCE, and PCE are met, and the total groundwater cumulative risk (including any degradation daughter products) allows for unlimited use and unrestricted exposure.

Response complete will be achieved once the SRGs have been met for all COCs and the total groundwater cumulative risk allows for unlimited use and unrestricted exposure.

Based on the screening of applicable technology types and process options, the following five remedial alternatives have been retained for evaluation and developed for the SS-28 site:

- Alternative 1 – No Action.
- Alternative 2 – Monitored Natural Attenuation (MNA) with Land Use Controls (LUCs).
- Alternative 3 – In Situ Biodegradation (ISB) and In Situ Chemical Reduction (ISCR) with Land Use Controls.
- Alternative 4 – In Situ Chemical Oxidation (ISCO) and In Situ Biodegradation with Land Use Controls.
- Alternative 5 – Groundwater Extraction and Treatment Using Wells with In Situ Biodegradation and Land Use Controls.

In addition to the primary remedies listed above, Alternatives 3 through 5 include LUCs and additional ISB injections to remediate the portion of the contaminated groundwater plume that has reached the grassy airfield.

The five remedial alternatives were evaluated in relation to one another based on seven of the nine National Oil and Hazardous Substances Pollution Contingency Plan (NCP) criteria with the purpose of identifying the relative advantages and disadvantages of each alternative. Each of the alternatives was also evaluated on its green or sustainable practice components. As a result of the

comparative analysis, the five alternatives were evaluated as satisfying the individual criteria to a high, moderate, or low/no (does not satisfy) degree. Alternatives 3 (ISB/ISCR) and 4 (ISB) were both judged to meet the RAOs and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) criteria to a high degree. **Table ES-1** summarizes the general evaluation for each of the five alternatives. Within **Table ES-1**, the time until action completed represents time to Response Complete (RC); whereas, present value costs represent the costs through Site Closure.

Based on evaluation of the remedial alternatives in this SS-28 FS, Alternative 3 (In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls) is proposed as the recommended alternative. Alternative 3 has the shortest remedial timeframe, the lowest cost, and manageable implementation issues. The final selection of the preferred alternative will depend on input from USEPA, Maryland Department of the Environment (MDE), Prince George's County, and the public.

Alternative 3 involves the direct injection of a water-dispersible, long-lasting carbon substrate with or without iron, bioaugmentation, and pH buffer. The aqueous formulation is designed to promote both in situ biological reductive dechlorination and chemical reduction of the contaminants in the site groundwater, while also providing a pH buffering effect. The amendments would be field mixed and injected through direct push (DP) points into a series of five or more rows of passive ISB/ISCR or ISB permeable biostimulation treatment zones (PBTZ) throughout the contaminant plume.

Table ES-1 List of Remedial Alternatives and the Degree to Which Each Meets the CERCLA Criteria
Site SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Criterion	Alternative 1 No Action	Alternative 2 Monitored Natural Attenuation with Land Use Controls	Alternative 3 In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls	Alternative 4 In Situ Chemical Oxidation and In Situ Biodegradation with Land Use Controls	Alternative 5 Groundwater Extraction and Treatment with In Situ Biodegradation and Land Use Controls
Overall Protection of Human Health and of the Environment					
Human Health	○	◎	●	●	●
Environmental Protection	○	○	◎	◎	◎ ♻
Compliance with ARARs					
Potential Chemical-specific ARARs	○	○	● ♻	◎	◎
Potential Action-specific ARARs	NA	◎	●	●	◎
Potential Location-specific ARARs	NA	◎	●	●	◎
Long-Term Effectiveness and Permanence					
Magnitude of Residual Risk	○	○	● ♻	●	◎
Adequacy of Controls and Monitoring	NA	◎	●	●	●
Reduction of TMV through Treatment					
Reduction of TMV	○	○	● ♻	●	◎
Statutory Preference for Treatment	○	○	● ♻	●	●
Short-Term Effectiveness					
Community Protection	○	○	●	●	●
Worker Protection	○	○	● ♻	●	◎
Environmental Impacts	○	○	●	● ♻	◎
Time Until Response Complete	40+ years	40+ years	23 years (20 + 3)	23 years (20 + 3)	32 years (29 + 3)
Implementability					
Feasibility of Construction and Operation	NA	● ♻	◎	◎	◎
Reliability of Technology	○	○	●	●	●
Administrative Feasibility	●	●	◎	◎	○
Cost (Present Value 2015)*	---	$3,157,000	$5,033,000	$563,000	$12,481,000
State/Supporting Agency Acceptance	To be determined	To be determined	To be determined	To be determined	To be determined
Community Acceptance	To be determined	To be determined	To be determined	To be determined	To be determined
Overall Ranking	○	○	●	◎	◎

Notes:

ARARs - applicable or relevant and appropriate requirement

NA - not applicable

TMV - toxicity, mobility, or volume

● - satisfies criterion to high degree in a timely manner

◎ - satisfies criterion to moderate degree in a timely manner

○ - satisfies criterion to low degree or does not satisfy criterion in a timely manner

♻ - most sustainable in each criterion

* - Cost (Present Value 2015) values are to Site Closure, including 3 years of long-term monitoring after the project reaches Response Complete

1.0 INTRODUCTION

This Feasibility Study (FS) report was prepared by Weston Solutions, Inc. (WESTON®) to support the Environmental Restoration Program (ERP) work being conducted at the Joint Base Andrews Naval Air Facility Washington (JBA) in Maryland for the United States Air Force (USAF) under United States Army Corps of Engineers (USACE) Performance-Based Contract W9128F-13-D-0002. The Air Force Civil Engineer Center (AFCEC), formerly the Air Force Center for Engineering and the Environment (AFCEE), is directing the work performed under this contract. Work under this contract is being led by Bay West, LLC (Bay West) in conjunction with its teaming partners AMEC Environment & Infrastructure, Inc. (AMEC) and WESTON.

This FS report identifies and evaluates remedial alternatives for contaminated groundwater at ERP Site SS-28 at JBA. For the purposes of this report, the overall site is defined as the area encompassed by the total extent of contamination and will be referred to as SS-28 or simply the site. The remedial investigation (RI) and FS process was developed in response to the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA). The fundamental purposes of the RI/FS process are as follows:

- Characterize the nature and extent of the contamination at a site and identify the risks posed by the site.
- Evaluate the potential options for remediating the site.
- Provide sufficient information to support decisions regarding the most appropriate remedy for the site.

The *Final Remedial Investigation Report - SS-28* (URS Group, Inc. [URS], 2013) provided an analysis of field and laboratory data collected during the field activities to characterize the site and identified and quantified the risks posed by contaminants at SS-28.

1.1 PURPOSE AND ORGANIZATION OF REPORT

The primary purpose of this FS is to identify and evaluate potential remedial options for contaminated groundwater at SS-28. The FS report has been organized into seven sections that are

consistent with the United States Environmental Protection Agency (USEPA) *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (USEPA, 1988).

The FS report is organized as follows:

- Section 1.0: Introduction—Presents background information, including the site description and history, summary of nature and extent of contamination, contaminant fate and transport, and summary of the baseline risk assessment.
- Section 2.0: Regulatory Considerations—Presents a discussion of the remedial action objectives (RAOs), applicable or relevant and appropriate requirements (ARARs), and preliminary site remediation goals (SRGs).
- Section 3.0: Screening of Technologies and Development of Alternatives—Presents the general response actions, discusses the identification and screening of applicable technology types and process options, and presents the remedial options.
- Section 4.0: Description of Remedial Alternatives—Evaluates the remedial options discussed in Section 3 and presents the relevant information necessary to allow decision-makers to select a remedy.
- Section 5.0: Detailed Analysis of Remedial Alternatives—Presents the individual analysis and assessment of each of the groundwater remedial alternatives with respect to the federal National Oil and Hazardous Substances Pollution Contingency Plan (more commonly called the National Contingency Plan [NCP] 40 Code of Federal Regulations [CFR] Part 300) evaluation criteria.
- Section 6.0: Comparative Analysis—Presents a comparison of the remedial alternatives to each other in order to identify the relative advantages and disadvantages of each alternative.
- Section 7.0: References—Lists the references cited in the report.

Costing estimate details for each of the remedial alternatives presented in this report are included in **Appendix A**. A groundwater flow and contaminant transport model was utilized to determine estimations on time to cleanup for each remedial alternative. The model simulations are discussed in detail in **Appendix B**.

1.2 SITE DESCRIPTION

The following site description includes information concerning geography, demography, wildlife habitat, meteorology, geology, hydrogeology, and surface water hydrology at SS-28. Environmental technical parameters supporting the conceptual design (e.g., hydraulic gradients

and hydraulic conductivities) are summarized. Additional details can be obtained from the SS-28 Preliminary Assessment/Site Investigation (PA/SI) Report (HydroGeoLogic, Inc. [HGL], 2007), and the RI Report (URS, 2013).

1.2.1 Geography

SS-28 is located within JBA in Prince George's County, Maryland, near the community of Camp Springs (**Figure 1-1**). Washington, DC, is located approximately 5 miles west of the base. SS-28 is located on the west side of the JBA airfield and covers approximately 55 acres (**Figure 1-2**).

1.2.2 Demography

JBA is the home of the 11th Wing, 89th Airlift Wing, and numerous tenant organizations, including units from the United States Navy, the United States Marine Corps, the District of Columbia Air National Guard (ANG), and the Air Force Reserve. More than 8,000 full-time military personnel are stationed at JBA, which also employs more than 2,000 civilians.

JBA covers approximately 4,360 acres, which include runways, airfield operations, industrial areas, and housing and recreational facilities. Residential housing is the second largest land use area on JBA. The majority of the housing is located on the west side of JBA. One residential area is located east of the airfield. Outdoor recreation land use includes golf courses, ball fields, a tennis court, a running track, and picnic areas. The majority of the outdoor recreation facilities are concentrated west of the airfield in the southwest corner of JBA.

The SS-28 site is located in the western portion of JBA and extends approximately 3,700 feet to the southeast and 3,000 feet to the east-southeast from the location of Building 1217, across four active aircraft taxiways and a concrete aircraft parking area (**Figure 1-2**). The structures encompassed within the site include Buildings 1201, 1202, 1206, 1207, 1217, 1285, 1287, 1288, 1290, 1291, and 1292, a basketball court, two sanitary sewage pump stations, and an open-air fire station storage pavilion. The site also contains the main aircraft taxiway used to access the Presidential Hangar. Most of the site is located within the high-security Pathfinder fence, so there is no public access.

There are many requirements and restrictions when working on the airfield. All remedial work will need to be approved through a Temporary Airfield Construction Waiver (TACW) and coordinated

with JBA airfield operations. Teams will need to have the proper Pathfinder escorting access badges when operating within the Pathfinder area. Any intrusive subsurface work (i.e., construction, monitoring well installation, direct-push borings) requires all of the base-affiliated utilities to review the work areas and mark out any underground utility lines that may pass through the work area. **Figure 1-3** presents an overview of the SS-28 underground utilities that would need to be avoided during any future proposed remedial actions and should be taken into consideration during the alternative implementability evaluations.

1.2.3 Wildlife Habitat

The ground surface at SS-28 generally slopes towards the southeast and is currently covered by concrete, asphalt, or grass. The ground surface elevation ranges from approximately 280 feet above mean sea level (amsl) near Building 1201 to 235 feet amsl in the southeastern portion of the site near Pad 94 (URS, 2013). Topography of the site was significantly altered during runway and air facility construction and the natural vegetation has been replaced by the cultivated grasses. There are no surface water features within the site boundaries (**Figure 1-2**). Vegetation in the grassy areas consists of cultivated grass that is mowed regularly to support flight line and security requirements. The proximity of the site to the runways, the high amount of human activity in this area, and the noise and disruption from air operations contribute to making this an unattractive location for wildlife.

1.2.4 Meteorology

JBA lies in a transition zone between a humid continental climate to the north and west and a humid subtropical climate to the south. Both zones influence the climate of JBA because prevailing winds vary in direction according to season. According to data collected at JBA and other locations in Prince George's County, winds are typically from the northwest during the months of November to April; whereas, winds are from the southwest during May to September. In addition, large water bodies surrounding JBA further influence local climate at JBA. JBA is on the upper end of a peninsula formed by the Potomac River on the west and south and Chesapeake Bay on the east; the Atlantic Ocean is located to the east, across the Delmarva Peninsula.

Based on data collected at the Upper Marlboro station that is located approximately 5 miles away from the base, the mean annual temperature for JBA is 54 degrees Fahrenheit (°F), with the

warmest month being July at a monthly average temperature of 76°F, and the coldest month being January at 32°F. The annual precipitation at JBA averages about 42 inches of rain, and the monthly distribution of precipitation is fairly uniform during the year (Bay West, 2013).

1.2.5 Geology

The subsurface stratigraphy comprises the Upland Deposits overlying the Calvert Formation (**Figure 1-4**). The Upland Deposits consist of orange-brown sand with variably interbedded discontinuous layers of gravel, silt, and clay, ranging from 12 to 46 feet in thickness across the site.

The Calvert Formation consists predominantly of greenish-grey silt and clay and typically serves as an aquitard. The top of the Calvert Formation ranges from 12 to 46 feet below ground surface (bgs) with elevations ranging from 216 to 248 feet amsl. The top of the Calvert Formation generally dips to the east and southeast beneath the majority of the site. The top of the Calvert Formation has two troughs: one is oriented easterly, extending from south of Taxiway W2 through the North-South Instrument Runway; the second is oriented southeasterly, running from north of Taxiway W3 through the area just north of Pad 94, where a topographic saddle (dip or low point between two areas of higher Calvert surface elevations) constricts flow across the length of Pad 94, which then continues off the southern edge of the site (**Figure 1-5**). These troughs are associated with clean, rounded sands and gravels that may indicate former stream channels that could provide preferential pathways for groundwater flow at higher rates than the rest of SS-28. Further discussion of the site's geology is included in the RI report (URS, 2013).

1.2.6 Hydrogeology

Groundwater was encountered in the Upland Deposits Formation at depths between approximately 4 and 22 feet bgs, depending primarily on surface topography. Gauging data indicate that groundwater flows to the east and southeast from a groundwater high (recharge area) just west of SS-28, mimicking the ground surface elevation (**Figure 1-6**). Based on groundwater elevations, it appears that Uplands Formation groundwater eventually discharges into the Piscataway Creek south of the runway. There are also localized elevation changes in the top of the Calvert Formation that influence the groundwater flow. Groundwater in the unconfined shallow water table is derived primarily from precipitation recharge near the buildings in the northwest part of the site.

During the RI field work, the hydraulic conductivity in the SS-28 Upland Deposits ranged from approximately 1.38 feet per day (ft/day) to 30.96 ft/day, with a geometric mean hydraulic conductivity of 14.45 ft/day. Given that geometric mean hydraulic conductivity value, the seepage velocity ranged from approximately 5 to 95 feet per year (ft/yr), with a geometric mean seepage velocity of approximately 49 ft/yr. Within the trough areas in the Calvert Formation, where stream channel deposits may increase groundwater flow, the seepage velocity was calculated to be approximately 90 ft/yr (based on data from monitoring well [MW] 07s). The horizontal hydraulic gradient was calculated to be 0.0030 feet/foot in the Upland Deposits, based on data from the RI field work. More details of the site's hydrogeology are discussed in the RI report (URS, 2013).

Underneath the Upland Deposits Formation is the Calvert Formation, which consists of approximately 80 to 90 feet of predominantly greenish-grey silt and clay at SS-28. The Calvert Formation is reported to be a regionally leaky confining unit that appears to be an aquitard of uniform nature beneath SS-28.

1.2.7 Surface Water Hydrology

Surface water flow at SS-28 is controlled by the precipitation runoff from the asphalt and concrete surfaces that make up the building region and nearby Taxiways Whiskey and W2. Surface water flows from these surfaces toward the adjacent grassy areas or into the stormwater sewer system through oil/water separators (OWSs). The stormwater sewer system at SS-28 is part of a local watershed that includes drains, drainage ditches, streams, and open concrete channels, covering approximately 1,888 acres of JBA (**Figure 1-7**). The system discharges to multiple streams that flow off JBA, including Piscataway Creek. Piscataway Creek is a waterway located just south of JBA and approximately 0.40 miles hydraulically downgradient of the southeastern most extent of SS-28. There are two OWSs, OWS-1217A and 1217B, located to the north and northwest of Building 1217. There are no major surface water bodies within the SS-28 site boundaries.

In storm situations, JBA is covered by two National Pollutant Discharge Elimination System (NPDES) General Discharge Permits (GDP); one for industrial stormwater (GDP No. 02-SW), and one for municipal stormwater (GDP No. 05-SF-5501). Both permits have expired (2007 and 2010, respectively) but they have been administratively extended by the Maryland Department of the Environment (MDE) until new permits are issued.

The base Utilities Privatization contractor, Terrapin Utilities, operates under an NPDES GDP for discharges from tanks, pipes, and other containment structures (MDE Permit No. 06HT) for routine testing of on-base fire hydrants because MDE controls the discharge of chlorine-treated potable water into waters of the state.

JBA developed a stormwater pollution prevention plan (SWPPP), as directed by the industrial stormwater permit, to identify potential sources of pollution that may be reasonably expected to affect the quality of stormwater discharges at JBA (Los Alamos Technical Associates, Inc. [LATA]/URS, 2011). The SWPPP includes voluntary semiannual sampling and analysis of the stormwater quality, including volatile organic compounds (VOCs), nitrogen, phosphorous, and sediment, at outfall NS003 at Piscataway Creek, and other discharge points around JBA to ensure compliance with the base NPDES permits and the implementation of pollutant reduction practices. Stormwater sampling data are available for the spring/summer periods of 1996, 2003, 2004, 2005, 2006, 2007, 2008, and 2010. Sampling results are compared to the USEPA National Recommended Water Quality Criteria for freshwater criterion and human health consumption. There have been no detections of any VOCs within the surface waters at NS003 since 2004, when the only VOCs detected were trichloroethene (TCE) (2.4 micrograms per liter [µg/L]) and benzene (0.52 µg/L estimated). The most recent stormwater sampling event at NS003 was in April 2010 (Ecology and Environment, 2010).

1.3 SITE HISTORY

The groundwater plumes associated with SS-28 originate in the vicinity of Building 1206, located at the intersection of Arnold Avenue and South Dakota Avenue, and extend east-southeast and southeast over approximately 3,700 feet across the airfield. Building 1206 has been an active military gasoline service station since 1980 and was once a maintenance facility for the Base fire trucks. Historically, there have been a number of fueling product underground storage tanks (USTs), hydraulic lifts, a waste oil aboveground storage tank (AST), and two solid waste management units (SWMUs) situated around Building 1206. SWMU-2 was a waste motor oil 250-gallon AST that operated from 1983 to 1986. SWMU-2 was removed following a failed leak test. SWMU-40 was a waste allocation point for anti-freeze, transmission fluid, and vehicle waste fluids stored in 55-gallon drums. Neither SWMU has a secondary containment setup, but there

have been no reported releases. Currently, Building 1206 is used for fleet maintenance and has two USTs: a 20,000-gallon gasoline UST and a 20,000-gallon diesel UST.

The area around Building 1206 was initially developed in 1943, when a clearing was created and a large tower was constructed. From 1943 through the 1950s, historical aerial photographs show additional clearing of vegetation and construction of several small structures, buildings (including Hangar 8), and a trench. Buildings 1205, 1208, a sanitary sewer pump station, several former buildings, and a former tower are visible in the 1964 historical photographs presented in the Historical Photograph Log in the RI. Building 1206 and the control tower were constructed by 1968. Other key buildings within the site were constructed in the 1970s through 2010, including Buildings 1201 (1970s), 1285 (1970s), 1287 (1982), Hangar 18 (1990), 1202 (2000), 1217 (2000), 1207 (2010), and 1223 (2010).

In September 1991, a failure of a product recovery delivery line connecting a 6,000-gallon diesel UST and a 15,000-gallon diesel UST, both located southeast of Building 1206, to the dispensing station was detected during integrity testing of the product storage, distribution, and delivery system. Repairs of the lines were made by JBA and subsequent testing was conducted by IT Corporation (IT) to confirm that system integrity had been restored (IT, 1997). Five soil samples were collected in February 1992 and tested for benzene, toluene, ethyl benzene, and total xylenes (BTEX) and total petroleum hydrocarbons (TPH). Laboratory results complied with MDE standards for TPH and USEPA standards for BTEX (HGL, 2007).

The 25,000-gallon gasoline UST south of Building 1206, and the 6,000- and 15,000-gallon diesel USTs southeast of Building 1206 were removed on November 6, 1998. The 1,000-gallon fuel oil UST east of Building 1206 was removed on January 29, 1999. Each of the USTs had passed Tracer Tight® leak tests in 1995, 1996, and 1997. The 25,000-gallon gasoline tank and the 1,000-gallon fuel oil UST were coated with a material containing polychlorinated biphenyls (PCBs) and were disposed of at a Toxic Substances Control Act (TSCA) landfill (HGL, 2007). Approximately 60 tons of excavated soil was disposed of off-site as non-hazardous, petroleum-impacted soil (URS, 2013).

After the UST removals in November 1998, confirmation soil samples were collected from the area of the UST excavations and analyzed for BTEX, TPH diesel range organics (DRO), TPH gasoline range organics (GRO), and PCBs. Of the BTEX and TPH compounds, only benzene (maximum detection of 6.9 milligrams per kilogram [mg/kg]) exceeded its MDE risk-based concentrations (RBCs) of 0.77 mg/kg (for resident soils) and 3.2 mg/kg (for industrial soils). An analysis of the coatings of the 1,000-gallon fuel oil tank, which was removed on January 29, 1999, and the 25,000-gallon gasoline UST, revealed maximum concentrations of 312 mg/kg and 1,680 mg/kg, respectively, of PCBs. These concentrations were higher than the MDE RBCs and the TSCA regulatory level at the time of 50 mg/kg (Ellis, 2006).

The two hydraulic lifts were removed in 1997. The approximate volume of free hydraulic fluid in the two pits was 250 gallons in the first pit and 75 gallons in the second pit. Soil samples taken after the lifts were removed revealed the presence of TPH, and the contaminated soil was subsequently removed. Samples collected from the pits following soil removal indicated that TPH concentrations did not exceed MDE standards (HGL, 2007).

1.4 NATURE AND EXTENT OF CONTAMINATION

1.4.1 Contaminant Sources

Available historical information does not document specific evidence of chemical releases to the ground surface within the site. Based on the RI sampling data, it is likely that there are four release locations that have contributed to the overall contamination at the site (**Figure 1-8**):

- A potential release area for TCE, an industrial solvent, was located in a grassy area east of Building 1217.
- A potential release area for carbon tetrachloride (CTC), a cleaning agent and former refrigerant, and TCE was located near SWMU-2 and SWMU-40, just north of Building 1206.
- A potential release area for benzene was located to the southwest of Building 1206. A former 1,000-gallon fuel oil UST and two fuel pumps were previously located in this same area.
- A second potential release area for benzene was located in a small grassy area between Taxiways W2 and W3, possibly from a surface gasoline spill or refueling hydrant line leak.

There is no evidence of a current source releasing VOCs to the groundwater at the site.

1.4.2 Soil Contamination

Soil samples were collected as part of four removal actions in 1992, 1997, 1998, and 1999, a PA/SI in 2004, a second PA/SI in 2007, and RI field work in 2011 to 2012. All of the soil samples collected before the RI field work focused in and around Building 1206 (**Figure 1-2**). This subsection will focus on the soil sampling that occurred as a part of the PA/SI and RI field efforts. Soil sampling that was conducted as a part of the removal actions is discussed in Section 1.3, Site History.

Ellis Environmental Group collected soil samples in the vicinity of the former and current USTs, SWMU-2, SWMU-40, and hydraulic lifts around Building 1206 in 2004 as a part of a PA/SI. The soil samples were analyzed for VOCs, semi-volatile organic compounds (SVOCs), PCBs, TPH-GRO, TPH-DRO, and specific metals (cadmium, chromium, and lead). Analysis of the samples revealed the presence of petroleum-related products in the vicinity of the USTs, but none of the analytes detected in unsaturated soil exceeded EPA Region III residential risk-based screening levels (RBSLs) or maximum contaminant level (MCL)-based soil screening levels (SSLs) for groundwater protection. The one soil sample obtained in the hydraulic pit area did not contain any constituents above regulatory standards. Prior to this 2004 field effort, no previous sampling or investigative activities had occurred at SWMU-2 or SWMU-40. At the SWMU sampling locations, none of the analytes exceeded regulatory standards, and PCBs were not detected (URS, 2013).

In 2007, HGL conducted a second PA/SI to determine the lateral extent of chlorinated solvents in the soil and groundwater at SS-28. Soil samples were collected from 13 soil boring locations, utilizing a direct-push technology (DPT) rig. Samples were collected from a given soil core if there were signs of visual evidence of contamination or elevated VOC readings on a photo-ionization detector (PID) along the length of the soil core. A total of 12 samples were analyzed for VOCs at an on-site mobile laboratory. An additional three soil samples were sent to a fixed-based laboratory if the mobile laboratory results detected elevated levels of contamination or if there were elevated PID detections along the soil cores. The samples that were sent to the fixed-based laboratory were analyzed for VOCs, SVOCs, metals, PCBs, TPH-GRO, and TPH-DRO (HGL, 2007).

The PA/SI sampling results from both the mobile laboratory and fixed-based laboratory showed that the vadose soil was not significantly impacted by site activities. Soil contamination was not evident at the SWMUs (HGL, 2007). Metals were the only other analytes detected above the Region III RBC screening values in the samples submitted to the fixed-based laboratory. Aluminum, arsenic, iron, and vanadium exceeded the Region III residential RBC screening levels in all samples collected. The concentrations are likely representative of background. When analyzing for risk due to the soil, HGL determined that the soil did not pose an unacceptable risk for human health (HGL, 2007).

URS collected subsurface soil samples from five membrane interface probe (MIP) locations near Building 1206 and 1217 in July 2012. Ten soil samples from various depths were collected from each MIP location in order to determine whether the electron capture detection (ECD) curve (which is sensitive to chlorinated organic compounds) was representative of any subsurface contamination. The ECD sensor has a sensitivity of about 200 µg/L for TCE and other chlorinated hydrocarbons, which can help in analyzing potential source area regions but is not necessarily ideal for delineating the edges of the plume. Soil sampling depths were selected based on elevated readings of any of the sensor signatures on the MIP logs. All of the soil samples were sent to a fixed laboratory for analysis.

The laboratory results showed that petroleum compounds (BTEX) and chlorinated compounds (TCE, CTC, and chloroform) were detected in the soil samples collected from below the groundwater table (18 to 20 feet bgs), which correlates with the MIP logs. Across the five MIP locations, four compounds were detected at depths above the groundwater table – chloroform, methylene chloride, cis-1,2-dichloroethene (cis-1,2-DCE), and TCE. All of these detections were flagged by the laboratory as "estimates" because they barely exceeded the method detection limit and are not indicative of any lingering chemical presence in the soils.

1.4.3 Indoor Vapor Intrusion

Indoor vapor samples were collected from within the breathing zone in Buildings 1201, 1202, 1205, 1206, 1207, 1208, 1217, 1223, 1285, and 1287 to assess the potential for vapor intrusion (VI) during the RI field work (**Figure 1-9**). URS sampled vapor from multiple locations within the buildings during two different field events (August 3, 2011 and March 6, 2012) and the analytical

results of this effort are summarized in **Figure 1-10** for Building 1287 and **Figure 1-11** for Building 1201.

After comparing the August 2011 analytical results to the RBSLs, Buildings 1202, 1205, 1206, 1207, 1208, 1217, 1223, and 1285 were determined not to require any further action with regard to VI. For Buildings 1202, 1205, 1206, 1207, 1208, 1217, 1223 and 1285, all samples either exhibited indoor air concentrations less than industrial RBSLs or indoor air concentrations that were less than industrial RBSLs after subtracting outdoor ambient air concentrations. Industrial usage was confirmed in these buildings, and no further action is required (URS, 2013).

Samples in Buildings 1201 and 1287 collected in August 2011 exhibited indoor air concentrations of chloroform greater than the industrial RBSL (0.53 micrograms per cubic meter [$\mu g/m^3$]) after subtracting outdoor ambient air concentrations from each building. In Building 1287, benzene and CTC indoor air concentrations of benzene and CTC after subtracting outdoor ambient air concentrations were calculated as greater than their respective residential RBSLs (0.31 $\mu g/m^3$ for benzene and 0.41 $\mu g/m^3$ for CTC) but below their respective industrial RBSLs (1.6 $\mu g/m^3$ for benzene and 2.0 $\mu g/m^3$ for CTC). As explained in a Technical Memo to the Tier 1 Team (November 2011), URS estimated more specific industrial RBSLs for these buildings based on their actual industrial usage. At Building 1201, employee hours were the same as standard inputs that EPA uses to calculate industrial RBSLs. At Building 1287 (fire department), employee hours varied between military and civilian personnel. However, after recalculating industrial RBSLs for both military and civilians using adjusted work schedule inputs, URS found military industrial RBSLs to be extremely similar to the default industrial RBSLs, and civilian RBSLs to be slightly higher than the default industrial RBSLs (URS, 2013).

URS re-sampled indoor and ambient breathing zone samples in Buildings 1201 and 1287 in March 2012 to ensure analytical results were reproducible and representative of groundwater VI. In Building 1287, all samples exhibited indoor air concentrations less than industrial RBSLs or indoor air concentrations less than industrial RBSLs after subtracting outdoor ambient air concentrations. At Building 1201, chloroform again exhibited indoor air concentrations greater than the industrial RBSL after subtracting outdoor ambient air concentrations of chloroform.

The RI data was compared to health-based screening levels based on current and anticipated future site use near the contaminant plumes and the evaluation indicated that this pathway is not of concern for continued industrial use. The data was not evaluated quantitatively under residential screening levels due to industrial usage of the site, the dynamic nature of VOC concentrations in the groundwater at specific locations, and because the source of the VI would be addressed through groundwater remediation. The RI concluded that the VI risk should be re-evaluated if the site use changes from "industrial" to "residential" as there is potential risk for future residents.

1.4.4 Groundwater Contamination

Benzene, CTC, and TCE made up the majority of the VOCs detected above their respective MCLs in the groundwater samples (**Table 1-1**). Non-aqueous phase liquid (NAPL) was not observed during the site investigations and the concentrations of these compounds were not indicative of the presence of dense non-aqueous phase liquid (DNAPL) within the site's subsurface. The highest detection of TCE was only 0.11 percent (%) of TCE's solubility in water, which is 1,100,000 µg/L. The highest detection of benzene was only 0.15% of benzene's solubility in water, which is 1,790,000 µg/L. The highest detection of CTC was only 0.26% of CTC's solubility in water, which is 846,100 µg/L. Generally, in order for DNAPL to be present, the concentrations should be greater than 1% (or 11,000 µg/L for TCE, 17,000 µg/L for benzene, and 8,461 µg/L for CTC) of the solubility.

Of these three compounds, TCE was detected across the largest area, covering 55 acres of buildings, taxiways, and grassy regions of the airfield. The TCE plume extended approximately 3,700 feet to the southeast and 3,300 feet to the east-southeast from Building 1206 (**Figure 1-12**). Although TCE covers this large area, the highest concentration was detected at MW05 near Building 1207 (210 µg/L).

The footprint for CTC is predominantly confined to the main building region in the northern portion of the site (**Figure 1-13**). The highest concentrations for CTC were found near Building 1206 at MW04 (CTC, 2,200 µg/L).

The benzene footprint has three regions. Two of these regions are shown on **Figure 1-14** with maximum concentrations above 50 µg/L: one in the building region expanding from Building 1206

to 1287 (maximum concentration from monitoring wells, 270 µg/L); and a second in the grassy region between Taxiways W2 and W3 (maximum concentration from direct push [DP] borings, 910 µg/L). There is a third region along the eastern edge of Taxiway Whiskey within the grassy infield (maximum concentration from DP borings, 18 µg/L), which is seen in **Figure 1-8**. According to the 2010 General Plan Update, there is an area where old aviation fuel lines run along the grass region between Taxiways W2 and W3, and the area coincides with one of the benzene footprint regions. These fuel lines are a part of the base's overall fuel transfer pipeline system. The General Plan Update stated that the majority of the fuel transfer pipeline is more than 50 years old, and it is not known whether there is any protective wrapping of the pipelines to reduce corrosion and leaking. A full pipe replacement was recommended because the pipeline had deteriorated (PBS&J, 2010). The highest benzene concentrations were found near Building 1206 at MW06 (benzene, 270 µg/L).

Other VOC compounds that were detected at levels exceeding their MCLs or MDE Cleanup Standard include 1,2-dichloroethane (1,2-DCA), chloroform, tetrachloroethene (PCE), and naphthalene (**Table 1-1**).

PCE was detected sporadically within the TCE footprint. Chloroform is a potential degradation daughter product from CTC through reductive dehalogenation and was detected sporadically at SS-28 within the CTC footprint. Naphthalene is a petroleum-related compound that was typically detected within the benzene plume footprint.

1.5 CONTAMINANT FATE AND TRANSPORT

The evidence for the exact location and timing of the specific solvent and petroleum releases at SS-28 is limited. It is unknown whether multiple spills occurred in the SS-28 area. No continuing source of contamination, such as leaking tanks or waste storage areas, was identified and no contamination was identified in the unsaturated soil above soil-to-groundwater leaching standards. Therefore, the groundwater contaminant concentrations are the best available indicator of the origin of the contaminants in the subsurface.

Based on the current plume configuration (**Figures 1-12** to **1-14**), the main release areas appear to be located near Building 1217 to the west, Building 1206 to the north, and the grass swale next to

Taxiway W2 to the southeast (**Figure 1-2**). The petroleum releases were predominantly subsurface and related to UST and fuel pipe line leaks. Solvent leaks were most likely at the ground surface from drums or ASTs. Released solvents and petroleum would have moved downward through the unsaturated Upland Deposit sands to the groundwater table at approximately 20 feet bgs, where the petroleum would tend to accumulate at the top of the groundwater table and the solvents would tend to continue moving downward deeper into the groundwater if sufficient mass was present.

The bulk of the VOC mass dissolved in the groundwater is located along the groundwater flow vector originating from these release areas, as shown in the groundwater contour maps. This situation implies that advection of groundwater is the dominant force controlling the VOC distribution in the Uplands Deposits groundwater.

The RI data indicate that groundwater passing through the Upland Deposits at SS-28 is flowing to the southeast and ultimately discharging into Piscataway Creek. The clay rich Calvert Formation below the Upland Deposits appears to be acting as an aquitard, limiting the downward flow of groundwater and contaminants. Based on the extent of the TCE plume (which covers the largest area), it appears the contamination plume has not reached the creek.

There is some evidence of biologically-mediated reductive dechlorination of the chlorinated VOCs occurring in the groundwater at SS-28, especially of CTC. Concentrations of chloroform of up to 610 µg/L were detected within the CTC plume. However, there are little to no detections of the other common degradation products for both TCE and CTC (cis-1,2-DCE and vinyl chloride for TCE; methylene chloride, and chloromethane for CTC). If these daughter compounds were measured in the groundwater, they were within or near the edge of the footprint for their respective parent compounds. The 2007 PA/SI included sampling to support the natural attenuation screening protocol (USEPA, 1998) and determined that the protocol score for the contaminant release area was 14, which indicates limited, but almost adequate, evidence of anaerobic degradation of chlorinated organic compounds.

The current subsurface system is not optimal for sustainable chlorinated VOC degradation by microbial reductive dehalogenation; however, microbial reductive dehalogenation has been very successful at adjacent site FT-02 after the injection of carbon substrate. Biological reductive

dechlorination is often catalyzed by certain species of bacteria. Dehalococcoides (DHC) and Dehalobacter have been identified as two of the important dechlorinating bacteria species. Groundwater samples were collected from two monitoring wells to assess the current native DHC populations in SS-28 near Building 1206. The results were 11.2 cells per milliliter (cells/mL) at MW04 and 20.6 cells/mL at MW02. The ideal DHC population for sustainable reductive dehalogenation in the subsurface needs to be on the order of 10,000 cells/mL (Environmental Security Technology Certification Program [ESTCP], 2011); however, populations ranging from 10 to 1,000 cells/mL have potential for complete dechlorination if an electron donor – such as a carbon substrate - is supplied to the subsurface to stimulate DHC growth (Lu, et. al., 2006) and the vinyl chloride reductase genes are also present in the subsurface to complete the dechloinating process down to ethene and prevent vinyl chloride from accumulating in the subsurface (Krajmalnik-Brown, et. al., 2004).. Currently, an inadequate amount of carbon substrate (i.e., carbon compounds, total organic carbon [TOC]) was observed in the groundwater to provide a sufficient food source with carbon-hydrogen bonds to support an enhanced microbial population.

The dechlorinating bacteria can be inhibited by the geochemistry of the subsurface system should the parameters fall outside the microbe's ideal ranges. The majority of the groundwater pH observed at the site during the RI field work ranged from approximately 3.88 to 6.52 with an average pH of 4.84. The dissolved oxygen (DO) content ranged from below 0.1 milligram per liter (mg/L) to 5.44 mg/L, with the median of 1.02 mg/L. The oxidation-reduction potential (ORP) at the site ranged from -52 millivolts (mV) to 407 mV, with the median of 274 mV. For geochemical conditions favorable for chlorinated VOC degradation, the ORP should be less than 0 mV, the DO less than 1 mg/L (creating an anaerobic system), and pH should be within the range of 5.5 to 8. The positive ORP and high DO concentrations are more indicative of aerobic conditions within the subsurface. Therefore, under current conditions, complete natural biodegradation of the chlorinated VOCs is unlikely at SS-28 within a reasonable timeframe (30 years or less).

1.6 RISK ASSESSMENTS

1.6.1 Human Health Risk Assessment

The Superfund site remediation goal set forth in the NCP designates an excess upper bound lifetime cancer risk of 10^{-6} (1 in 1,000,000) to 10^{-4} (1 in 10,000). This range is designed to be protective of human health and to provide flexibility for consideration of other factors in risk

management decisions. The CERCLA site remediation goal for non-carcinogens is a total hazard index (HI) of less than 1.0 for chemicals with similar toxic endpoints. Estimated HIs of less than 1.0 are considered negligible and do not generally warrant remedial action.

Groundwater data collected from monitoring wells during the SS-28 RI were reviewed for the HHRA. Risks resulting from contaminants in soil were not quantified because the evaluation of the RI data as compared to health-based screening levels indicated that soils concentrations are not of concern because the contaminants were either below their respective RBSLs or consistent with background conditions. Risks resulting from VI related to groundwater contamination also were not quantified because the evaluation of the RI data as compared to health-based screening levels based on current and anticipated future site use near the contaminant plumes indicated that this pathway is not of concern for continued industrial use. More restrictive residential screening levels would be applied and a supplemental risk evaluation or mitigation required if residential houses are built on the site in the future as there is potential risk for future residents. Chemicals were identified as contaminants of potential concern (COPCs) if they contribute to a reasonable maximum exposure (RME) cumulative cancer risk estimate that exceeds 10^{-4} or a cumulative RME target-organ-specific non-cancer HI that exceeds 1, and were not omitted as a result of factors such as central tendency exposure (CTE) risk estimates, MCLs, frequency of detection, magnitude of exceedances, site activities, or uncertainties in the risk estimates such as use of provisional toxicity values.

Based on the results of the HHRA, the identified groundwater COPCs include 1,2-DCA, benzene, CTC, cis-1,2-DCE, chloroform, ethylbenzene, methyl tert-butyl ether (MTBE), PCE, and TCE. **Tables 1-2** through **1-5** summarize the findings of the HHRA and present the risks associated with the COPCs identified in the RI report. No COPCs were identified in the soil or indoor air (see Section 1.6.2 of the RI; URS, 2013).

The shallow groundwater at SS-28 poses an unacceptable risk and/or hazard levels to human health over a limited area for the following receptors:

- Future child resident.
- Future adult resident.
- Future child/adult resident.

Cancer risk estimates for future residents were driven by ingestion of CTC from the groundwater, dermal contact with CTC in the groundwater, and inhalation of CTC and chloroform vapors from the groundwater while showering. The exposure route total for cancer risk was 2×10^{-3}. The HI values for future residents were driven by the ingestion of CTC and TCE from the groundwater, and inhalation of TCE. The non-cancer hazard exposure route total was 26 for adult residents and 35 for child residents.

Results of the risk assessment indicate that cancer risk and non-cancer hazard to the current, on-site indoor worker; current and future on-site outdoor workers; and current and future on-site excavation workers exposed to media at SS-28 are less than USEPA target levels. Hypothetical future residents using on-site groundwater as a source of potable water would incur significant levels of risk and hazard from exposure to groundwater. The COPCs for groundwater at SS-28 were determined based on the HHRA presented in the RI (URS, 2013), which assumed that SS-28 groundwater would be used for potable drinking water or showering purposes.

Risk to future residents attributable to VI was not evaluated quantitatively because of the industrial usage of the site, the dynamic nature of VOC concentrations in the groundwater specific locations, and because groundwater remediation is planned that would eliminate or reduce the VI source. A supplemental VI evaluation should be undertaken prior to occupancy of any future residential buildings constructed within the SS-28 boundaries showing that VI concentrations allow for unlimited use and unrestricted exposure, or any residential construction on the site will require mitigation measures that achieve unlimited use and unrestricted exposure.

The following six compounds have been determined to be the COCs for groundwater cleanup at SS-28 based on and a weight-of- evidence evaluation of the COPCs versus drinking water standards, frequency of detection, cancer risk, and non-cancer hazard:

- Benzene.
- CTC.
- Chloroform.
- 1,2-DCA.

- TCE.
- PCE.

The FS did not include cis-1,2-DCE, ethylbenzene, or MTBE as COCs because the weight-of-evidence evaluation revealed that the cancer risks and HIs for these three compounds were each well below 1% of the total cancer risk or HI for each receptor analyzed during the remedial investigation. Additionally, none of the three compounds exceeded their MCLs (70 µg/L for cis 1,2-DCE and 700 µg/L for Ethylbenzene) or drinking water advisory levels (20 – 40 µg/L for MTBE). Ethylbenzene was only detected in one well at 33 µg/L, which is an order of magnitude less than the EPA MCL or MDE Cleanup Standard of 700 µg/L and the calculated cancer risks for MTBE were all below 1E-06. Although these three compounds have not been included as COCs, they will all be evaluated during the performance monitoring of the remedial action.

1.6.2 Ecological Risk Assessment

The habitat at SS-28 was evaluated during the RI. The RI concluded that there was little-to-no evidence of soil contamination within 5 feet of the ground surface, and any VOC detections in the soil were observed at depths that were consistent with the top of the groundwater table. The RI also determined that an ecological risk assessment was not warranted because the site had been severely altered by human activity and large areas were covered with pavement. The natural habitat at SS-28 has been severely altered by human activity. The site is located within a highly industrialized area where large areas of ground surface are covered with pavement with little or no vegetation present. Vehicle traffic to and from buildings and facilities in the area is frequent. In addition, air operations create a significant disturbance to any potential ecological receptors. Based on these factors, URS concluded that there was no benefit to be derived from performance of an ecological risk assessment (URS, 2013).

2.0 REGULATORY CONSIDERATIONS

This section describes the regulatory framework and presents the RAOs, ARARs, and SRGs, for groundwater contamination at SS-28. In Section 1.6.1, benzene, CTC, chloroform, 1,2-DCA, TCE, and PCE were identified as groundwater COCs for SS-28. As described in Section 1.4.2, no site-related contaminants are present in soil at concentrations that pose an unacceptable risk; thus, no remedial action is necessary for soil contamination at the site.

2.1 FEDERAL REGULATION OBJECTIVES

The NCP requires that the remedy meet the following objectives:

- USEPA "expects to return usable groundwaters to their beneficial uses wherever practicable, within a timeframe that is reasonable given the particular circumstances of the site. When restoration of groundwater to beneficial uses is not practicable, USEPA expects to prevent further migration of the plume, prevent exposure to the contaminated groundwater, and evaluate further risk reduction" (40 CFR 300.430 (a)(1)(iii)(F)).
- "The alternatives shall be assessed to determine whether they attain applicable or relevant and appropriate requirements under federal environmental laws and state environmental or facility siting laws or provide grounds for invoking one of the waivers under paragraph (f)(1)(ii)(C)" (40 CFR 300.430(e)(9)(iii)(B)).
- "Each remedial action selected shall be protective of human health and the environment" (40 CFR 300.430 (f)(1)(ii)(A)).
- 40 CFR 300.430 (f)(1)(ii)(B) states that "on-site remedial actions that are selected must attain those ARARs that are identified at the time of the record of decision signature or provide grounds for invoking a waiver under 40 CFR 300.430(f)(1)(ii)(C)."
- "Each remedial action selected shall be cost-effective, provided that it first satisfies the threshold criteria set forth in 40 CFR 300.430 (f)(1)(ii)(A) and (B). A remedy shall be cost-effective if its costs are proportional to its overall effectiveness" (40 CFR 300.430 (f)(1)(ii)(D)).
- "Each remedial action shall utilize permanent solutions and alternative treatment technologies or resource-recovery technologies to the maximum extent practicable. This requirement shall be fulfilled by selecting the alternative that satisfies 40 CFR 300.430 (f)(1)(ii)(A) and (B) and provides the best balance of trade-offs among alternatives in terms of the five primary balancing criteria noted in 40 CFR 300.430 (f)(1)(i)(B)" (40 CFR 300.430(f)(1)(ii)(E)).

2.2 REMEDIAL ACTION OBJECTIVES

RAOs are site-specific initial cleanup objectives that have been established based on the nature and extent of contamination, potential for human and environmental exposure, and ARARs. The RAOs provide the basis for selecting appropriate response actions and remedial technologies, and for developing alternatives.

The following RAOs have been identified for groundwater at SS-28:

- Protect humans from unacceptable risk levels related to exposure by breathing vapor from or touching contaminated groundwater.
- Reduce groundwater concentrations of the COCs to their respective SRGs.
- Monitor the groundwater during the remedial treatment to ensure that the potential degradation products of the COCs do not exceed their respective MCLs.
- Restrict the use of groundwater so that it is not used for drinking water or showering purposes until the SRGs are met and the total groundwater cumulative risk allows for unlimited use and unrestricted exposure.

The COCs for groundwater at SS-28 and their SRGs are discussed in Section 2.4.

No remedial action is necessary for soil at SS-28 as discussed in Section 1.4.2.

2.3 PRELIMINARY EVALUATION OF APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS

The ARARs are local, state, and federal regulations that guide the selection of remedial alternatives. The NCP requires compliance with ARARs during, and at completion of, remedial actions. Identification of potential ARARs is performed on a site-specific basis. CERCLA, as amended by SARA, and the NCP do not provide across-the-board standards for determining whether a particular remedy will produce an adequate cleanup at a particular site. Rather, the process recognizes that each site will have unique characteristics that must be evaluated and compared to those requirements that apply under the given circumstances. Under CERCLA, permits for compliance with the Resource Conservation and Recovery Act (RCRA), NPDES, and Clean Air Act (CAA) regulations for on-site remedial actions are not required. CERCLA does require that the selected remedial alternative meet ARARs where possible. The remedial action

selected must meet all enforceable and applicable requirements unless a waiver from specific requirements has been granted.

An evaluation of state and federal requirements was conducted to identify the potential ARARs pertinent to groundwater remediation for SS-28. The ARARs are identified on a site-specific basis using a two-part analysis: (1) determining whether or not a given requirement is applicable and, if it is not applicable, (2) determining whether a requirement is relevant and appropriate.

Applicable requirements are cleanup standards, standards of control, and other substantive environmental protection requirements, criteria, or limitations promulgated under federal or state law that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance at a CERCLA site. Only those state standards that are identified by a state in a timely manner and that are more stringent than federal requirements may be applicable.

Relevant and appropriate requirements are cleanup standards and environmental protection regulations in accordance with federal or state law that do not directly and fully address a specific hazardous substance, contaminant, remedial action, location, or other circumstance at a CERCLA site, but address problems or situations similar to those encountered at the CERCLA site. Only those state standards that are identified in a timely manner and are more stringent than federal requirements may be relevant and appropriate (NCP, 1994).

To determine whether a requirement is relevant and appropriate, characteristics of the remedial action, the hazardous substances present, and the physical characteristics of the site must be compared to those addressed in the statutory or regulatory requirement. In some cases, a requirement may be relevant but not appropriate. In other cases, only part of a requirement will be considered relevant and appropriate. When it has been determined that a requirement is both relevant and appropriate, the requirement must be complied with to the same degree as if it were applicable (USEPA, 1988).

Remedial actions may have to comply with the following requirements (USEPA, 1988):

- **Chemical-Specific ARARs**—Health- or risk-based numerical values or methodologies that, when applied to site-specific conditions, result in the establishment of the acceptable amount or concentration of a chemical that may be found in, or discharged to, the ambient

environment. In general, chemical-specific requirements are set for a single chemical or closely related group of chemicals. These requirements typically do not consider mixtures of chemicals that might be found at CERCLA sites. For this reason, cleanup goals set at levels of single chemical-specific requirements may not adequately protect human health or the environment at a site. When this occurs, cleanup goals are set below the chemical-specific requirements (i.e., at more stringent levels).

- **Action-Specific ARARs**—Technology- or activity-based requirements of, or limitations on, actions taken with respect to the COC(s). These requirements are triggered by the specific remedial activities selected to accomplish a remedy. Action-specific requirements do not in themselves determine the remedial alternative; rather, they indicate how a selected alternative must be achieved (e.g., emission standards for air strippers and incinerators, UST regulations, or land disposal restrictions).
- **Location-Specific ARARs**—Restrictions placed on the concentrations of hazardous substances or the conduct of activities only because they occur in specific or sensitive locations (e.g., wetlands, areas of historical significance, or a federally regulated air facility).

"To be considered" (TBC) items are non-promulgated advisories, proposed rules, criteria, or guidance documents issued by federal or state government that are not legally binding and do not have the status of potential ARARs. However, these items are to be considered when determining protective cleanup levels where no ARAR exists or where ARARs are not sufficiently protective of human health and the environment.

Federal and state requirements for groundwater were considered to determine whether they were ARARs, based on site characteristics, site location, and the alternatives considered. Those requirements that were identified as ARARs are listed in **Table 2-1** (Potential Chemical-Specific ARARs), **Table 2-2** (Potential Action-Specific ARARs), and **Table 2-3** (Potential Location-Specific ARARs), and are briefly described below.

2.3.1 Chemical-Specific ARARs

Chemical-specific ARARs set health- or RBC limits or discharge limitations for specific hazardous substances, pollutants, or contaminants in various environmental media. These requirements generally set protective cleanup levels for COCs in the designated media or indicate a safe level of discharge that may be incorporated in a remedial activity (**Table 2-1**).

This FS takes a conservative approach by applying ARARs assuming potable use of shallow groundwater at SS-28 and that degradation products of the COCs will be detected in the groundwater during an active in situ remedial treatment. However, many factors indicate that potable use of Upland Deposits groundwater is unlikely at this site. These factors are discussed further in Section 4.2.2. The potential chemical-specific federal ARARs include:

- 40 CFR 122.26(a)(4) and 125.3(a), (c) and (f) —Provide for the monitoring and limitation of pollutant discharges from point sources into waters of the U.S. 40 CFR 122.26 relates to stormwater discharge permits, and 40 CFR 125.3 relates to technology-based treatment requirements in permits. Each of these citations would be applicable if the pump-and-treat remedial alternative was selected and effluent water was to be discharged to the JBA stormwater system. Although the substantive provisions cited above would apply to JBA, federal facilities are not required to obtain permits for on-base remedial activities.
- 40 CFR 141.61—Provides MCLs for select organic chemicals in drinking water. Primary drinking water regulations include health-based allowable concentrations of carcinogens and non-carcinogens in drinking water sources. For the site-specific COCs, the respective USEPA MCLs are the following:
  - Benzene: 5 µg/L
  - CTC: 5 µg/L
  - Chloroform: 80 µg/L (based on trihalomethane total)
  - 1,2-DCA: 5 µg/L
  - TCE: 5 µg/L
  - PCE: 5 µg/L
- For any alternative that includes enhanced bioremediation or natural attenuation as a part of the remedy, there is potential for degradation products of the COCs to temporarily exceed their respective USEPA MCL during the remedial treatment:
  - Methylene chloride: 5 µg/L (degradation product of CTC)
  - cis-1,2-DCE: 70 µg/L (degradation product of TCE)
  - Vinyl chloride: 2 µg/L (degradation product of TCE)

The potential chemical-specific State of Maryland ARARs include:

- Code of Maryland Regulations (COMAR) 26.08.02.03-2A, E, and G(2)—Establishes numerical criteria for toxic substances in surface waters.. This is applicable should a pump-and-treat remedial alternative be selected as the preferred treatment alternative. For the site-specific COCs, the respective surface water quality standards for drinking water and organisms are the following:

  - Benzene: 5 µg/L
  - CTC: 5 µg/L
  - Chloroform: 80 µg/L (based on trihalomethane total)
  - 1,2-DCA: 5 µg/L
  - TCE: 5 µg/L
  - PCE: 5 µg/L

- COMAR 26.11.06.06B(1)(b)—Provides general emissions standards and restrictions for air emissions from construction activities, vents, and treatment technologies such as air strippers. VOC emissions from any new source cannot exceed 20 pounds per day without treatment. This regulation would be applicable should an air stripper be utilized and vapors released as a part of the pump-and-treat remedial alternative.

The potential chemical-specific State of Maryland TBC criteria include:

- MDE Cleanup Standards for Soil and Groundwater Interim Final Guidance, Table 1 – Provides cleanup standards for groundwater and soil that represent concentration levels at which no further action would be required at a property by MDE. These standards would only be used if the compound does not have a federal cleanup criterion (i.e. MCL). This guidance would be applicable for any alternative that includes enhanced bioremediation or natural attenuation as a part of the remedy because of the degradation compound, chloromethane, does not have a MCL but has a MDE cleanup standard:

  - Chloromethane: 19 µg/L

2.3.2 Action-Specific ARARs

Action-specific ARARs are usually technology- or activity-based requirements or limitations on actions taken with respect to site remediation. These requirements are triggered by the particular remedial activities that are selected to accomplish an alternative. Because there are usually several alternative actions for any remedial site, various requirements may be applicable or relevant and appropriate. These action-specific requirements do not in themselves determine which remedial alternative will be selected; rather, they indicate how a selected alternative must be implemented.

The potential action-specific federal ARARs include:

- Standards applicable to generators of hazardous waste, 40 CFR Part 262, Subparts A, B, C, and D—General facility standards that provide for hazardous waste determination, waste manifest preparation, handling requirements, recordkeeping, and reporting. If the groundwater extraction and treatment alternative is selected, granular activated carbon containers may be used to collect VOC vapors and the waste containers will need to be handled appropriately.

The principal potential action-specific State of Maryland ARARs include:

- Air Quality Regulations Pertaining to VOC Treatment COMAR 26.11.06.01, .06, .08, and .09—Provides restrictions for VOC air emissions from construction activities, vents, and treatment technologies such as air strippers (26.11.06.06). Also includes nuisance (26.11.06.08) and odor control (26.11.06.09). This regulation would be applicable should an air stripper be utilized as a part of the pump-and-treat remedial alternative.
- Well Construction Standards, COMAR 26.04.04.16 to .23.A(2), and COMAR 26.04.04.34—Provide specifications for well construction (.16 to .23.A(2)) and well abandonment (.34).
- Maryland Underground Injection Control Program, COMAR 26.08.07.01—Prohibits any underground injection except as authorized by rule or permit. Applicable for the three injection alternatives.

The specific parts of the potential action-specific ARARs are identified in **Table 2-2.**

2.3.3 Location-Specific ARARs

Location-specific requirements set restrictions on activities depending on the characteristics of a site or its immediate environments. In determining the use of these location-specific ARARs for selection of remedial actions at CERCLA sites, one must investigate the jurisdictional prerequisites of each regulation. Basic definitions and exemptions should be analyzed on a site-specific basis to confirm the correct application of the requirements.

No identified wetlands or historic or cultural resources are present in the area. **Table 2-3** states that no potential location-specific federal, state, or local regulations associated with SS-28 have been identified.

2.4 CONTAMINANTS OF CONCERN AND SITE REMEDIATION GOALS

The COCs for groundwater at SS-28 were determined based on the HHRA presented in the Final RI Report (URS, 2013), which assumed that SS-28 groundwater would be used for potable purposes. Benzene, CTC, chloroform, 1,2-DCA, TCE, and PCE were recommended in Section 1.6.1 of the FS as the COCs in groundwater at SS-28.

Several remedial alternatives identified in this FS, such as monitored natural attenuation (MNA) or enhanced bioremediation of chlorinated ethenes and chlorinated methanes, could produce chloroform, methylene chloride, chloromethane, cis-1,2-DCE, and vinyl chloride as part of the primary degradation pathways involved in the remedial process. It can be reasonably expected that concentrations of these compounds may increase temporarily in site monitoring wells during the process of implementing the groundwater treatment alternatives. The concentrations of these compounds may also temporarily exceed their regulatory or risk-based cleanup criteria under potential remedial alternatives. Therefore, as a protective measure, methylene chloride, chloromethane, cis-1,2-DCE, and vinyl chloride will need to be monitored during the remedial treatment to ensure that these compounds do not exceed their respective MCL or groundwater standard if the selected alternative features enhanced bioremediation.

Table 2-4 summarizes the SRGs for groundwater at SS-28. The chemicals listed in **Table 2-4** require remediation and monitoring under the remedial alternatives evaluated in this FS. The SRGs for groundwater at SS-28 were determined based on the USEPA MCL for drinking water. Reducing the contaminant concentrations to SRGs will be protective under the residential scenario, which would allow unlimited use and unrestricted exposure to groundwater.

2.5 EVALUATION CRITERIA

Each remedial alternative should be developed to address potential threats to human health and the environment posed by contaminated groundwater. The NCP requires that the alternatives be evaluated against the nine criteria listed below:

- Threshold Criteria:
    1. Protection of human health and the environment.
    2. Compliance with ARARs.

- Balancing Criteria:
    3. Long-term effectiveness and permanence.
    4. Reduction of toxicity, mobility, and volume through treatment.
    5. Short-term effectiveness.
    6. Implementability.
    7. Cost.

- Modifying Criteria:
    8. State acceptance.
    9. Community acceptance.

The first two criteria are requirements that must be met unless specific ARARs are waived. Alternatives must be protective and comply with ARARs to be considered for a remedy. The next five criteria are balancing criteria, by which the relative advantages and disadvantages of the criteria are evaluated. The first seven criteria are addressed in this FS. The final two criteria are modifying criteria, in which the state and the community express whether they support or oppose the alternatives. These last two criteria are evaluated by the end of the public comment period and are not part of the FS.

Section 5.0 of this FS provides a discussion relative to criteria used to evaluate groundwater remedial alternatives and assesses the effects of implementing the remedial alternatives.

3.0 SCREENING OF TECHNOLOGIES AND DEVELOPMENT OF ALTERNATIVES

This section identifies and screens technologies applicable to remediation of the groundwater contamination at SS-28. In addition, this section also identifies the remedial alternatives that can satisfy the RAOs that are discussed in Section 2.2. The details of each alternative are discussed in Section 4.0.

3.1 GENERAL RESPONSE ACTIONS

General response actions are response categories that will satisfy the RAOs. General response actions applicable to the RAOs for groundwater at SS-28 include the following:

- No Action—No control or cleanup of groundwater contamination. Serves as a baseline for comparison.
- Land Use Controls (LUCs)—Restrictions on groundwater use or exposure at the site until contaminant levels are reduced to concentrations that allow for unlimited use and unrestricted exposure.
- Monitored Natural Attenuation (MNA)—Long-term monitoring of biological, chemical, and physical processes that reduce mass, toxicity, mobility, volume, or concentration of contaminants without active remediation.
- Groundwater Treatment—Physical, chemical, or biological measures applied to groundwater, either in situ or ex situ, that reduce the toxicity, mobility, and/or volume of the contaminants present.
- Groundwater Extraction—Recovery of contaminated groundwater using vertical wells with ex situ treatment and disposal of the treated water either to a surface water body under an NPDES permit or directly back into the aquifer by injection wells or infiltration galleries.

The following sections address the technologies and processes that could meet RAOs.

3.2 IDENTIFICATION AND SCREENING OF TECHNOLOGY TYPES AND PROCESS OPTIONS

The purpose of this section is to identify and screen remedial technologies and process options that could meet the RAOs for the groundwater contamination defined in Section 2.2 and the SRGs listed in **Table 2-4**. Remedial technologies are the methods by which a general response action

may be undertaken. Process options are the specific processes within a technology type by which the technology may be implemented.

The remedial technologies and process options evaluated in this section are presented in **Table 3-1** as either eliminated from further consideration or retained for detailed analysis based on technical implementability or potential feasibility at SS-28. A primary factor for determining the feasibility of each technology is its ability to be implemented at SS-28 without impeding airfield operations. Site access is limited and sporadic because of the highly active nature of the airfield. Thus, technologies that require frequent visits to the SS-28 site are not considered feasible. In addition, technologies that would require extensive subsurface modifications, such as trenching or installation of slurry walls or shoring or physically excavating soils beneath the flight line apron or building areas, are not considered feasible because their implementation would disrupt airfield operations or impact critical underground utilities. In addition, patching of the apron surface and installation of aboveground structures on the airfield must be minimized because of safety requirements inherent at SS-28. Technologies requiring frequent interference with airfield operations near the Presidential Air Group (PAG) facilities were not considered feasible in light of the current base mission. As shown in **Table 3-1**, the unique features of SS-28 precluded a number of applicable remedial alternatives for shallow groundwater plumes from consideration. The technologies that were retained for detailed analysis are discussed in the remainder of this section.

3.2.1 No Action

Under this option, no active groundwater remediation measures or LUCs would be implemented at SS-28. This alternative is required by the NCP and CERCLA to provide a baseline for comparison with the risk reduction achieved by other alternatives.

3.2.2 Monitored Natural Attenuation with Land Use Controls

MNA, sometimes referred to as intrinsic remediation, makes use of natural processes to reduce the concentration and mass of VOCs at an impacted site. This means that site contaminants are left in place while natural physical, biological, and chemical processes, such as dilution, volatilization, biodegradation, dispersion, adsorption, and chemical reactions with subsurface materials, are allowed to reduce contaminant concentrations to acceptable levels. MNA sampling normally

involves a more extensive suite of analyses than just the site COCs (i.e., VOCs). Constituents included in MNA sampling often include an array of geochemical analytes such as ferrous iron, sulfate, nitrate, chlorides, carbon dioxide, and TOC, all of which may increase or decrease in concentration depending upon the rate and degree of biodegradation or dechlorination that is occurring as a result of natural attenuation processes.

Although MNA has several advantages over active remedial technologies (less generation of wastes, less use of natural resources such as materials and energy, less intrusive, lower costs), unless contaminant levels are generally low or near the permissible drinking water standards, these advantages are often outweighed by the longer timeframes necessary to achieve remedial objectives. Along with the generally longer timeframe needed by MNA to achieve ARARs as compared to active technologies, natural degradation processes can sometimes stall at the lighter daughter products such as vinyl chloride, which is more toxic than its parent compounds, cis-1,2-DCE and TCE. However, if the geochemical conditions are favorable, MNA has the potential to achieve remedial objectives for TCE, CTC, and benzene (plus their respective daughter products).

As a result of the generally longer timeframes required to achieve remediation objectives through MNA, as compared to active remediation technologies, LUCs preventing groundwater use and exposure would be necessary at the site under the MNA alternative until contaminant amounts decline to acceptable levels. Based upon some of the potential advantages over other active remedial technologies, MNA with LUCs has been retained as a standalone alternative for comparative analysis at SS-28.

3.2.3 Enhanced Bioremediation

Bioremediation is a general term used to describe the destruction of contaminants by biological processes in which indigenous or specialized microorganisms degrade contaminants found in soil and/or groundwater. Although biodegradation of contaminants can occur in the subsurface naturally (as cited above), enhanced bioremediation can greatly reduce the timeframes required to achieve cleanup goals. Two components of enhanced bioremediation are biostimulation and bioaugmentation. Biostimulation attempts to accelerate the natural biodegradation processes by providing nutrients (electron donors or acceptors) to indigenous microbes to stimulate a rapid conversion of contaminants to innocuous end products. Biostimulation or enhanced

bioremediation is performed to ensure that the biological processes are not nutrient limited. During bioaugmentation, naturally occurring microbes that have demonstrated the ability to degrade contaminants, such as chlorinated solvents, are introduced into the subsurface. Under the proper geochemical conditions (i.e., low ORP, pH levels from 6 to 8, sufficient organic carbon), the introduced microorganisms will thrive, creating a population of microbes able to degrade the contaminants in situ.

Bioremediation can occur under aerobic or anaerobic conditions. Under aerobic conditions, microorganisms metabolize carbon sources and consume oxygen in order to function. Under aerobic conditions, less oxidized chlorinated compounds such as benzene, cis-1,2-DCE, and vinyl chloride can be oxidized by microorganisms to form innocuous compounds. Highly oxidized compounds such as TCE cannot be further oxidized by microorganisms. Under anaerobic conditions, limited oxygen is present and the microorganisms metabolize carbon sources and consume other chemical compounds in the soil or groundwater to obtain the energy they need. Highly oxidized compounds such as TCE and CTC can be reduced (dechlorinated) by microorganisms to less oxidized compounds if sufficient concentrations of dissolved hydrogen are present in the subsurface. Less oxidized chlorinated compounds such as chloroform, methylene chloride, cis-1,2-DCE, and vinyl chloride can also be further reduced if the right microorganisms are present. Chloride and ethene are the final byproducts of the complete reductive dechlorination process.

Enhanced bioremediation results in the reduction of contaminant mass in situ rather than transferring contamination to other locations (e.g., landfills or water treatment facilities) or phases (atmospheric vapors) for treatment.

3.2.3.1 Anaerobic In Situ Biodegradation (ISB) with In Situ Chemical Reduction (ISCR)

Anaerobic bioremediation is a well-documented technology that may be suited to in situ treatment of contaminants, depending on aquifer chemistry. Anaerobic bioremediation of chlorinated solvents (reductive dechlorination) requires an adequate supply of dissolved hydrogen in the groundwater and a low ORP. The addition of a carbon substrate provides material for facultative bacteria to ferment, producing hydrogen. Other bacteria consume the hydrogen (an electron donor) to reduce the following electron acceptors in the general order presented below:

DO > Nitrate [NO_3^-] > Ferric Iron [Fe(III)] and Manganese [Mn(IV)] > Sulfate [SO_4^{2-}] > Chlorinated Solvents > Carbon Dioxide [CO_2]

Many, but not all, chlorinated solvents are typically reduced concurrently with sulfate reduction. As the native microorganisms successively consume these electron acceptors, the ORP decreases and dissolved hydrogen concentrations increase. Common carbon substrates that promote anaerobic biodegradation alone or in combination include the following (Air Force Center for Engineering and the Environment [AFCEE], 2004):

- Molasses—A short-lasting substrate.
- Lactate—A short-lasting substrate.
- Glucose or fructose—Both short-lasting substrates.
- Hydrogen Release Compound (HRC®)—A short-lasting polylactate ester formulated for gradual release of lactic acid upon hydration.
- Vegetable oil—A long-lasting substrate.
- Emulsified vegetable oil (EVO)—A long-lasting substrate.
- Chitin and fibrous solid powders—A long-lasting substrate.

"Long-lasting" is defined in this FS as a carbon substrate that will maintain low ORP conditions in the groundwater for more than 2 years after injection. A "short-lasting" substrate is defined as a material that will maintain low ORP conditions for 2 years or less after injection. Short-lasting carbon substrates would not be used at SS-28 to minimize the number of injection events because of site access limitations. The carbon substrate can often be introduced into the subsurface using DP equipment, which eliminates the installation of semipermanent injection wells. Again, considering the SS-28 access limitations, this option would eliminate operation and maintenance (O&M) visits to the site to perform well rehabilitation activities associated with well fouling issues. Several of the commonly used commercial products that represent long-lasting carbon substrates include:

- EOS™ (Edible Oil Substrate), a mixture of a small amount of lactic acid, nutrients, and emulsified vegetable oil.
- SRS™, a 60% soybean oil emulsified substrate with Vitamin B12.

- 3-D Emulsion™, a mixture of a small amount of lactic acid, HRC®, and an esterified fatty acid.
- EHC® (Reduction Potential [Eh] Compound), a mixture of a powdered fibrous carbon and zero-valent iron (ZVI) that combines anaerobic biostimulation with abiotic chemical reduction of chlorinated solvents.

The use of anaerobic biostimulation is a proven and effective technology for the groundwater contaminants found at SS-28. It has been used in numerous soil and groundwater restoration projects in the United States to treat chlorinated solvents. In addition, anaerobic biostimulation has been successfully used at the FT-04 and FT-02 sites at JBA (URS, 2005; 2008; WESTON, 2013) and is currently being used at the ST-14 and Brandywine (SS-01) sites. It is widely accepted by regulatory agencies and can be applied quickly. The use of a long-lasting carbon substrate maximizes the treatment period and allows for the treatment of contaminants diffusing out of low-permeability zones in the subsurface. In addition, the use of a long-lasting carbon substrate with ZVI allows for the injection of the substrate in fewer rows and uses both biotic and abiotic degradation of contaminants (Dofling et al., 2008). Groundwater contaminants would be treated as they flow through these rows of injected substrate (referred to as "permeable biostimulation treatment zones" (PBTZs) in this document), which minimizes the number of injection points and rows. By combining a long-lasting carbon substrate with ZVI, strong reducing conditions are created, which often eliminates the requirement for bioaugmentation or the follow-up addition of specialty microorganisms or inoculants (Adventus, 2011). The use of ISB/ISCR amendments, such as EHC®, stimulate rapid and complete dechlorination of organic solvents by means of the following physical, chemical, and microbiological processes:

- Biological reduction/consumption of oxygen and other electron acceptors such as nitrate and sulfate caused by the biological oxygen demand generated by the addition of complex organic carbon.
- Direct chemical reduction of oxidized compounds by the reduced iron or indirectly by the formation of hydrogen, which is used by the dechlorinating bacteria as an electron donor (Scherer et al., 2000).
- Direct chemical oxidation by beta-elimination reactions and additional oxygen scavenging and reduced Eh by ZVI oxidation/reduction reactions.

The desired pH range for biostimulation to induce reductive dechlorination is 5.0 to 9.0 and the optimal pH range for biostimulation is 6.0 to 8.0 (AFCEE, 2004). Groundwater pH observed at the site during the RI field work ranged from 3.88 to 6.52. The majority of the groundwater was observed in the pH range of 4.13 to 6.52 with an average pH at the site of 4.88. One monitoring well, MW07d, had a pH that was below 4 during the RI field efforts. This pH is believed to be an anomaly after reviewing the pH values recorded during the well's development. The well development log for MW07d presented data that suggested the system pH is closer to 4.31 (URS, 2013). Therefore, the groundwater aquifer system has a natural pH range of 4.0 to 6.5, which is just outside of the optimal pH range for biostimulation. Because the use of a carbon substrate can further reduce groundwater pH through the production of organic fatty acids, a buffer or alkaline additive may be necessary to increase the pH in the PBTZs to more than 5.0. Anaerobic ISB/ISCR has been retained for comparative analysis with other feasible remedial technologies at SS-28.

3.2.3.2 Bioaugmentation

Bioaugmentation can be an effective treatment method when indigenous microbes are present in small numbers or are not able to biodegrade a specific contaminant. Bioaugmentation involves the addition of microbial cultures of naturally occurring dechlorinating bacteria to the subsurface to perform a specific remediation task in a given environment. The microbes are usually injected using DP equipment. Bioaugmentation can establish anaerobic dechlorinating bacteria at sites to stimulate reduction of contaminants and to accelerate biodegradation rates to meet treatment goals. Bioaugmentation is usually undertaken when the population of suitable dechlorinating bacteria is absent or low. DHC is the only bacteria species known to completely dechlorinate PCE or TCE to ethene; other dechlorinating bacteria, such as Dehalobacter, are only capable of reducing PCE or TCE to cis-1,2-DCE. The lack of DHC bacteria is a common reason for "DCE stall" (the incomplete dechlorination of DCE to ethene) at sites contaminated with chlorinated solvents (ESTCP, 2005). The native DHC populations detected in the SS-28 groundwater samples during the RI field work ranged from 11.2 to 20.6 cells/mL. The ideal DHC population for sustainable reductive dehalogenation in the subsurface needs to be at least 10^4 cells/mL (ESTCP, 2011); however, populations ranging from 10 to 1,000 cells/mL have shown potential for complete dechlorination, provided that an electron donor is supplied to the subsurface and that vinyl chloride reductase genes are present (Lu, et. al, 2006; Krajmalnik-Brown, et. al., 2004).

CTC can be degraded by a variety of anaerobic bacteria; however, its initial daughter product, chloroform, has been identified as a potential inhibitor of DHC biodegradation of chlorinated ethenes at chloroform concentrations exceeding 50 µg/L (Duhamel et al., 2002). Fortunately, Dehalobacter is capable of effectively biodegrading chloroform and dichloromethane (the next CTC daughter product) to acetate (Grostern et al., 2010 and Lee et al., 2011). Once the chloroform concentrations are reduced below 50 µg/L, the DHC will be able to biodegrade TCE and its daughter products with no inhibition.

For the plume areas where both TCE and its daughter products are comingled with chloroform, the bioaugmentation will need to utilize a mixed bacterial culture containing DHC and Dehalobacter. Both DHC and Dehalobacter mixed cultures are commercially available, so bioaugmentation has been retained for comparative analysis with other feasible remedial technologies at SS-28.

3.2.3.3 Aerobic In Situ Biodegradation with Oxygen Releasing Compounds

Aerobic bioremediation involves microbial reactions that require oxygen. The bacteria use a carbon substrate as the electron donor and oxygen as the electron acceptor. Under aerobic conditions and in the presence of appropriate nutrients, microorganisms can convert many organic contaminants to carbon dioxide and water. Aerobic metabolism is commonly exploited for remediation and can be effective for petroleum hydrocarbons and fuel oxygenates such as MTBE. Many organisms are capable of degrading hydrocarbons using oxygen as the electron acceptor and the hydrocarbons as carbon and energy sources.

Aerobic bioremediation is most often used at sites with mid-weight petroleum products (e.g., diesel fuel and jet fuel), because lighter products such as gasoline tend to volatilize readily and can be removed more rapidly using other technologies. Heavier petroleum products, such as lubricating oils, generally take longer to biodegrade than the lighter products, but enhanced aerobic bioremediation technologies may still be effective. It is generally not practical to use enhanced aerobic bioremediation technologies to address free product or petroleum contamination in low permeability soil (USEPA, 2004).

Enhanced aerobic bioremediation technologies include biosparging, bioventing, and the use of oxygen releasing compounds. These technologies work by providing a supply of oxygen to the subsurface, which becomes available to aerobic, hydrocarbon-degrading bacteria. Oxygen is considered to be the primary growth-limiting factor for hydrocarbon degrading bacteria, but it is normally depleted in zones that have been contaminated with hydrocarbons. By using these technologies, rates of biodegradation of petroleum hydrocarbons can be increased at least one, and sometimes several, orders of magnitude over naturally-occurring, non-stimulated rates.

Commonly used oxygen releasing compounds include calcium and magnesium peroxides (e.g., PermeOx® and ORC®) that are introduced to the saturated zone in solid or slurry phases. These peroxides release oxygen to the aquifer when hydrated by groundwater as the peroxides are ultimately converted to their respective hydroxides. Magnesium peroxide has been more commonly applied in field applications than calcium peroxide because of magnesium peroxide's lower solubility and, consequently, prolonged release of oxygen. Magnesium peroxide formulations placed in the saturated zone during a short-term injection event can release oxygen to groundwater over a 4- to 8- month period. Oxygen releasing compounds may be introduced into the saturated zone by various methods, including injecting a slurry using DP borings and by releasing the compounds from "socks" in monitoring wells.

3.2.4 In Situ Chemical Oxidation

In situ chemical oxidation (ISCO) technology for the remediation of contaminated groundwater has gained widespread acceptance and development over the past 15 years. The use of permanganates for the destruction of chlorinated ethene DNAPLs such as PCE and TCE by oxidation has been demonstrated in various batch, column, and field experiments (Schnarr et al., 1998). ISCO involves the injection of chemical oxidants (and potentially co-amendments or catalysts), directly into the source zone and portions of the downgradient plume. The oxidant chemicals react and destroy the contaminants in place, producing innocuous bi-products such as carbon dioxide, water, and inorganic chloride (Interstate Technology and Regulatory Council [ITRC], 2005). The most commonly used oxidants for ISCO include the following:

- Permanganates ($NaMnO_4$ or $KMnO_4$)—Persistently reactive (>3 months) powder or liquid and well-developed technology.

- Persulfate/Activated Persulfate ($S_2O_8^{2-}$ or SO_4)—Moderately persistent (hours to weeks) powder or liquid as an established technology.
- Hydrogen Peroxide/Fenton's Chemistry (H_2O_2)—Strong, rapid oxidant but limited persistence (minutes to hours), liquid. Widely used in the wastewater industry for years ex situ, with developing in situ applications.
- Ozone (O_3, OH^-)—Strong, rapid oxidant but limited persistence (minutes to hours), gas. Limited application primarily in soils but developing and emerging technology.

For ISCO to effectively destroy contaminants, the oxidant must come into direct contact with the contaminant molecules. Another consideration is natural oxidant demand, which refers to the consumption of an oxidant due to reactions related to the organic and inorganic components in the matrix (soil or groundwater). As a result, the selection of the oxidant to use at a site is greatly dependent on the site conditions such as the aquifer permeability, size, and concentration of the contaminant target, and the persistence of the oxidant in that environment. For example, strong rapid oxidants, such as hydrogen peroxide, are well suited to treating small DNAPL source zones in moderately permeable settings. As a result of their low reactive persistence, they would not remain effective in low permeability settings in which achieving direct contact is problematic. Whereas permanganates, although generally weaker oxidants than peroxide, have much greater persistence in the subsurface and can diffuse into low permeability materials and be transported over greater target distances.

Following a review of the available oxidants applicable to SS-28, sodium persulfate ($Na_2S_2O_8$) has been retained as a remedial alternative for the site. Dissolution of sodium persulfate results in the formation of the persulfate ion ($S_2O_8^{2-}$) and two sodium ions (Na^+). The persulfate anion ($S_2O_8^{2-}$) is a strong oxidant, which itself can degrade many environmental contaminants or it can be catalyzed with various reactants to form the more powerful sulfate radical. The use of persulfates in groundwater treatment applications is a technology developed for use with BTEX contaminants and CTC, which are not amenable to oxidation using other persistent oxidants such as permanganate. In addition, persulfate does not appear to react as readily with soil organic matter as permanganate, suggesting that the natural oxidant demand for persulfate is low (Brown and Robinson, 2004). Persulfate is also more stable in the subsurface than peroxides (H_2O_2) or ozone (O_3) and will remain persistently reactive in the subsurface for weeks (Huang et al., 2002).

Persulfate activation is required to convert the persulfate into the highly reactive persulfate radical, a very strong oxidant capable of destroying a wide range of contaminants. Selection of the persulfate activation method, however, depends on many factors, including the target contaminants, lithology, hydrogeology, and other specific site conditions such as presence of structures or underground utilities. Potential persulfate activators include the following:

- Metals and chelated metals—Ferrous iron (Fe (II)) is the most common metal incorporated in this activation method. Chelated iron provides efficient activation while maintaining persulfate longevity within the subsurface. The use of a chelating agent, such as ethylenediamine tetra-acetic acid (EDTA) or citrate, helps to maintain iron solubility and transportability at elevated pHs. Determination of the amount of iron needed is straightforward and dependent on the volume of groundwater to be treated.
- Heat—Heating the post-injection system to temperatures exceeding 40° C results in the production of highly reactive sulfate free radicals from the injected persulfate, which can speed up the contaminant degradation kinetics as the contaminants are oxidized.
- High pH (alkaline)—High pH activation is known to generate super oxide radicals, providing a source of reductive species capable of destroying compounds such as CTC, as well as the chlorinated ethenes, BTEX, TPH, and MTBE. The alkalinity can also provide additional benefits by increasing desorption of contaminants from soil surfaces or aiding in the dissolution of non-aqueous phase liquids (NAPLs) for better contact with the persulfate. The target pH for proper activation is in the range of 10.5 to 12.
- Peroxides—Peroxides, such as hydrogen peroxide, through reaction with persulfate and generation of heat due to decomposition, activates persulfate rapidly through the peroxide reacting with the persulfate and generation of heat due to decomposition, providing an aggressive approach to treating recalcitrant compounds; however, this can result in a shortened persulfate lifetime in the subsurface.

The mechanism for sodium persulfate oxidation of contaminants is direct oxidation and free radical formation. Direct oxidation involves utilizing the oxidation capacity of the persulfate ion itself, converting to the sulfate ion (SO_4^{2-}) upon reaction. This oxidation method is capable of oxidizing VOCs, including benzene-based and CTC-related compounds. In these reactions, several byproducts, including carbon dioxide, sulfate, chloride, and hydrogen ions, are generated and released to the groundwater. The byproducts of this reaction are not expected to pose water quality problems because most of the byproducts are either innocuous or will readily react with aquifer material and subsequently stabilize. In situ persulfate oxidation technology using alkaline-

activated sodium persulfate has been retained as an option for the remediation of the benzene-impacted regions of groundwater within the SS-28 site.

3.2.5 Pump and Treat Using Vertical Extraction Wells to Recover Contaminated Groundwater for Ex Situ Treatment and Disposal

Groundwater pump and treat technology has been widely used in the remediation industry for decades, offering the combined advantages of hydraulic containment of contaminant plumes while also recovering contaminants from the subsurface for ex situ treatment. The downside of pump and treat technology is that the process relies on multiple pore flushes to remove contaminants from the groundwater and aquifer matrix. As a result of the relatively low aqueous solubility of most VOC compounds, especially if DNAPL source material is present, it can take decades or longer to clean up a groundwater plume if the DNAPL is not able to be removed. Additional obstacles to pump and treat technology are subsurface heterogeneities or low permeability aquifers where slow groundwater velocities and matrix diffusion make contaminant recovery very inefficient. Groundwater pump and treat technology can also require significant O&M costs over the life of a project. Issues such as well fouling, pump maintenance, mechanical failures, and the ex situ treatment system maintenance all contribute to generally extensive O&M activities. Treated water disposal, permitting, and sampling operations are also factored into the long-term life cycle costs of this technology.

Despite the other downsides of pump and treat technology cited above, historical groundwater concentrations from SS-28 do not indicate the presence of DNAPL. In addition, the hydrogeologic setting at the site is shallow (< 35 to 40 feet bgs), consisting primarily of sands and gravels with some minor silty lenses. Under these conditions, pump and treat technology may represent a viable remedial option for the site, capable of achieving the groundwater cleanup goals in a reasonable timeframe. Although the installation and operation of numerous vertical groundwater recovery wells in the elevated portion of the contaminant plume at SS-28 is not feasible (because of the sensitivity to airfield operation disruptions), vertical well technology coupled with ex situ treatment and disposal is a viable remedial alternative for the site. As a result, pump and treat technology using vertical well(s) has been retained as a remedial alternative for further evaluation.

3.2.5.1 Air Stripping and/or Granular Activated Carbon Treatment and Disposal

Air stripping is a mass transfer process that typically uses a cylindrical column containing a high surface area packing material. Air blowers force air upward from the base of the stripper column while the untreated water is sprayed into the top of the stripper column. As the water and air move concurrently through the packing media, VOCs are stripped or transferred to the air stream and the clean water flows out the base of the column. Shallow tray and venturi-type air strippers are also available commercially that have a low-profile design when vertical limitations on space are an issue, such as at an airfield. The stripped VOCs are usually treated by a granular activated carbon (GAC) adsorption system or thermal/catalytic oxidation system. The need for additional VOC removal treatment of the air discharge is dependent on the permissible state or federal air discharge limits, the treatment flow rate, and the groundwater concentrations.

Air stripping is effective for removing a wide range of VOCs from the aqueous phase (e.g., TCE, CTC, benzene, and associated breakdown products). The effectiveness of air stripping technology depends on the types and concentrations of the compounds to be removed as well as the overall groundwater chemistry. Air stripping with off-gas polishing using GAC adsorption is a proven technology that has been used for decades in conjunction with the recovery of contaminated groundwater prior to disposal. Because of the potential for interference with airfield operations at SS-28, low-profile air strippers would likely be a necessary approach for the pump and treat alternative. Typical column-style air strippers are normally 30 feet or more in height; however, low-profile air strippers (preferred for this site due to Unified Facilities Criteria (UFC) 3-260-01 structure height restrictions of 35 feet above ground level) are typically less than 10 feet tall. A pretreatment process may not be necessary because of the low iron levels in the site groundwater detected during the RI field efforts (average 1.86 mg/L). A pretreatment process would remove iron prior to air stripping in order to prevent premature fouling of the stripper packing material. Air stripping technology has been retained for comparative analysis with the other feasible remedial technologies at SS-28.

3.2.5.2 Disposal to Stormwater Sewer System or Surface Water by NPDES Permit

Disposal of the treated groundwater to either the local stormwater sewer system or nearby surface water body by an NPDES permit are viable options for SS-28. Depending on the local stormwater

regulations or state surface water regulations, both options are likely to require regular monthly sampling and analysis of the treated discharge to document the removal of VOCs or possibly metals constituents to permissible levels. The regular sampling of the treated discharge is normally incorporated into the site O&M plan and analytical results are provided to the state agency through monthly NPDES reports. It is assumed that the local stormwater regulations would require a similar level of documentation for compliance purposes. These disposal options will be retained for further evaluation under the pump and treat alternative for SS-28.

4.0 DESCRIPTION OF REMEDIAL ALTERNATIVES

This section presents descriptions of the rationale, conceptual design, and performance monitoring of the retained remedial alternatives for the treatment of the groundwater contamination at the SS-28 site. For each alternative, the SRGs or achievement of ARARs (drinking water MCLs) were used to estimate the remedial timeframe to cleanup so that specific details of each alternative could be quantified and compared. A detailed comparison of the retained alternatives and their ability to achieve SRGs is provided in Section 5. The following five remedial alternatives have been retained for evaluation and developed for the SS-28 site:

- Alternative 1 – No Action
- Alternative 2 – Monitored Natural Attenuation with Land Use Controls
- Alternative 3 – In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls
- Alternative 4 – In Situ Chemical Oxidation and In Situ Biodegradation with Land Use Controls
- Alternative 5 – Groundwater Extraction and Treatment Using Wells with In Situ Biodegradation and Land Use Controls

4.1 ALTERNATIVE 1 – NO ACTION

The No Action alternative assumes no active remedial measures or LUCs would be implemented. This alternative is required by NCP and CERCLA to provide a baseline for comparison of risk reduction potentially achieved by other remedial alternatives.

4.2 ALTERNATIVE 2 – MONITORED NATURAL ATTENUATION WITH LAND USE CONTROLS

Alternative 2 involves the monitoring of natural attenuation processes at the site while maintaining LUCs that restrict the use and exposure to groundwater until SRGs are achieved. As summarized in Section 3, natural attenuation includes a number of physical, biological, and chemical processes that reduce the mass, toxicity, mobility, and concentration of contaminants without human intervention. These naturally occurring processes of biodegradation, volatilization, dispersion, and

dilution can reduce contaminant concentration to acceptable levels, given enough time. MNA is a remedial alternative that evaluates and tracks the rate at which these natural processes are occurring. The LUCs component of this remedial alternative prevents human exposure to contaminated groundwater by maintaining the existing prohibitions on potable uses of groundwater at JBA and other ICs to prevent exposure to contaminated groundwater, as described in Section 4.2.2.

A preliminary steady state groundwater flow and contaminant transport model was constructed for SS-28 using available site-specific geochemistry, hydraulic testing results, and published degradation rates for TCE, CTC, and benzene (**Appendix B**). The purpose of the model was to estimate and compare the predicted time to cleanup for each of the retained alternatives for the site. Based upon the results of the modeling effort, it was estimated that the COC concentrations at the site could naturally attenuate to the site SRGs of 5 µg/L in 40 years. This estimate is based on a degradation half-life of 3.2 years for TCE because TCE has a longer degradation half-life when compared to CTC (48 days) and benzene (58 to 693 days) (United States Geological Survey [USGS], 2006; Aronson et al., 1999) (see **Appendix B** for half-life discussion). This estimate also assumes that there is no area on-site that serves as a continuing source releasing VOCs to groundwater. The presence of both CTC and its breakdown daughter products (chloroform, methylene chloride) within the site plume suggests that some naturally occurring biotic or abiotic degradation processes are likely active at the site; however, the average pH value of the groundwater at the SS-28 site (4.88 [URS, 2013]) is below the optimal range of 6.0 to 8.0 for biological degradation of chlorinated VOCs (AFCEE, 2004). In addition, the measured values of ORP in the site groundwater are generally positive, suggesting that the groundwater system is fairly aerobic in nature, which are less than optimal conditions for natural biodegradation of chlorinated VOCs. These existing geochemical conditions at SS-28, however, are more favorable for the natural attenuation of the benzene plumes. Benzene half-lives reported in technical literature for aerobic environments range from 58 to 693 days (Aronson et al., 1999). Therefore, benzene is expected to naturally attenuate faster than TCE and CTC at SS-28.

Based on the TCE degradation rate, the estimated timeframe to site cleanup for the No Action and MNA/LUCs alternatives is greater than 40 years.

4.2.1 Rationale for Alternative Selection

Despite a potentially long timeframe to achieve site cleanup, the MNA with LUCs alternative would be protective of human health because of the restrictions placed on groundwater use and exposure. In addition, groundwater conditions would be monitored and evaluated on a regular basis to determine when SRGs have been achieved and LUCs can be safely lifted. As a result, this alternative forms a basis with which to compare the remaining active remedial technologies.

As discussed in Section 1.5, there is limited evidence of biologically-mediated reductive dechlorination of the chlorinated VOCs due to the lack of degradation products (i.e. cis-1,2-DCE and vinyl chloride for TCE, methylene chloride and chloromethane for CTC), and the subsurface not having optimal geochemical conditions for a sustainable microorganism population needed for this type of degradation. While the selection of this alternative may be ideal in terms of it dealing with the least interference with airfield operations, it might not be the most viable or effective due to the current state of the groundwater plume and subsurface conditions.

4.2.2 Conceptual Design

As part of the monitoring component of this alternative, selected wells located down the centerline of the individual plume segments would be sampled and analyzed on an annual basis, and 5-year reviews would be conducted of the MNA program. The MNA program would remain in effect for 40 years or until contaminant concentrations decrease to levels below the SRGs (**Figure 4-1**). In general, samples collected from these indicator wells would be analyzed for VOCs and MNA parameters. In addition, EPA's guidance document entitled *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water* (USEPA, 1998) would be used to ensure that site conditions promote natural attenuation and that site contaminants are degrading and their concentrations are decreasing over time. Under Alternatives 2 through 5, LUCs would be implemented with the goal of preventing exposure of site users and workers to contaminated groundwater at the site, including preventing direct contact and ingestion, preventing inhalation of vapors, and preventing dermal/inhalation exposure during construction activities. The proposed LUC boundary for Alternatives 2 through 5 is depicted in **Figure 4-1**. LUCs may include the following:

- Prohibit drinking of or other human contact with surface water or groundwater. Review of Work Orders and Dig Permits by JBA environmental staff would ensure that potable groundwater wells are not installed at SS-28 and that no construction or excavation activities would be permitted within the area without written authorization by the USAF.
- Prohibit residential use of the site unless (1) a supplemental risk assessment shows VI concentrations allow for unlimited use and unrestricted exposure, or (2) any construction on the site requires mitigation measures that achieve unlimited use and unrestricted exposure.
- Include the LUCs at SS-28 in the Installation Development Plan (IDP). SS-28 would be designated as a "land use control" area in the Land Management map layer of the Base Geographical Information System. This designation prohibits activities such as residential development and potable use of groundwater.
- Review and approve of any proposed land use changes, including construction of new facilities or additions to existing facilities at SS-28, by the JBAs Facility Review Board and the environmental staff.
- Review of proposed construction activities by JBA environmental staff through the Environmental Impact Analysis Process (EIAP) and National Environmental Policy Act (NEPA) design reviews of the proposed construction.
- Post signs at the site identifying SS-28 as a CERCLA site and stating that construction, excavation, and groundwater use are prohibited.
- Restrict access to the site to only authorized base and environmental personnel. SS-28 is partially enclosed by a security fence controlled by JBA security personnel.
- Review of work orders and excavation permits by environmental and civil engineering personnel at JBA to ensure continued enforcement of the LUCs.

Annual inspections/monitoring of LUCs would be performed to ensure that they are being protective. The following subsections describe the monitoring program, including the performance goals, rationale for the monitoring well network, analytical protocols and sampling frequency, and anticipated duration of the MNA component of the alternative.

4.2.2.1 Green and Sustainable Practices

A preliminary assessment of the energy consumption, gas emissions, resource consumption, and environmental benefits for Alternative 2 was performed using the software program SiteWise™. Based on the preliminary assessment, the greatest environmental impacts that would occur while

implementing this alternative would be from gas emissions from equipment use and transportation during regular annual sampling events. The transportation gas emissions could be reduced by using biofuel vehicles instead of regular gasoline trucks and by reducing the number of vehicles used for transportation. The equipment gas emissions could be reduced by using batteries that could be charged from the electrical grid or solar power instead of a diesel- or gasoline-powered generator to operate the groundwater sampling pump. An assessment of the environmental benefits would be included in the final remedial action completion report (RACR) should this alternative be selected for this site.

4.2.3 Performance Monitoring

A groundwater monitoring program would be implemented at the site to track potential changes to groundwater flow and plume extent, the rate and degree of VOC decline, and the geochemical changes that would occur in the aquifer over time. The scope of the monitoring program was used for formulating the cost estimate for the alternatives comparison and is based on an estimated 40-year timeframe for achieving the SRGs.

A total of three additional rounds of VI monitoring would be conducted at Buildings 1201 and 1287 to support the remedial design and help evaluate post-injection VI conditions. The first round will be conducted during the remedial design phase. The results from this baseline round would assist in the design of the selected remedy. The latter two monitoring rounds would occur once the remedy is implemented to monitor the changing subsurface conditions. Indoor air (five locations), sub-slab (3 to 4 locations) and ambient outdoor air (one location) samples would be collected and analyzed for VOCs (all COCs and degradation products) from each building. These results will be compared to the appropriate residential and industrial screening levels. The sub-slab locations will be installed during the round of baseline sampling as permanent ports so the locations can be resampled at later events. The monitoring rounds would be conducted during heating or cooling seasons and in separate years to show seasonal variation and possible temporal trends.

4.2.4 Performance Monitoring Goals

The performance goals for the groundwater monitoring program include tracking the changes in contaminant concentrations throughout the plume and evaluating the extent to which natural attenuation processes are acting to reduce VOC levels. In addition, whereas the contaminant plume is likely in a steady state condition (i.e., slowly retracting in area and declining in concentration), the monitoring program would be used to verify that plume expansion or migration is not occurring. The degradation rates will be calculated once data is available. The rates will be compared to the remedy's estimated cleanup time to assess if the remedy is progressing as anticipated. If not, then treatment would need to be optimized to assure the estimated cleanup time is met. Ultimately, the overall objective of the monitoring program is to determine when contaminant levels in groundwater have declined below the SRGs, whereupon LUCs can be lifted at the site.

4.2.4.1 Performance Monitoring Network

The monitoring well network for the site would consist of approximately 15 existing and eight new wells located primarily down the centerlines of the plume segments (i.e., TCE, CTC and benzene plume segments) and in regions that will help determine the extent of the contamination as the remedy is implemented. One such configuration is shown in **Figure 4-1**.

A total of eight new monitoring wells would be installed within the SS-28 site boundaries and added to the performance monitoring network in order to monitor the contaminants and assess treatment effectiveness during the monitoring period. One new monitoring well location is proposed south of Building 1206 near South Dakota Avenue in the area of the highest concentrated portion of the chlorinated solvent plume. Three new monitoring wells are proposed in the downgradient region of the anaerobic ISB injections as a part of the performance monitoring program for the alternative. The remaining four new monitoring well locations will be determined during the remedial design stage, based on future monitoring data, site accessibility, and plume configuration.

Samples would be collected according to the specific monitoring needs developed in the remedial design work plan for the selected alternative. The final configuration of the monitoring well network would be included in the remedial action work plan for the site. This configuration would

be determined through discussions with USEPA and MDE and evaluations of the network through environmental decision support software such as Visual Sample Plan or Optimal Well Locator.

Throughout the course of the remedy implementation, the network of monitoring wells in the monitoring program might change as areas of the site cleanup and other locations are deemed more appropriate for measuring the effectiveness of the alternative.

Monitoring of the 23 proposed locations is assumed for the purpose of estimating the costs of the monitoring programs for each of the alternatives presented in this FS.

4.2.4.2 Analytical Protocol

The wells included in the monitoring program for Alternative 2 would be sampled for VOCs and a suite of parameters that are considered useful in evaluating the degree to which destructive or non-destructive natural attenuation processes are occurring. The VOC analytical suite will include the possible degradation products of the COCs, as these compounds are anticipated to temporarily increase in concentration during the remedial treatment as the COCs degrade. Monitoring these degradation compounds will help calculate the dechlorination rate. These natural attenuation parameters include anions (NO_3^-, SO_4^{2-}, chlorides), dissolved gases (methane, ethene, and ethane), TOC, sulfide, alkalinity, and ferrous iron and/or manganese. The iron and manganese parameters are included to track potential metal concentration increases related to geochemistry changes caused by the substrate injections. Field measurements such as ORP, DO, and pH would be collected during purging/sampling activities. When a significant database of geochemical parameters for the site groundwater has been established (i.e., following six to eight rounds of sampling), the scope of the laboratory MNA sampling list would likely be reduced to include only the analytes determined to be critical in evaluating the ongoing effectiveness of the remedy. As an example, for the active remedial alternatives designed to stimulate biodegradation (Alternatives 3 and 4), sampling for DHC populations would be an important analyte with which to measure performance in the early years of remedy implementation.

4.2.4.3 Sampling Frequency and Duration of Monitoring

Sampling frequency would be annual for 40 years for the MNA with LUCs alternative. Annual sampling is considered a sufficient sampling frequency for Alternative 2 because of the non-active

nature of the MNA with LUCs alternative and the extended timeframes associated with the monitoring program.

4.3 ALTERNATIVE 3 – IN SITU BIODEGRADATION AND IN SITU CHEMICAL REDUCTION WITH LAND USE CONTROLS

Alternative 3 involves the direct injection of a water-dispersible, long-lasting carbon substrate with iron and pH buffer into the higher concentrated portions of the plume near the release areas in the building region. The aqueous formulation is designed to promote both in situ biological reductive dechlorination and chemical reduction of the contaminants in the site groundwater, while also providing a pH buffering effect. These injection locations will include a bioaugmentation option, which would involve the injection of DHC and Dehalobacter inoculants to boost the populations of dechlorinating microorganisms in the site groundwater. The proposed alternative would achieve the SRGs within 20 years of remedy implementation.

A number of physical, chemical, and microbiological processes would be stimulated to create very strong reducing conditions that promote the rapid and complete dechlorination of organic solvents following the injection of the ISB/ISCR amendment. The long-lasting carbon substrate is nutrient rich and contains high surface area, which supports the growth of indigenous, heterotrophic bacteria. As reported in the RI report, the native DHC populations are considered to be below the levels considered “optimal” for effective biodegradation (URS, 2013). These bacteria consume oxygen as they grow and reduce the ORP in the site groundwater. As the bacteria grow, they ferment the available carbon and release a variety of fatty acids and hydrogen, which diffuse into the groundwater and serve as electron donors for anaerobic, dechlorinating bacteria such as DHC. The pH buffer would help to stabilize the groundwater pH within the pH range preferable for DHC growth. In addition to these biological processes, ZVI would stimulate the direct chemical reduction of oxidized compounds and a further drop in the ORP of the groundwater through chemical oxygen scavenging. These abiotic chemical reactions also would result in the formation of hydrogen that is used by DHC bacteria as an electron donor (Scherer et al., 2000).

The combination of these physical, chemical, and biological processes often results in extremely low ORPs in groundwater following ISB/ISCR treatment (ORP values down to -550 mV have been reported), which stimulates the dechlorination of otherwise persistent compounds such as

DCE or vinyl chloride. As a consequence, ISB/ISCR technology frequently avoids the accumulation of biodegradation intermediates and eliminates the need for bioaugmentation, often achieving complete mineralization of contaminants through beta elimination pathways (Adventus, 2008). This is potentially a significant factor at SS-28, which, like other remediation sites at JBA (SS-27, FT-02), has been shown to contain initial populations of DHC bacteria that are too low (less than 100 cells/mL) to completely dechlorinate TCE to ethene within reasonable timeframes (URS, 2008). ISB/ISCR amendments could provide long-lasting biotic and abiotic degradation of the site plume (remains active in the subsurface for 3 to 5 years), which would minimize the effects of contaminant rebound and reduce the need for re-applications requiring repeated site visits. If during the post-injection sampling period there is evidence of contaminant rebound or increasing unfavorable geochemical conditions, re-application of the ISB/ISCR amendment would be considered in order to achieve the cleanup criteria within the specified timeframe.

A noted advantage of using a persistent amendment is its ability to counteract the effects of reverse matrix diffusion. When the more permeable areas of the aquifer become depleted of contaminants, the contaminant mass contained in the silt/clay lenses that exist within the Upland Deposits would begin to diffuse back into the sands and gravel. The persistently reactive amendment would then be able to react with these contaminants and the effects of contaminant rebound would be reduced or negated.

Bioaugmentation or introduction of DHC and Dehalobacter inoculants would be implemented with the initial injection of nutrients and pH buffer in order to increase the rate of dehalogenation at the start of the remedial action. Bioaugmentation has been retained for this alternative at SS-28 based on varying results from other cleanup sites at JBA where enhanced bioremediation has been implemented. Bioaugmentation was deemed necessary at nearby sites SS-27 and FT-02 where the populations of DHC bacteria were determined to be insufficient for complete dechlorination of TCE through ethene within a reasonable timeframe. This alternative would also feature a series of ISB injections located downgradient of the building region and in the grassy portions of the airfield. These injections would include a small-scale aerobic ISB injection near Taxiway W2 and at least four treatment zones of anaerobic ISB injections between Taxiway W2 and Pad 94. The small scale aerobic ISB injection would address the observed benzene plume detected in a series of DPT samples (ranging from 32 to 910 µg/L) located south of Taxiway W2 during the RI. At

least four treatment zones of anaerobic ISB amendment would address the leading edges of the chlorinated solvent plume, where the highest TCE concentration observed during the RI was 35 µg/L from a DPT groundwater sample. The anaerobic ISB injections would help prevent the plume from extending further downgradient towards Piscataway Creek. Additional injection events for these regions would be determined based on the results of the post-injection monitoring rounds.

A total of eight new monitoring wells would be installed within the SS-28 site boundaries in order to monitor the contaminants and assess the treatment effectiveness during the post-injection monitoring period. One new monitoring well is proposed to be located south of Building 1206 near South Dakota Avenue in the area of the highest concentrated portion of the chlorinated solvent plume, as shown in **Figure 4-2**. Three new monitoring wells are proposed in the downgradient region of the anaerobic ISB injections as a part of the performance monitoring program for the alternative, as shown in **Figure 4-3**. The remaining four new monitoring well locations will be determined during the remedial design stage, based on future monitoring data, site accessibility, and plume configuration. As noted previously, this alternative would also require the LUCs and groundwater monitoring outlined in Section 4.2.2 for Alternative 2 to limit access and/or exposure to the site groundwater until SRGs are achieved.

Details about the chemical formulations utilized as part of the costing estimate and conceptual design are discussed in **Appendix A.2**.

4.3.1 Rationale for Alternative Selection

ISB/ISCR amendments have been used at more than 100 sites to date throughout the world, including at JBA, for soil and groundwater cleanup. The technology has been accepted by the State of Maryland and federal regulatory authorities in both the United States and Canada (Adventus, 2011). The cost of in situ groundwater treatments is significantly lower than the capital and O&M costs of traditional remediation technologies and timeframes to site cleanup are often shorter. The choice of which amendments to use in the actual remedial action would be determined during the remedial design phase because new site data or products may become available.

4.3.2 Conceptual Design

Alternative 3 would involve the field mixing and DP injection of the ISB/ISCR amendments and microbial inoculants into a series of eight or more rows of PBTZs in the building region around Building 1206 in order to address the highest concentrated regions of the plumes. The downgradient portion of the plume would involve the field mixing and injection of ISB amendments into five or more PBTZs. The benzene treatment zone would be treated with aerobic ISB amendments while the remaining TCE plume areas would be treated with anaerobic ISB amendments. The conceptual layout of Alternative 3 presented in **Figures 4-2** (building region) and **Figure 4-3** (downgradient region) shows the proposed amendment injection rows, four of the eight proposed new monitoring well locations, and indicator wells that would be used for performance monitoring. The exact injection layout is expected to be determined based on PAG and other nearby mission operational considerations during the development of the remedial action work plan. The remaining four new monitoring well locations will be determined during the remedial design stage, based on future monitoring data, site accessibility, and plume configuration.

The DP injection borings would be used to emplace the amendments across a 10- to 20-foot thick vertical target interval of saturated, sandy sediments overlying the Calvert Formation confining unit. This would require injecting across two to three 5-foot intervals within each boring, depending on its location within the plume. Based on available drilling logs from the site, the saturated sediments in the contaminant plume are approximately 20 feet thick in the building area near Building 1206, and 10 feet thick in the downgradient area near the Pad 94 off Taxiway Whiskey (**Figure 1-4**).

Injection points would be spaced approximately 40 feet apart for the ISB/ISCR, based on using a 20- to 25-foot injection radius of influence (ROI) at each location. The aerobic ISB injection locations were designed to be spaced approximately 20 feet apart, using an ROI of 15 feet, and the anaerobic ISB injection locations were designed to be spaced approximately 50 feet apart, using an ROI of 30 feet. ROI is a combination of the amendment volume injected and the additional distribution that occurs through diffusion, dispersion, and advection in the subsurface. The ROI for DP applications is greatest in more permeable lithologies such as the sand and gravel described

in SS-28 logs. Angled DPT injection points may be utilized to treat areas under buildings, roads, and utility corridors to reduce the impact of the remedial actions on JBA operations.

The treatment zones in the building region would be spaced approximately 200 feet apart, which takes into account the calculated mean groundwater flow velocity at the site of 50 feet per year (URS, 2013) and a reported ISB/ISCR amendment persistence of 3 to 5 years (Adventus, 2011). The treatment zones in the downgradient portion would be spaced approximately 1,000 feet apart, because the goal for these injections is to treat the lower concentration leading edge of the plume (maximum TCE concentration of 35 µg/L) so that the contaminants do not discharge into Piscataway Creek. A single treatment zone for the aerobic ISB injection is proposed to treat the benzene plume near Taxiway W2. The individual injection point locations, if possible, would be placed off paved surfaces (i.e. roads, taxiways) in order to limit impacts of local mission activities. If any of the injection points need to be situated on a paved surface, these points would be located at least 15 feet from aircraft taxi lines to limit impacts to air operations. In the operational areas, a 40-foot injection spacing would be utilized to allow enough distance away from the taxiway lines. The length of each treatment zone is variable. The ISB/ISCR injection zones are designed to be within the current 50-µg/L TCE isoconcentration contour area within the building region; whereas, the anaerobic ISB injection zones are designed to treat within the 5-µg/L TCE isoconcentration contour area in the downgradient plume portions. By treating the plume in this manner, groundwater in the immediate areas of the treatment zones would become strongly reducing and increased organic carbon concentrations in groundwater would stimulate further anaerobic dechlorination of the target VOCs. The ZVI component in the ISCR amendment would also promote direct chemical reduction of contaminants as they pass through the treatment zones, resulting in a further reduction in VOC concentrations within the plume. The aerobic ISB injection row is designed to treat within the 50-ug/L benzene isoconcentration contour by Taxiway W2. The groundwater in the immediate area of the treatment row would become strongly oxidized and enhance the natural aerobic subsurface conditions to promote further aerobic biodegradation of benzene.

Based on an ISB/ISCR amendment persistence of approximately 4 years, it is anticipated that three injection events would be performed over a 15-year period. Anaerobic ISB amendments have a persistence timeframe similar to that of the ISB/ISCR amendment. It is anticipated that three

anaerobic ISB injection events would be needed to treat the downgradient region of the TCE plume while only one aerobic ISB injection would be needed to treat the benzene plume along Taxiway W2. If the post-injection monitoring does not provide evidence of sufficient degradation in the downgradient and benzene portions of the plume, additional injections can be scheduled or changes can be made to the injection formulation.

After completing the third ISB/ISCR injection event and monitoring for several years, the VOC concentrations are expected to drop to a level at which a fourth injection would not be cost effective; however, additional injections would be considered if the post-injection sampling does not show the appropriate degradation trends to attain SRGs. Results of the steady state groundwater flow and contaminant transport model (**Appendix B**) indicate that the proposed ISB/ISCR technology would achieve the SRGs within 20 years of remedy implementation. The overall time-to-cleanup is primarily driven by the time it takes for TCE to reach its SRG of 5 µg/L because TCE is the most widespread contaminant at the site and it has a slower degradation rate compared to CTC and benzene under the injection conditions. The estimated times-to-cleanup for CTC and benzene for Alternative 3 are 18 and 10 years, respectively.

The precise injection intervals, injection point spacings, amendment type and/or dosage, pH buffer and bioaugmentation requirements, and treatment zone layout would be further refined during the formulation of the remedial design document. Given the anticipated injection array presented in **Figures 4-2** and **4-3**, the injection depths, and the volume of injectants, it is likely that the injection period would be on the order of 4 weeks for the initial application. The estimate is based primarily on the 30-day injection period experienced during the 2013 application at JBA site FT-02, which averaged approximately 4,630 gallons of injectants per day.

4.3.2.1 Green and Sustainable Practices

A preliminary assessment of the energy consumption, gas emissions, resource consumption, and environmental benefits for Alternative 3 was performed using the software program SiteWise™. Based on the preliminary assessment, the greatest environmental impacts that would occur while implementing this alternative would be from gas emissions; the injection media (long-lasting carbon substrate, ZVI, and pH buffer for the VOC plumes); and water use from the injection events, with contributions from transportation and equipment use during post-injection

monitoring. The injection media break down the contamination into its most stable compounds: carbon dioxide, ethene, and chloride. The chloride would stay in the groundwater; whereas, the carbon dioxide and ethene could potentially dissolve out. Local potable water or site well water (a more sustainable and technically preferable solution, if practical) would be mixed in with the amendments to create the injection solutions needed for the remedial action. . The only way to reduce the gaseous emissions or the volume of water used would be to reduce the volume of injection media used for the remedial action.

The transportation gas emissions could be reduced by using biofuel vehicles instead of regular trucks and by reducing the number of vehicles used for transportation. The equipment gas emissions could be reduced by using batteries that could be charged from the electrical grid or solar power instead of a diesel- or gasoline-powered generator to operate the groundwater sampling pump. An assessment of the environmental benefits would be included in the RACR should this alternative be selected for this site.

4.3.3 Performance Monitoring

A groundwater monitoring program would be implemented at the site to track the rate and degree of VOC decline as well as the geochemical changes that occur in the aquifer as a result of the amendment injection program. Following a baseline sampling event prior to amendment injections, performance monitoring of indicator wells at the site would be conducted to assess the effectiveness of the ISB/ISCR injections. Results of the performance monitoring would be used to determine whether adjustments to the amendment injection program are warranted, whether the monitoring well network and/or monitoring frequency should be modified, and to track remediation progress.

A total of three additional rounds of VI monitoring would be conducted at Buildings 1201 and 1287 to support the remedial design and help evaluate post-injection VI conditions. The first round will be conducted during the remedial design phase. The results from this baseline round would assist in the design of the selected remedy. The latter two monitoring rounds would occur once the remedy is implemented to monitor the changing subsurface conditions. Indoor air (five locations), sub-slab (3 to 4 locations) and ambient outdoor air (one location) samples would be collected and analyzed for VOCs (all COCs and degradation products) from each building. These

results will be compared to the appropriate residential and industrial screening levels. The sub-slab locations will be installed during the round of baseline sampling as permanent ports so the locations can be resampled at later events. The monitoring rounds would be conducted during heating or cooling seasons and in separate years to show seasonal variation and possible temporal trends.

The scope of the performance monitoring program provided the basis for estimating the cost of the ISB/ISCR alternative, which is based on a projected 20-year timeframe to achieve SRGs.

4.3.4 Performance Monitoring Goals

The performance goals for Alternative 3 include tracking the changes in contaminant concentrations throughout the plume and evaluating the extent to which amendment injections are affecting the site geochemistry and stimulating the biologic degradation and chemical reduction of VOCs in groundwater. Information on the effective ROI from the injection points and the degree to which the diffusive effects of the amendments are spread both laterally and vertically from the injection intervals would be useful in modifying the design of subsequent injection events. The long-term goals of the performance monitoring program would be to determine when contaminant levels in groundwater have declined below the SRGs, whereupon LUCs might be lifted at the site. Additional injection events would be proposed if the post-injection sampling results do not support the achievement of the cleanup criteria within the specified timeframe.

4.3.4.1 Performance Monitoring Network

As shown in **Figure 4-2**, the post-injection performance monitoring wells for Alternative 3 would be the same as those proposed for the Alternative 2 monitoring program. In general, the 15 existing and eight new wells that make up the monitoring network would be positioned in upgradient and downgradient locations within the centerline of the plume and selected cross-gradient locations. One new monitoring well location is proposed south of Building 1206 near South Dakota Avenue in the area of the highest concentrated portion of the chlorinated solvent plume. Three new monitoring wells are proposed in the downgradient region of the anaerobic ISB injections as a part of the performance monitoring program for the alternative (**Figure 4-3**). The remaining four new monitoring well locations will be determined during the remedial design stage, based on future monitoring data, site accessibility, and plume configuration.

Samples and field measurements would be collected according to the specific monitoring needs developed in the remedial design work plan for the selected alternative. The final configuration of the post-injection monitoring well network would be included in the remedial action work plan for the site. This configuration would be determined through discussions with USEPA and MDE, and the evaluation of the network through environmental decision support software, such as Visual Sample Plan or Optimal Well Locator. Throughout the course of remedy implementation, the network of monitoring wells might be adjusted (i.e., number of wells, monitoring frequency) based on overall trend analyses to assure the remedy will achieve the cleanup criteria within the required timeframe, or change if areas of the site cleanup or other locations are deemed more appropriate for measuring the effectiveness of the ISB/ISCR alternative.

4.3.4.2 Analytical Protocol

The indicator wells for Alternative 3 would be sampled for VOCs and a suite of parameters that are considered useful in evaluating the degree to which ISB/ISCR amendments are changing the geochemistry for favorable stimulation of biodegradation and chemical reduction processes. The VOC analytical suite will include the possible degradation products of the COCs, as these compounds are anticipated to temporarily increase in concentration during the remedial treatment as the COCs degrade. Monitoring these degradation compounds will help calculate the dechlorination rate. The suite of analyses is similar to the natural attenuation parameters with a greater focus on TOC, chlorides; dissolved gases such as methane, ethene, and ethane; and microbial populations. Field measurements of ORP, DO, ferrous iron, manganese, and pH are important indicators of changing geochemistry driven by ISB/ISCR amendment injections. The iron and manganese parameters are included to track potential metal concentration increases related to the geochemistry changes caused by the substrate injections. Analytical protocols related to the aerobic ISB amendment for the benzene plume area are similar to the anaerobic amendments, but do not include the DHC populations. Modifications to the analytical suite may be made throughout the course of remedy implementation based on which parameters are determined to be critical in documenting the ongoing effectiveness of the remedy.

Multiple lines of evidence would be used to determine whether additional injections are required in order to achieve cleanup criteria within a reasonable timeframe. The rate of dechlorination would be assessed after each post-injection sampling event to assure that the groundwater

concentrations would reach the cleanup criteria by the end of the project timeframe. The rate of dechlorination would depend on the VOC concentration trends and whether the geochemical conditions are favorable for chlorinated VOC degradation (ORP less than 0 mV, DO less than 1 mg/L, and pH ranging between 5.5 and 8). If the dechlorination rate is not projected to meet the timeframe due to rebound or unfavorable geochemical conditions, another injection event and/or changes to the injection formulation would be proposed.

4.3.4.3 Sampling Frequency and Duration of Monitoring

For the ISB/ISCR alternative, sampling frequency would initially occur more frequently after the initial injection and then slowly be reduced to annual sampling events. After the first injection, groundwater samples would be collected on a semiannual basis, as semiannual sampling would occur from 6 months to 3 years after the initial injection. Annual sampling would begin 3 years after the initial injection and would remain at that interval until either the cleanup criteria are met or the sampling frequency is modified based on the observed degradation trends.

It is anticipated that the configuration of each successive amendment injection event (i.e., locations of rows, injection point spacings) would change somewhat due to the temporal and spatial changes that are likely to occur in the plume as cleanup progresses. If the sampling results show evidence of rebound or not degrading to the degree anticipated, additional injection events would be considered in order to continue the remedial action.

4.4 ALTERNATIVE 4 – IN SITU CHEMICAL OXIDATION AND IN SITU BIODEGRADATION WITH LAND USE CONTROLS

Alternative 4 involves the direct injection of a persistent oxidant with iron chelate and sodium hydroxide (alkaline persulfate activator) into a series of PBTZs near Building 1206 and the direct injection of a long-lasting carbon substrate with ZVI and pH buffer into a series of PBTZs between Buildings 1217 and 1202. The proposed oxidant, sodium persulfate, is a persistent, liquid oxidant whose primary application is the in situ chemical destruction of chlorinated hydrocarbons and petroleum products like CTC, chloroform, TCE, and benzene. The increased reactive persistence in the subsurface (greater than 3 to 5 months) allows diffusive transport of the oxidant into low permeability zones. This can be beneficial in lessening the effects of contaminant rebound that result when reverse matrix diffusion of contaminants occurs from low permeability strata (Parker,

2002). The density of persulfate is greater than water; therefore, density-driven transport allows greater lateral and vertical distribution of oxidants into the aquifer that can further enhance the contact between oxidants and contaminants. With persulfate persistence in the subsurface proportional to its injected concentration and inversely proportional to the natural oxidant demand by the aquifer material and/or contaminants, injection of sodium persulfate at higher concentrations would allow increased reactive persistence in the subsurface for months.

Once the ISCO injections are complete and the persistent oxidant has been depleted, a long-lasting carbon substrate with ZVI and pH buffer would be injected into a series of at least five treatment zones in order to treat the remaining chlorinated hydrocarbons present in the groundwater. This alternative also includes a provision for injecting DHC and Dehalobacter inoculants into the treatment zones to boost the populations of dechlorinating microorganisms in the site groundwater, which have been reported to be well below the levels considered optimal for effective biodegradation (URS, 2013). The carbon substrate is fermented by the naturally occurring microbes causing bacterial populations to grow, hydrogen to be produced, oxygen to become depleted, and ORP levels to decline. The ZVI would assist in keeping the ORP levels low enough to induce favorable reductive dechlorination conditions. TCE and its breakdown products have been shown to biologically degrade most favorably under anaerobic conditions (reductive dechlorination); however, anaerobic biological processes can also result in the production of volatile fatty acids that can lower pH levels in the aquifer. In the absence of natural buffering capacity within the aquifer matrix, these lower pH levels can be detrimental to effective biodegradation. Although acceptable pH levels for reductive dechlorination range between 5 and 9, optimal pH levels are between 6 and 8 (AFCEE, 2007). To counteract the effect of aquifer acidification, an alkaline pH buffer, such as potassium bicarbonate, would be mixed with the ISB/ISCR amendments in the field during injections.

A noted advantage of using a persistent amendment is its ability to counteract the effects of reverse matrix diffusion. When the more permeable areas of the aquifer become depleted of contaminants, the contaminant mass contained in the silt/clay lenses that exist within the Upland Deposits would begin to diffuse back into the sands and gravel. The persistently reactive amendment would then be able to react with these contaminants and the effects of contaminant rebound would be reduced or negated.

This alternative would also feature a series of ISB injections located downgradient of the building region and in the grassy portions of the airfield, similar to the ISB injections described in Section 4.3 for Alternative 3. These injections would include a small-scale aerobic ISB injection near Taxiway W2 and at least four treatment zones of anaerobic ISB injections between Taxiway W2 and Pad 94. The small scale aerobic ISB injection would address the observed benzene plume detected in a series of DPT samples (ranging from 32 to 910 µg/L) located south of Taxiway W2. At least four treatment zones of anaerobic ISB amendment would address the leading edge of the chlorinated solvent plume, where the highest observed TCE concentration during the RI was 35 µg/L from a DPT sample. The anaerobic ISB injections would help prevent the leading edge of the plume from extending further downgradient towards Piscataway Creek. Additional injection events for these regions would be determined based on the results of the post-injection monitoring rounds.

As noted previously, this alternative would also require the LUCs and groundwater monitoring outlined in Section 4.2.2 for Alternative 2 to limit access and/or exposure to the site groundwater until SRGs are achieved.

4.4.1 Rationale for Alternative Selection

The rationale for considering the application of ISCO with sodium persulfate in the building region release area at SS-28 is the relatively low levels of contaminant (i.e., no NAPL), and the proven success of sodium persulfate in oxidizing chlorinated ethenes, chlorinated methanes, and petroleum constituents. Numerous bench-, pilot-, and full-scale applications of persulfate have been successfully implemented at a wide range of sites and under a variety of conditions. The reaction kinetics are well understood, especially for chlorinated ethenes, and the long-term persistence of persulfate in the subsurface can result in good distribution of the oxidant (ITRC, 2005). With ISCO's potential for effectively oxidizing benzene release area mass and reducing the contaminant mass flux migrating from the release area, the downgradient permeable treatment zones would provide effective in situ treatment polishing or biodegradation of the remaining site plume.

ISCO reagents are normally applied to treat site source areas and not throughout dissolved phase plumes. For this alternative, the ISCO reagents would be focused within the overlapping footprint

of the TCE, CTC, chloroform, and benzene plumes within the building region near Buildings 1206 and 1287. The thin saturated thickness of the unconfined aquifer makes this technology potentially applicable. If applied effectively, ISCO reagents could greatly reduce the contaminant mass at the site in a relatively short period of time. Although short-term reductions in microbial activity have been observed at sites where persulfate oxidants have been injected, this effect has been shown to be relatively short term. Post-oxidation increases in microbial populations, activity, and contaminant attenuation are often reported (USEPA, 2006). For these reasons, ISCO technology using sodium persulfate has gained widespread acceptance by state and federal agencies, even when combined with subsequent ISB polishing.

4.4.2 Conceptual Design

Alternative 4 would involve the field mixing of sodium persulfate with iron chelate and sodium hydroxide in order to activate the oxidizing properties when it interacts with the contaminated groundwater. The amount of iron chelate and sodium hydroxide needed for this mixture would depend on the field measurements of natural oxidant demand, site contaminant mass, and aquifer porosity. The oxidant solution would then be injected into a series of eight rows of treatment zones using DP injection methods. Two separate ISCO injections are planned, approximately 6 months apart. The conceptual layout of Alternative 4 presented in **Figure 4-4** shows the proposed ISCO injection rows and indicator wells that would be used for performance monitoring. Oxidants would be targeted into the upper 10 to 15 feet of the saturated aquifer zone.

Density-driven transport of the sodium persulfate reagents would distribute oxidants vertically into the deeper sands and gravels overlying the Calvert Formation confining unit. ISCO injections would be spaced approximately 25 feet apart, using a 15-foot injection ROI across the center of the overlapping TCE, CTC, and benzene plume near Building 1206. As a result of the soluble nature of sodium persulfate reagents and the generally sandy, gravelly nature of the site sediments, a 25-foot spacing between injection point locations would likely result in an overlap of ISCO reagents. Angled DPT injection points may be utilized to treat areas under buildings, roads, and utility corridors to reduce the impact of the remedial actions on JBA operations.

The proposed spacing between rows of ISCO permeable treatment barriers is approximately 50 feet. This takes into account the two 15-foot ROIs (30 feet) between adjacent rows and an

approximate groundwater travel time of 6 months (25 feet) using the calculated mean groundwater velocity at the site of 50 feet/year (URS, 2013). The oxidant persistence of between 3 to 6 months (depending on the injected persulfate concentration) would be followed by a post-injection monitoring period to assess the effects of contaminant rebound prior to planning the second injection. As cited above, a noted advantage of using a persistent oxidant such as persulfate is its ability to counteract the effects of reverse matrix diffusion. When the more permeable areas of the aquifer become depleted of contaminants, the contaminant mass contained in the silt/clay lenses that exist within the Upland Deposits would begin to diffuse back into the sands and gravel. The persistently reactive oxidants would then be able to react with these contaminants and the effects of contaminant rebound would be reduced or negated.

After the ISCO injections have been completed and the aquifer geochemistry has had at least 6 months to recover, the ISB/ISCR injects would be conducted. The ISB/ISCR injections would be spaced approximately 40 feet apart, using a 20- to 25-foot ROI across the center of the remaining TCE plume (> 50 µg/L) between Buildings 1217 and 1202. The proposed spacing between the ISB/ISCR treatment zones in the building complex is approximately 200 feet. This takes into account an approximate travel time of 4 years using the calculated mean groundwater velocity at the site of 50 feet/year (URS, 2013). The individual injection point locations, if possible, would be placed off paved surfaces (i.e. roads, taxiways) in order to limit impacts to local mission activities. Given the anticipated injection array presented in **Figures 4-4** and **4-3**, the injection depths, and volume of injectate, it is likely that the injection period would be on the order of 5 weeks for the initial application. The estimate is largely based upon the 30-day injection period for injection of amendment and dilution water during the 2013 application at JBA site FT-02, which averaged approximately 4,630 gallons of injectate per day.

Post-injection monitoring would provide the necessary data to effectively evaluate the effectiveness of the ISCO injection rounds. It is estimated that two ISCO injections would be required to effectively reduce the size and concentration of the central core of the site VOC plume to levels approaching SRGs. After VOC concentrations have been reduced to asymptotic levels and further ISCO injections are no longer feasible, the site would enter into final groundwater monitoring. Results of the steady state groundwater flow and contaminant transport model

(**Appendix B**) indicate that the proposed ISCO remedy would achieve SRGs within 20 years. The proposed program would include the following:

- First ISCO injection in building region and the start of performance monitoring.
- ISCO substrate is active and persists for up to 6 months.
- Conduct performance monitoring at 1 month, 3 months, and 6 months after initial injection.
- Second ISCO injection in building region after 6-month performance monitoring event.
- ISCO substrate is active and persists for up to 6 months.
- Conduct performance monitoring at 1 month, 3 months, and 6 months after second injection.
- First ISB/ISCR injection in building area and downgradient plume regions (approximately 1 year after first ISCO injection).
- Conduct semiannual performance monitoring for 3 years, followed by annual monitoring.
- Second ISB/ISCR injection in building region and downgradient plume regions based on performance monitoring results (approximately 4 years after first ISB/ISCR injection).
- Annual performance monitoring results would determine the need for any additional substrate injections.

After two ISCO injections (1 year) and two ISB/ISCR injections (8 years), an additional 11 years of post-injection monitoring may be required before SRGs are achieved. The time-to-cleanup is primarily driven by the time it takes for TCE to reach its SRG of 5 µg/L because TCE is the most widespread contaminant at the site and it has a slower degradation rate compared to CTC and benzene under the injection conditions. For Alternative 4 the estimated times-to-cleanup for CTC and benzene are 16 and 6 years, respectively.

4.4.2.1 Green and Sustainable Practices

A preliminary assessment of the energy consumption, gas emissions, resource consumption, and environmental benefits for Alternative 4 was performed using the software program SiteWise™. Based on the preliminary assessment, the greatest environmental impacts that would occur while implementing this alternative would be from gas emissions from the injection media (long-lasting carbon substrate with ZVI and pH buffer for the TCE plume; sodium persulfate for the overlapping TCE-CTC-benzene plume) and water use from the injection events, with contributions from transportation and equipment use from the post-injection monitoring phase.

The injection media breaks down the contamination into its most stable compounds: carbon dioxide, ethene, and chloride, which would be released into the environment. The chloride would stay in the groundwater; whereas, the carbon dioxide and ethene could potentially volatilize out of the groundwater. Local potable water or site well water (a more sustainable and technically preferable solution, if practical) would be mixed in with the amendments to create the injection solutions needed for the remedial action. The only way to reduce the gaseous emissions or the volume of water used would be to reduce the volume of injection media used for the remedial action.

The transportation gas emissions could be reduced by using biofuel vehicles instead of regular gasoline trucks and by reducing the number of vehicles used for transportation. The sodium persulfate would require additional chemicals to be added to the injection solution in order to properly activate the persulfate for treatment. This would require additional equipment shipments to the site, requiring additional gasoline consumption. The equipment gas emissions could be reduced by using batteries that could be charged from the electrical grid or solar power instead of a diesel- or gasoline-powered generator to operate the groundwater sampling pumps. An assessment of the environmental benefits would be included in the RACR should this alternative be selected for this site.

4.4.3 Performance Monitoring

A groundwater monitoring program would be implemented at the site to track the rate and degree of VOC decline in groundwater, the aquifer geochemistry, and the distribution of substrate and chemicals in the aquifer as a result of the injection program. Following a baseline sampling event, oxidant injections would be performed in the building region at the site. The ISB/ISCR and downgradient injections would begin to take place at the site after sufficient time has passed from the second ISCO injection to assure that the persulfate has been depleted. Performance monitoring of indicator wells at the site would be conducted to assess the effectiveness of the injections. Results of the performance monitoring would be used to determine amendment persistence and/or depletion, whether additional injections are warranted, whether the monitoring well network and/or monitoring frequency should be modified, and to track remediation progress.

A total of three additional rounds of VI monitoring would be conducted at Buildings 1201 and 1287 to support the remedial design and help evaluate post-injection VI conditions. The first round will be conducted during the remedial design phase. The results from this baseline round would assist in the design of the selected remedy. The latter two monitoring rounds would occur once the remedy is implemented to monitor the changing subsurface conditions. Indoor air (five locations), sub-slab (3 to 4 locations) and ambient outdoor air (one location) samples would be collected and analyzed for VOCs (all COCs and degradation products) from each building. These results will be compared to the appropriate residential and industrial screening levels. The sub-slab locations will be installed during the round of baseline sampling as permanent ports so the locations can be resampled at later events. The monitoring rounds would be conducted during heating or cooling seasons and in separate years to show seasonal variation and possible temporal trends.

The scope of the performance monitoring program provided the basis for estimating the post injection costs for the ISCO and ISB/ISCR alternative, which is based on a 20-year timeframe for achieving the SRGs.

4.4.4 Performance Monitoring Goals

The performance goals for Alternative 4 include tracking the changes in contaminant concentrations throughout the plume and evaluating the extent to which the injections are affecting the site geochemistry and stimulating the destruction of VOCs in groundwater. The performance monitoring results would be useful in modifying the design of any subsequent injection events. The long-term goals of the performance monitoring program would be to determine when contaminant levels in groundwater have declined below the SRGs, whereupon LUCs may be lifted at the site. Additional injection events should be considered if the post-injection sampling results do not support the achievement of the cleanup criteria within the specified timeframe.

4.4.4.1 Performance Monitoring Network

As shown in **Figure 4-4**, the performance monitoring wells for Alternative 4 would be the same as those for Alternative 2. In general, the 15 existing and eight new wells that make up the monitoring network would be positioned in upgradient and downgradient locations within the centerline of the plume segments and selected cross-gradient locations. One new monitoring well

is proposed to be located south of Building 1206 near South Dakota Avenue in the area of the highest concentrated portion of the chlorinated solvent plume, as shown in **Figure 4-4**. Three new monitoring wells are proposed to be located in the region of the anaerobic ISB injections as a part of the performance monitoring program for the alternative, as shown in **Figure 4-3.** The remaining four new monitoring well locations will be determined during the remedial design stage, based on future monitoring data, site accessibility, and plume configuration.

Samples would be collected according to the specific monitoring needs developed in the remedial design work plan for the selected alternative. The final configuration of the monitoring well network would be included in the remedial action work plan for the site. This configuration would be determined through discussions with USEPA and MDE, and the evaluation of the network through environmental decision support software, such as Visual Sample Plan or Optimal Well Locator. Throughout the course of remedy implementation, the network of monitoring wells and/or monitoring frequency would be modified or changed if areas of the site attain cleanup or other locations are deemed more appropriate for measuring the effectiveness of this alternative.

4.4.4.2 Analytical Protocol

The indicator wells for Alternative 4 would be sampled for VOCs and a suite of parameters that are considered useful in evaluating the degree to which oxidants are changing the site geochemistry and/or destroying site contaminants (i.e., production of chlorides, ethene). The VOC analytical suite will include the possible degradation products of the COCs, as these compounds are anticipated to temporarily increase in concentration during the remedial treatment as the COCs degrade. Monitoring these degradation compounds will help calculate the dechlorination rate. Field measurements of ORP, DO, pH, iron, and manganese are important indicators of changing geochemistry driven by ISCO reagent injections. Analytical protocols related to the ISB/ISCR amendments for the TCE plume area are similar to the natural attenuation parameters with a greater focus on TOC; chlorides; dissolved gases, such as methane, ethene, and ethane; and DHC populations. Field measurements of ORP, DO, ferrous iron, manganese, and pH are important indicators of changing geochemistry driven by ISB/ISCR amendment injections. The iron and manganese parameters would be included to track potential metal concentration increases related to the geochemistry changes caused by the substrate injections. The aerobic ISB amendment injections would follow similar analytical protocols as the anaerobic injections, except they would

not include the monitoring of the DHC populations. Modifications to the analytical suite may be made throughout the course of remedy implementation based on which parameters are determined to be critical in documenting the ongoing effectiveness of the remedy. It is anticipated that in the final 11 years of monitoring, the analytical suite would focus more on natural attenuation parameters than on oxidant/dechlorination indicators.

Multiple lines of evidence would be used to determine whether additional injections are required in order to achieve cleanup criteria within a reasonable timeframe. The rate of dechlorination would be assessed after each post-injection sampling event to assure that the groundwater concentrations will reach the cleanup criteria by the end of the project timeframe. The rate of dechlorination will depend on the VOC concentration trends and if the geochemical conditions are favorable for chlorinated solvent degradation (ORP less than 0 mV, DO less than 1 mg/L, and pH ranging between 5.5 and 8). If the dechlorination rate is not projected to meet the timeframe due to rebound or unfavorable geochemical conditions, scheduling another injection event would be considered.

4.4.4.3 Sampling Frequency and Duration of Monitoring

For the ISCO and ISB/ISCR alternative, sampling frequency would initially occur more frequently after the initial ISCO and ISB/ISCR injections and then slowly be reduced to annual sampling events. Following the ISCO injections, groundwater samples would be collected after 1 month, 3 months, and then 6 months. These initial sampling results would be used to determine the initial effectiveness of the remedy. The 6-month sampling events would serve as a baseline sampling event for the next injection. After the ISB/ISCR injection, groundwater samples would be collected on a semiannual basis until 3 years after the first injection. Annual sampling would begin 3 years after the initial injection and would remain at that interval until either the cleanup criteria are met or the sampling frequency is modified based on the performance monitoring results.

It is anticipated that the configuration of each successive amendment injection event (i.e., locations of rows, injection point spacing) would change somewhat due to the temporal and spatial changes that are likely to occur in the plume as cleanup progresses. If the sampling results show evidence of rebound or contaminants not degrading at the rate anticipated, additional injection events would be considered in order to complete the remedial action.

4.5 ALTERNATIVE 5 – GROUNDWATER EXTRACTION AND TREATMENT USING WELLS WITH IN SITU BIODEGRADATION AND LAND USE CONTROLS

Alternative 5 involves the installation and operation of a series of vertical wells installed near the highest contaminant concentration areas of the site. The vertical well screening would span the saturated thickness of the Upland Deposits (approximately 20 to 25 feet) to the top of the Calvert Formation so that it could capture the contamination along the entire vertical profile. This alternative would extract contaminated groundwater, which would be piped off-site for ex situ treatment. The final location of the ex situ treatment plant would be determined through following NEPA guidelines and the EIAP, which would analyze the potential environmental impacts resulting from the implementation of this alternative. The treated discharge would be directed to the stormwater sewer system under an NPDES permit. The pumping well system would be focused in the building region, where the highest groundwater contaminations were observed during the RI field efforts. For this alternative, the proposed extraction layout would include four vertical wells placed in regions in the building area where the highest VOC concentrations were measured during the RI field efforts (**Figure 4-5**). A total groundwater extraction rate of approximately 12 gallons per minute (or 3 gallons per minute at each well) is recommended, based on groundwater modeling results, for this layout to effectively extract the contaminated groundwater for treatment without excessive groundwater drawdown.

This alternative would also feature a series of ISB injections located downgradient of the building region and in the grassy portions of the airfield, like the ones described in Section 4.3 for Alternative 3. These injections would include a small-scale aerobic ISB injection near Taxiway W2 and at least four treatment zones of anaerobic ISB injections between Taxiway W2 and Pad 94. The small scale aerobic ISB injection would address the observed benzene plume detected in a series of DPT samples (ranging from 32 to 910 µg/L) located south of Taxiway W2. At least four treatment zones of anaerobic ISB amendment would address the leading edge of the chlorinated solvent plume, where the highest observed TCE concentration during the RI was 35 µg/L from a DPT sample. The anaerobic ISB injections would help prevent the leading edge of the plume from extending further downgradient towards Piscataway Creek. Three new monitoring wells are proposed in the region of the anaerobic ISB injections as a part of the performance

monitoring program for the alternative, as shown in **Figure 4-3**. Additional injection events for these regions would be determined based on the results of the post-injection monitoring rounds.

Pump and treat technology is a recognized groundwater cleanup technology that relies on the dissolution of contaminants from the aquifer matrix and, through repeated pore flushes, eventually restores the groundwater to beneficial reuse. Pump and treat technology also provides a measure of hydraulic control by inducing a hydraulic gradient preferentially toward the well. The downsides of this technology include the generally high O&M costs and energy to operate the pumps, air strippers, and associated transfer pumps and/or discharge lines. In addition, the timeframes to cleanup are generally longer than more aggressive in situ technologies; however, in the absence of DNAPL/source material, the technology can achieve SRGs much faster than natural attenuation processes. Based on the steady state groundwater flow and contaminant transport model (**Appendix B**), it is estimated that the vertical well technology would achieve the SRGs within 29 years. The time-to-cleanup is primarily driven by the time it takes for TCE to reach its SRG of 5 µg/L because TCE is the most widespread contaminant at the site. The estimated times-to-cleanup for CTC and benzene for Alternative 5 are 20 and 8 years, respectively.

This alternative would also require the LUCs and groundwater monitoring outlined in Section 4.2.2 for Alternative 2 to limit access and/or exposure to the site groundwater until SRGs are achieved.

4.5.1 Rationale for Alternative Selection

The rationale for considering groundwater extraction and treatment technology is the potential for achieving site cleanup while controlling or reversing the plume migration using a well-tested and successful remedial technology. In the groundwater extraction and treatment alternative, access to the paved aircraft taxi areas would be needed only during the periodic groundwater sampling and/or performance monitoring of the wells, which is common to each of the alternatives. The downgradient injections proposed with this alternative would only take place in the grassy airfield portions off Taxiway Whiskey, which may not require any temporary closures of the active taxiway.

4.5.2 Conceptual Design

Alternative 5 would involve the O&M of vertical extraction wells in the areas of the higher concentrated portions of the groundwater plume in the building complex. A conceptual layout of Alternative 5 is presented in **Figure 4-5** that shows the proposed locations of the extraction wells and pipeline configuration. The conveyance line for the extracted groundwater is shown running underground to the treatment system building located to the north of Building 1208 and east of Building 1205. The total length of underground piping needed is estimated to be 1,500 feet. This proposed treatment building location was based on the requirements of UFC 3-260-01. Also shown are the indicator wells that would be used for the performance monitoring of the extraction well system.

The vertical wells would be installed using mud rotary drilling techniques. The final well completion would include a 4-inch-diameter, slotted high-density polyethylene (HDPE) screen or continuously wound polyvinyl chloride (PVC) well screen. Depending on the grain size distribution of the target aquifer interval, a geomembrane might also be used to provide additional filtration of fine-grained solids.

A groundwater treatment facility would be required at the site with the capacity to handle approximately 10 to 20 gallons per minute. The estimated sustainable flow rate of the vertical well system is 12 gallons per minute, based on the steady state groundwater flow and contaminant transport model (**Appendix B**). The sustainable flow rate of the wells would likely vary depending on seasonal changes in aquifer levels, precipitation, recharge, and evapotranspiration effects throughout the year. The groundwater treatment facility would generally include, but not be limited to, some or all of the following components: an equalization tank, a low-profile air stripper, a series of GAC units for the polishing of the stripper air stream, zeolite adsorption system for vinyl chloride removal, well pump and transfer pump control panels with a power supply system, and a treated effluent line to the NPDES discharge location in the storm sewer system along Operations Drive. The storm sewer in the Operations Drive area discharges to the Piscataway Creek.

4.5.2.1 Green and Sustainable Practices

A preliminary assessment of the energy consumption, gas emissions, resource consumption, and environmental benefits for Alternative 5 was performed using the software program SiteWise™.

Based on the preliminary assessment, the greatest environmental impacts that would occur while implementing this alternative would be from transportation and equipment gas emissions during the construction of the groundwater extraction and treatment system, the performance monitoring and the O&M of the plant. Over the long term, the O&M of the treatment plant would have the greatest impact, with daily/weekly maintenance activities and treatment waste disposal. The transportation gas emissions could be reduced by using biofuel vehicles instead of regular gasoline trucks and by reducing the number of vehicles used for transportation.

The treatment plant equipment emissions and electrical use could be reduced by utilizing high-efficiency motors and variable motor speed controllers, and by adjusting the operation time intervals. Solar panels could be considered to provide energy for low-powered items (i.e., utilities) or the treatment equipment, if proved feasible. The downgradient injection suite would also have gas emissions from the injection media (long-lasting carbon substrate and pH buffer) and use local potable water for the injection events in order to create the injection solutions. The injection media breaks down the contamination into its most stable compounds: carbon dioxide, ethene, and chloride. The chloride would stay in the groundwater; whereas, the carbon dioxide and ethene could potentially dissolve out. Because this alternative does not require as many injection events as Alternatives 3 and 4, these environmental impacts would not be as prevalent as the ones from the groundwater extraction well implementation. An assessment of the environmental benefits would be included in the RACR should this alternative be selected for this site.

4.5.3 Performance Monitoring

A groundwater monitoring program would be implemented at the site to track the rate and degree of VOC decline in the site plume and to evaluate the drawdown effects in the aquifer as a result of the pumping. Following installation of the extraction wells, a baseline sampling event would be performed prior to startup of the groundwater extraction and treatment system. Performance monitoring and/or sampling of the indicator wells at the site would be conducted semiannually for the first 3 years of the program to track remediation process. The degradation rates will be calculated once data is available. The rates will be compared to the remedy's estimated cleanup time to assess if the remedy is progressing as anticipated. If not, then treatment would need to be optimized to assure the estimated cleanup time is met. Groundwater levels would also be measured

at the site indicator wells to assess the hydraulic influence of the extraction wells and to make periodic adjustments to the well flow rate. Water level transducers might be used in select indicator wells to provide continuous tracking of aquifer levels and to minimize the need for accessing restricted access areas. Aquifer level data would be used to make adjustments to the extraction well flow rates to ensure that the optimal drawdown is maintained.

A total of three additional rounds of VI monitoring would be conducted at Buildings 1201 and 1287 to support the remedial design and help evaluate post-injection VI conditions. The first round will be conducted during the remedial design phase. The results from this baseline round would assist in the design of the selected remedy. The latter two monitoring rounds would occur once the remedy is implemented to monitor the changing subsurface conditions. Indoor air (five locations), sub-slab (3 to 4 locations) and ambient outdoor air (one location) samples would be collected and analyzed for VOCs (all COCs and degradation products) from each building. These results will be compared to the appropriate residential and industrial screening levels. The sub-slab locations will be installed during the round of baseline sampling as permanent ports so the locations can be resampled at later events. The monitoring rounds would be conducted during heating or cooling seasons and in separate years to show seasonal variation and possible temporal trends.

The scope of the performance monitoring program provided the basis for estimating the cost of the groundwater extraction and treatment alternative, which is based on an estimated 29-year timeframe for achieving the SRGs. The duration of construction and activation of a groundwater extraction and treatment system, wells, and associated piping would likely occur over several months and would cause the greatest impact to site operations, primarily due to installation of the groundwater conveyance lines and the on-going need for system maintenance.

4.5.4 Performance Monitoring Goals

The performance goals for Alternative 5 include tracking the changes in VOC contaminant concentrations throughout the plume and evaluating the extent to which the groundwater extraction system is maintaining hydraulic control of the site groundwater and contaminant plumes. In addition, performance monitoring would be used to determine when well fouling may be occurring (i.e., issues such as iron bacteria growth), at which time well treatment/rehabilitation measures

would be required to return well efficiency to normal. The long-term goals of the performance monitoring program would be to determine when contaminant levels either reach asymptotic levels, negating the need for further O&M of the groundwater extraction and treatment system or to determine when contaminant levels in groundwater have declined below the SRGs, whereupon LUCs may be lifted at the site.

4.5.4.1 Performance Monitoring Network

As shown in **Figure 4-5**, the performance monitoring wells for Alternative 5 would be the same as those for Alternative 2. In general, the 15 existing and eight new wells that make up the monitoring network would be positioned in upgradient and downgradient locations within the centerline of the plume segments and selected cross-gradient locations. One new monitoring well is proposed to be located south of Building 1206 near South Dakota Avenue in the area of the highest concentrated portion of the chlorinated solvent plume, as shown in **Figure 4-5**. Three new monitoring wells are proposed to be located in the region of the anaerobic ISB injections as a part of the performance monitoring program for the alternative, as shown in **Figure 4-3.** The remaining four new monitoring well locations will be determined during the remedial design stage, based on future monitoring data, site accessibility, and plume configuration.

Samples would be collected according to the specific monitoring needs developed in the remedial design work plan for the selected alternative. The final configuration of the monitoring well network will be included in the remedial action work plan for the site. This configuration will be determined through discussions with USEPA and MDE, and the evaluation of the network through environmental decision support software, such as Visual Sample Plan or Optimal Well Locator. Throughout the course of remedy implementation, the network of monitoring wells and/or monitoring frequency would be modified or changed if areas of the site attain cleanup or other locations are deemed more appropriate for measuring the effectiveness of the groundwater extraction and treatment alternative.

4.5.4.2 Analytical Protocol

The indicator wells for Alternative 5 would be sampled primarily for VOCs in order to track the changes in the size and concentration of the site contaminant plume. The VOC analytical suite will include the possible degradation products of the COCs, as these compounds are anticipated to

temporarily increase in concentration during the remedial treatment as the COCs degrade in the downgradient portions of the plume where the ISB injections would be implemented. Monitoring these degradation compounds will help calculate the dechlorination rate in regions that are not influenced by the extraction wells. In addition, the extraction wells would be sampled for VOCs and a suite of inorganic parameters (primarily metals). Inorganics results are useful in assessing when extraction well fouling issues could become a concern. Monthly influent and effluent samples for VOCs and metals would be collected at the treatment system, which would likely be required by the State of Maryland in accordance with the NPDES permit limits. Modifications to the analytical suite may be made throughout the course of remedy implementation based on which parameters are determined to be critical in documenting the ongoing effectiveness of the remedy. It is anticipated that in the final 3 to 4 years of groundwater monitoring, the analytical suite would focus more on natural attenuation parameters when asymptotic levels have been achieved by the groundwater extraction and treatment system.

4.5.4.3 Sampling Frequency and Duration of Monitoring

The sampling frequency would be monthly for the treatment plant and annually for the indicator wells. Annual sampling would continue until either the cleanup criteria are met or the sampling frequency is modified based on the sampling trends. As the size and concentration of the VOC plume decreases, the USAF might request discontinuation of sampling of specific site monitoring wells that achieve cleanup or SRGs for four successive sampling events. Monthly influent and effluent sampling of the treatment system would be maintained in accordance with the requirements of the NPDES permit. Groundwater elevation monitoring would be conducted monthly at the indicator wells to verify the extent of the groundwater capture zone.

5.0 DETAILED ANALYSIS OF REMEDIAL ALTERNATIVES

This section presents an individual analysis of each of the five remedial alternatives presented previously in Section 4.0. Each of the alternatives is evaluated against seven of the nine NCP criteria. The first two criteria are threshold criteria and the alternative must comply with them to be considered a remedy. The next five balancing criteria are used to evaluate the relative advantages and disadvantages of each remedial alternative. The seven NCP evaluation criteria for which the five alternatives will be evaluated in this section are as follows:

THRESHOLD CRITERIA

1. **Overall protectiveness of human health and the environment—**Determines whether an alternative eliminates, reduces, or controls threats to public health and the environment through LUCs, engineering controls, or treatment.
2. **Compliance with ARARs—**Evaluates whether the alternative meets federal and state environmental statutes, regulations, and other requirements that pertain to the site.

BALANCING CRITERIA

3. **Long-term effectiveness and permanence—**Considers the ability of an alternative to maintain protection of human health and the environment over time.
4. **Reduction of toxicity, mobility, or volume (TMV) of contaminants through treatment—**Evaluates an alternative's ability to reduce the harmful effects of principal contaminants, reduce their ability to move in the environment, and reduce the amount of contamination present.
5. **Short-term effectiveness—**Considers the length of time needed to implement an alternative and the risks the alternative poses to workers, residents, and the environment during implementation.
6. **Implementability—**Considers the technical and administrative feasibility of implementing the alternative, including factors such as the relative availability of goods and services.
7. **Cost—**Includes estimated capital and annual O&M costs, as well as present worth cost. Present worth cost is the total cost of an alternative over time in terms of today's dollar value. Cost estimates are expected to be accurate within a range of ±30 to 50%.

The last two NCP criteria will be evaluated later and the results will be presented in the Proposed Plan (PP) and Record of Decision (ROD) documents. These criteria are as follows:

8. **Regulatory agency acceptance—**Considers whether the federal (USEPA, Region III) and state (MDE) regulatory agencies agree with the USAF analyses and recommendations, as described in the RI, FS, and PP.
9. **Community acceptance—**Considers whether the local community agrees with the USAF's analyses and preferred alternative. Comments received on the PP are an important indicator of community acceptance.

The following five remedial alternatives for groundwater at SS-28 are included in the detailed analysis presented in this section:

- Alternative 1 – No Action
- Alternative 2 – Monitored Natural Attenuation with Land Use Controls
- Alternative 3 – In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls
- Alternative 4 – In Situ Chemical Oxidation and In Situ Biodegradation with Land Use Controls
- Alternative 5 – Groundwater Extraction and Treatment Using Wells with In Situ Biodegradation and Land Use Controls

Alternatives 3 through 5 include LUCs and additional ISB injections located near Taxiway W2 and further downgradient in order to address the leading edges of the chlorinated solvent plume.

Detailed descriptions of these five remedial alternatives were presented in Section 4.0 to develop the preliminary process specifications and to support the order-of-magnitude cost estimates presented in this section. The LUCs identified for Alternative 2 will be incorporated into all of the remaining active alternatives (3 through 5) because restrictions on groundwater use/exposure are required until each remedy achieves SRGs. Costs for LUCs and groundwater monitoring have been added to the total costs for each of the active remedies, including the costs of the CERCLA statutory 5-year reviews.

A series of ISB injections have been incorporated into Alternatives 3, 4, and 5 to remediate the benzene plume area situated between Taxiways W2 and W3 and the low (< 35 µg/L) TCE

concentrations extending from Taxiway W2 down to the Pad 94. The benzene plume would be treated through an aerobic ISB injection in a single treatment zone. The TCE plume would be treated through an anaerobic ISB injection with long-lasting carbon substrate and pH buffer in at least four treatment zones. The cost for these injections is included in **Appendix A** for each alternative.

The cost estimates for each of the alternatives presented were prepared in conformance with USEPA guidance (USEPA, 2000) and are based on direct experience associated with JBA and other Department of Defense (DoD) sites across the country. The cost estimates include extra time for coordination, permitting, security, utility clearance, anticipated delays due to air operations, escorts, and debris prevention and cleanup. The cost estimates for each alternative were developed using vendor quotes and are presented in 2015 dollars. Expenditures that occur over different time periods are returned to present worth (2015 dollars), which discounts all future costs to a common base year. Present-worth analysis allows the cost of remedial action alternatives to be compared on the basis of a single figure representing the amount of money that, if invested in the base year and disbursed as needed, would be sufficient to cover all costs associated with the life of the remedial action. Assumptions associated with the present-worth calculations include a discounted rate of 2% for a 30-year or longer timeframe (United States Office of Management and Budget [OMB], 2012).

The results of the individual evaluations presented in this section will be expanded in Section 6.0. The remedial alternatives will be compared to one another with respect to their ability to meet the NCP criteria and to achieve the RAOs and SRGs for the site. This comparison of alternatives will provide the information needed for selecting the optimal remedial alternative for achieving SRGs associated with groundwater at SS-28.

In July 2011, the Office of the Under Secretary of Defense set aggressive goals in a memorandum to achieve Response Complete (RC) at DoD sites by fiscal years (FY) 2018 and FY2021. These aggressive goals were considered during the development of remedial alternatives in this FS, but the location of the site within an active building region and airfield taxiways has limited the available options to speed up the remediation and the FY2018 and FY2021 goals will not be met by any of the alternatives being evaluated. Additionally, the requirements specified in the Federal

Facility Agreement (FFA) for JBA and UFC 3-260-01, Airfield and Heliport Planning and Design, were considered during the evaluation of the alternatives and during the development of the cost estimates for the individual alternatives.

5.1 ALTERNATIVE 1—NO ACTION

The No Action alternative is the baseline to which all other alternatives are compared. There is no monitoring. It does not comply with ARARs nor is it protective of human health and the environment. As a result, there is no need to evaluate the No Action Alternative to the modifying criteria. In addition, the No Action is not an active remedy and does not include 5-year reviews because there is no action; therefore, there is no cost associated with this alternative. This alternative is required by the NCP for detailed analysis as a baseline for comparison of the risks and costs of the other alternative.

5.1.1 Overall Protection of Human Health and the Environment

The No Action alternative does not include any LUCs to prevent exposure to the contaminated site groundwater, and there is no way to monitor migration of the contaminant plume. As a result, this alternative would not be sufficiently protective of human health or the environment because this alternative would not meet the basic threshold criteria of protecting human health and the environment, and there is documented excess risk associated with the site groundwater. There are no periodic documentations or monitoring required, resulting in a total net present worth (NPW) cost of $0.

5.1.2 Compliance with ARARs

Without a monitoring program, compliance with chemical-specific ARARs cannot be determined. There are no location-specific ARARs associated with this alternative. Action-specific ARARs are not applicable because there are no remedial actions associated with this alternative.

5.1.3 Long-Term Effectiveness and Permanence

The No Action alternative could be effective in the long term because of contaminant reduction resulting from natural attenuation processes but its effectiveness cannot be determined without

groundwater monitoring. The potential risk from the COCs would continue to exist. Without the implementation of LUCs, the potential risk of using contaminated groundwater for drinking purposes would remain.

5.1.4 Reduction of Toxicity, Mobility, or Volume

In the No Action alternative, there would be no active treatment process for the contaminated groundwater. Therefore, TMV would only be reduced through natural attenuation processes. The extent or the rate of reduction would not be known without a groundwater monitoring program. This alternative would not satisfy the statutory preference for treatment as a principal element of a remedial action.

5.1.5 Short-Term Effectiveness

There would be no additional risks to the community or the workers because there would be no remedial work at the site in this alternative.

5.1.6 Implementability

The No Action alternative can be easily implemented. No technical or administrative issues are associated with the No Action alternative.

5.1.7 Cost

The total NPW costs associated with Alternative 1 is $0 over a 40-year project lifetime (**Table 5-1**). Detailed cost estimates for all remedial alternatives are provided in **Appendix A**.

Table 5-1 Cost Analysis for Alternative 1 – No Action

Total Project Lifetime	40+ years
Capital Cost	$ -
Annual O&M Cost	$ -
Periodic Cost	$ -
Total Cost	$ -
Total Present Worth	$ 0

5.2 ALTERNATIVE 2 – MONITORED NATURAL ATTENUATION WITH LAND USE CONTROLS

Alternative 2 includes long-term MNA sampling of site wells and the application and maintenance of LUCs through groundwater and land use restrictions, building/excavation permits, and other controls. MNA sampling would be used to track the rate at which natural destructive and nondestructive processes are reducing contaminant concentrations in the site groundwater. Although there are little or no capital costs associated with this alternative, annual sampling, reporting, signage installation, and 5-year reviews would be conducted until SRGs are achieved.

5.2.1 Overall Protection of Human Health and the Environment

Alternative 2 would neither reduce nor eliminate existing groundwater contamination at the site, aside from that which would be accomplished through natural attenuation processes. Natural attenuation is ongoing at SS-28, as evidenced by the reported concentrations of CTC degradation products, but the geochemistry and microbial population at the site are less than ideal for biodegradation. However, by maintaining the existing prohibition on the use of groundwater for potable purposes within JBA, LUCs would provide protection to human health by minimizing the risk of exposure to the site contaminant plume.

5.2.2 Compliance with ARARs

Alternative 2 would comply with potential action-specific ARARs because there would be only minimal impact to airfield operations during annual sampling events. No potential location-specific ARARs associated with SS-28 have been identified. This alternative would not comply with the chemical-specific ARARs and TBCs associated with the state and federal MCLs for the

site COCs in a reasonable timeframe. The estimated time required to achieve MCLs under the MNA with LUCs alternative is at least 40 years. This alternative would not satisfy USEPA preference for treatment at CERCLA sites.

5.2.3 Long-Term Effectiveness and Permanence

LUCs would be effective in preventing or reducing exposure of site workers to contaminated groundwater through restrictions on potable uses and requiring controls and/or permits on construction or excavation activities. However, this alternative is not considered an effective long-term remedy for the site because natural attenuation processes would not be likely to achieve SRGs within a reasonable timeframe due to the natural conditions of the subsurface showing limited evidence of dechlorination.

5.2.4 Reduction of TMV of Contaminants through Treatment

Alternative 2 would not accelerate the reduction in the TMV of contaminated groundwater at the site because of a lack of active treatment. The TMV of the site contaminants would diminish only as a result of natural attenuation processes, which have been shown to be slow as a result of the site geochemistry (i.e., low pH and high ORP).

5.2.5 Short-Term Effectiveness

Although the short-term effectiveness of LUCs would be satisfactory to prevent exposure of site workers to contaminated groundwater, there would be minimal reduction in site VOC levels. Annual groundwater sampling of the site indicator wells would have little or no short-term impact on site workers. The VI sampling would provide evidence of any potential soil vapor impact on site workers in Building 1201 and 1287.

5.2.6 Implementability

Alternative 2 would be easily implemented because there is no construction associated with this remedy, outside of installing additional monitoring wells to monitor the extent of contamination. Administratively, prohibitions on potable uses of groundwater are already in place at JBA. Annual MNA sampling of wells in and around the PAG operations area would not adversely affect airfield operations. To implement this alternative, extra time and effort will be required for coordination,

LUCs, permitting, airfield construction waivers for wells, security, utility clearances, and anticipated delays due to air operations.

5.2.7 Cost

The total NPW cost associated with Alternative 2 is estimated at $3,157,000 (**Table 5-2**). Detailed cost estimates for all remedial alternatives are provided in **Appendix A**. These costs include the establishment/enforcement of LUCs, monitoring, and 5-year reviews and are based on a 40-year project lifetime.

Table 5-2 Cost Analysis for
Alternative 2 – Monitored Natural Attenuation with Land Use Controls

Total Project Lifetime	40+ years
Capital Cost	$ 225,351
Annual O&M Cost	$ 3,808,910
Periodic Cost	$ 557,821
Total Cost	$ 4,592,082
Total Present Worth	$ 3,157,000

5.3 ALTERNATIVE 3 – IN SITU BIODEGRADATION AND IN SITU CHEMICAL REDUCTION WITH LAND USE CONTROLS

Alternative 3 would involve the direct injection of long-lasting carbon substrate amendments with pH buffer and ZVI into a series of eight or more rows of passive ISB/ISCR PBTZs in the site's building region (**Figure 4-2**), as well as additional passive ISB injections in the grassy infield portions of the airfield located downgradient of the building complex. The anaerobic ISB/ISCR amendments have a reactive persistence in the subsurface of 3 to 5 years, during which time the VOCs in the groundwater would be treated by chemical reduction and enhanced biodegradation. The ISB/ISCR treatment zones would be spaced approximately 200 feet apart in the building region, which represents a 4-year groundwater travel time. The downgradient treatment zones would be spaced approximately 1,000 feet apart and would be used to treat the contaminant plume before it reaches Piscataway Creek. Based on the groundwater transport modeling, three amendment injections implemented 4 to 5 years apart are expected to achieve the SRGs within 20

years of the initial injection. Long-term monitoring, vapor intrusion assessments of Building 1201 and 1287, and LUCs have been included in Alternative 3.

5.3.1 Overall Protection of Human Health and the Environment

Alternative 3 would be protective of human health and the environment through the implementation of LUCs until SRGs are achieved. Through in situ treatment using synergistic technologies (i.e., stimulating microbial activity through the addition of long-lasting carbon substrate and chemical reduction using iron), Alternative 3 would accelerate the cleanup of the site groundwater with minimal O&M cost and only short-term disruption to airfield operations during injection events.

5.3.2 Compliance with ARARs

Alternative 3 would be anticipated to comply with potential action-specific ARARs because there would be minimal impact to airfield operations during performance monitoring events and little or no waste generated. No potential location-specific ARARs associated with SS-28 have been identified. In addition, because of the long-lasting nature of the ISB/ISCR amendments, the three anticipated injection events are planned at 5-year intervals, which would lessen the frequency of impacts to airfield operations. Alternative 3 would also be expected to comply with all chemical-specific ARARs and TBCs associated with state and federal groundwater MCLs within 20 years from startup. This alternative would also satisfy the USEPA preference for treatment in accordance with 40 Code of Federal Regulations (CFR) Part 264.

5.3.3 Long-Term Effectiveness

Alternative 3 would satisfy the criteria of long-term effectiveness and permanence because SRGs would be achieved within 20 years. Through the implementation of LUCs and the monitoring of the groundwater, indoor air, ambient air and sub-slab conditions, the effectiveness of the remedy would be fully documented and exposure of site workers to site contaminants would be minimized.

5.3.4 Reduction of TMV of Contaminants through Treatment

Alternative 3 would be anticipated to significantly reduce and/or eliminate the TMV of groundwater contaminants within 20 years of implementation. The synergistic effects of stimulated biodegradation and abiotic chemical reduction are predicted to rapidly decrease the

toxicity, mobility and size of the site contaminant plume. The TMV will be measured through long-term groundwater monitoring, as well as continued vapor intrusion assessments at Buildings 1201 and 1287.

5.3.5 Short-Term Effectiveness

Alternative 3 would be effective in the short term because implementation of this technology involves the mixing and injection of food grade amendments, which pose little or no risk to workers during application. Amendment injection pressures are low and safe work practices and guidelines are well established for this technology. LUCs would be in effect throughout the monitoring phase of the alternative, which would minimize exposure risk to potential receptors until SRGs have been attained.

5.3.6 Implementability

Alternative 3 would use long-lasting carbon substrate, ZVI, bioaugmentation, and pH buffer amendments to remediate the VOC groundwater contamination in situ. This is a relatively new but proven technology in groundwater remediation and has been successfully implemented at numerous sites. This type of injection approach has been successfully implemented twice in a similar airfield situation at JBA at nearby site FT-02; however, an extra level of security and logistical planning would be required to work around the operational area of the PAG along Taxiway Whiskey. To minimize the duration of amendment injections, multiple DP rigs would be used simultaneously, thus limiting the disturbance to airfield operations. Groundwater performance monitoring would also not be expected to impede airfield operations because none of the indicator wells are located on any active, paved taxiways or airfield areas.

To implement this alternative, extra time and effort would be required for coordination with stakeholders (airfield operations, security, PAG), LUCs, permitting, airfield construction waivers, security, anticipated delays due to air operations, utility clearances, Pathfinder escort procedures, and construction cleanup. It is also anticipated that the work would be scheduled for time periods with fewer active operations (such as weekends) to limit the impact on the airfield operations. The project team will need to work closely with base operations and the airfield groups impacted by the work to move injection locations, if necessary. Multiple lines of evidence will need to be

utilized for the utility clearances, including the use of a private utility clearance contractor, plus soft-dig procedures should be utilized for DPT locations proposed near utility lines.

5.3.7 Cost

The total NPW cost associated with Alternative 3 is estimated at $5,033,000 over the predicted 20-year lifespan of the alternative and the additional 3 years of monitoring and documentation required for Site Closure (**Table 5-3**). This includes the capital costs for three injections of anaerobic ISB/ISCR amendments, three injections of anaerobic ISB substrate in the grassy airfield portions, and a single injection of aerobic ISB for the benzene plume area near Taxiway W2. Detailed cost estimates for all remedial alternatives are provided in **Appendix A**.

Table 5-3 Cost Analysis for Alternative 3 – In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls

Total Project Lifetime	23 years (20+3)
Capital Cost	$ 3,084,782
Annual O&M Cost	$ 2,190,123
Periodic Cost	$ 430,306
Total Cost	$ 5,705,211
Total Present Worth	$ 5,033,000

5.4 ALTERNATIVE 4 – IN SITU CHEMICAL OXIDATION AND IN SITU BIODEGRADATION WITH LAND USE CONTROLS

Alternative 4 would involve the field mixing and injection of an activated sodium persulfate solution into a series of 13 rows of PBTZs, followed by field mixing and injection of long-lasting carbon substrate with ZVI and pH buffer into a series of 5 rows of PBTZs (**Figure 4-4**). Density-driven transport of the sodium persulfate reagents would distribute oxidants vertically into the deeper sands and gravels overlying the Calvert Formation confining unit. The proposed spacing between the ISCO treatment zones would be approximately 50 feet; whereas, the ISB/ISCR treatment zones would be spaced approximately 200 feet apart. This represents an approximate travel time of 6 months between the ISCO treatment zones and 4 years between the ISB/ISCR

treatment zones in the building region. The oxidant persistence is between 3 and 6 months; whereas, the carbon substrate persistence is between 3 and 5 years.

A noted advantage of using a persistent oxidant such as persulfate is its ability to counteract the effects of reverse matrix diffusion. After the more permeable areas of the aquifer have become depleted of contaminants, the contaminant mass contained in the lower permeability silts/clays would begin to diffuse back into the groundwater in the sands and gravels. The persistently reactive oxidants would then be able to react with these contaminants and the effects of contaminant rebound would be minimized. It is estimated that two ISCO injections (6 months apart) would be required to effectively oxidize the overlapped TCE-CTC-benzene portion of the building region groundwater plume. The following ISB/ISCR injections would address the remaining TCE plume in the building area after the ISCO amendments have been depleted. After the primary mass of VOCs has been converted by the ISCO injections, the mass of contaminants migrating to other less impacted parts of the plume would be greatly reduced. Results of groundwater flow and transport modeling indicate that the ISCO and ISB/ISCR remedy could achieve SRGs within 20 years. Long-term monitoring, vapor intrusion assessments of Building 1201 and 1287, and LUCs have been included in Alternative 4.

5.4.1 Overall Protection of Human Health and the Environment

Alternative 4 would be potentially or moderately protective of human health and the environment through the implementation of LUCs until SRGs have been achieved. Through in situ treatment using a persistent oxidant, Alternative 4 would accelerate the destruction of the elevated concentration portion of the VOC plume. This would quickly reduce the contaminant mass and reduce the mass flux of contaminants into the remaining portions of the plume. As with the other in situ alternatives, O&M activities would be essentially eliminated with little or no disruption to airfield activities while shortening the timeframe for achieving SRGs.

5.4.2 Compliance with ARARs

Alternative 4 would be anticipated to comply with potential action-specific ARARs because there would be minimal impact to airfield operations during performance monitoring events and little or no waste generated. No potential location-specific ARARs associated with SS-28 have been identified. Alternative 4 would also be expected to comply with all chemical-specific ARARs and

TBCs associated with state and federal groundwater MCLs within 20 years from startup. This alternative would also satisfy the USEPA preference for treatment in accordance with 40 CFR Part 264.

5.4.3 Long-Term Effectiveness and Permanence

Alternative 4 would satisfy the criteria of long-term effectiveness and permanence because SRGs would be achieved within approximately 20 years. Through the implementation of LUCs and the monitoring of the groundwater, indoor air, ambient air and sub-slab conditions, the effectiveness of the remedy would be fully documented and exposure of site workers to site contaminants would be minimized.

5.4.4 Reduction of TMV of Contaminants through Treatment

Alternative 4 would be anticipated to reduce and/or eliminate the TMV of groundwater contaminants within approximately 20 years of implementation. By oxidizing or destroying the site contaminants in place, this alternative would be predicted to rapidly decrease the strength of the site contaminant plume with minimal O&M. The TMV will be measured through long-term groundwater monitoring, as well as continued vapor intrusion assessments at Buildings 1201 and 1287.

5.4.5 Short-Term Effectiveness

Alternative 4 would be effective in the short term because implementation of this technology involves the mixing and/or injection of a sodium persulfate and sodium hydroxide solution, which poses little risk to workers, wearing proper protective equipment, that have been trained to handle the injection chemicals during application. Amendment injection pressures are low and safe work practice guidelines are well established for this technology. LUCs would be in effect throughout the monitoring phase of the alternative, which would minimize exposure risk to potential receptors until SRGs have been attained.

5.4.6 Implementability

Alternative 4 would use a persistent sodium persulfate solution in situ to oxidize and destroy the elevated VOC levels in the site groundwater. This is proven technology in groundwater remediation and has been successfully implemented at numerous sites worldwide over the past 20

years. Chemical oxidation has been a proven ex situ technology in the wastewater industry for the past 50 years. To minimize the duration of amendment injections, multiple DP rigs would be used simultaneously, thus limiting the disturbance to airfield operations. Extra care would be needed to ensure there are no spills or break outs of sodium persulfate through cracks in the concrete apron during the injections.

As a result of the less persistent nature of the sodium persulfate solution (as compared to the ISB substrates), two ISCO injections and one ISB/ISCR event are planned within 1 year, which would impact airfield operations more frequently than Alternative 3. Groundwater performance monitoring would not be expected to impede airfield operations because none of the indicator wells would be located on the paved portion of the site.

To implement this alternative, extra time and effort would be required for coordination, LUCs, permitting, airfield construction waivers, security, utility clearances, anticipated delays due to air operations, Pathfinder escort procedures, and construction cleanup. It is also anticipated that the work would be scheduled for time periods with fewer active operations (such as weekends) to limit the impact on the airfield operations. The project team will need to work closely with base operations and the airfield groups impacted by the work to move injection locations, if necessary. Multiple lines of evidence will need to be utilized for the utility clearances, including the use of a private utility clearance contractor, plus soft-dig procedures should be utilized for DPT locations proposed near utility lines.

5.4.7 Cost

The total NPW cost associated with Alternative 4 is estimated at $5,630,000 based on a 20-year project lifetime and the additional 3 years of monitoring and documentation required for Site Closure (**Table 5-4**). This includes the capital costs for two injections of sodium persulfate solution, two injections of ISB/ISCR amendment, two injections of anaerobic ISB amendment and a single injection of aerobic ISB amendments for the benzene plume area near Taxiway W2 over the course of the entire project lifespan. Detailed cost estimates for all remedial alternatives are provided in **Appendix A**.

Table 5-4 Cost Analysis for Alternative 4 – In Situ Chemical Oxidation and In Situ Biodegradation with Land Use Controls

Total Project Lifetime	23 years (20+3)
Capital Cost	$ 3,749,396
Annual O&M Cost	$ 2,190,123
Periodic Cost	$ 430,306
Total Cost	$ 6,369,826
Total Present Worth	$ 5,630,000

5.5 ALTERNATIVE 5 – GROUNDWATER EXTRACTION AND TREATMENT USING WELLS WITH IN SITU BIODEGRADATION AND LAND USE CONTROLS

Alternative 5 would involve the installation and operation of vertical extraction wells in the building region and ISB injections in the downgradient grassy infield portion of the airfield (**Figure 4-5**). The vertical wells would be installed in the areas of highest concentration within the building region, with conveyance lines for the extracted groundwater running north to a treatment system building located to the northeast of Building 1206. A groundwater treatment facility would be built and operated at the site for the ex situ removal of VOCs from the extracted water, which would subsequently be treated and discharged to the nearby stormwater system under an NPDES permit. Although groundwater extraction technology relies on the dissolution of contaminants from the aquifer matrix through multiple pore flushes, it can achieve SRGs much faster than natural attenuation processes. Based upon groundwater flow and contaminant transport modeling, it is estimated that the vertical well technology with downgradient injections would achieve the SRGs within 29 years; however, in the absence of on-going source material or principal threat waste at the site (i.e., DNAPL), the actual cleanup timeframe might be shorter. LUCs would be implemented to protect human health and the environment until SRGs are reached.

5.5.1 Overall Protection of Human Health and the Environment

Alternative 5 would be moderately protective of human health and the environment through the implementation of LUCs until SRGs have been achieved. By focusing groundwater extraction in the area of the highest concentrated portions of the contaminant plume, the more elevated VOC levels would be captured and removed for treatment first, which would accelerate the site cleanup. A degree of hydraulic capture would be imparted on a significant portion of the site plume, which

would minimize further lateral or downgradient migration. There are higher energy costs and a number of O&M activities associated with the extraction and treatment system. These may include, but not be limited to, periodic well rehabilitation/fouling treatment, pump replacements, treatment train maintenance, and monthly NPDES permit sampling.

5.5.2 Compliance with ARARs

Alternative 5 would be anticipated to comply with potential action-specific ARARs because there would be no impact to airfield operations during the well installation and treatment plant operation. Air emissions from the air stripper would be controlled in accordance with the applicable ARARs and spent GAC waste containers would be handled appropriately. No potential location-specific ARARs associated with SS-28 have been identified. Performance monitoring events would be the only occasion for entering the airfield operations area. Some residual wastes would be generated from the drilling and installation of the extraction wells, but the cuttings and/or drilling mud would likely be disposed of off-site as residual waste. Alternative 5 would also be expected to comply with all chemical-specific ARARs and TBCs associated with state and federal groundwater MCLs within 29 years from startup. This alternative would also satisfy the USEPA preference for treatment in accordance with 40 CFR Part 264.

5.5.3 Long-Term Effectiveness and Permanence

Alternative 5 would satisfy the criteria of long-term effectiveness and permanence because SRGs would be achieved within approximately 29 years. Through the implementation of LUCs and the monitoring of the groundwater, indoor air, ambient air and sub-slab conditions, the effectiveness of the remedy would be fully documented and exposure of site workers to site contaminants would be minimized.

5.5.4 Reduction of TMV of Contaminants through Treatment

Alternative 5 would be anticipated to reduce and/or eliminate the TMV of groundwater contaminants within approximately 29 years of implementation. By capturing and removing contaminated groundwater for treatment, this alternative would be predicted to rapidly remove the elevated levels of VOCs in the building region while also decreasing the size and strength of the outer edges of the plume. The downgradient injections would address the contamination that is outside the influence of the extraction wells by treating the leading edges of the plume. The TMV

will be measured through long-term groundwater monitoring, as well as continued vapor intrusion assessments at Buildings 1201 and 1287.

5.5.5 Short-Term Effectiveness

Alternative 5 would be effective in the short term because implementation of this technology would involve the drilling and installation of the vertical wells and construction of the treatment system building and components. These activities would pose no risk to base personnel and minimal risk to rig workers during drilling and workers during treatment plant and pipeline construction. Safe work practices and guidelines are well established for vertical drilling technology and treatment plant construction. LUCs would be in effect throughout the monitoring phase of the alternative, which would minimize exposure risk to potential receptors until SRGs have been attained.

5.5.6 Implementability

Alternative 5 would include extraction and ex situ removal and treatment technology and/or well installation techniques. These technologies are well-established and proven methods for the capture, extraction, and treatment of contaminated groundwater. This technology has been used at numerous USAF bases in the United States to clean up groundwater and/or soil contamination under runways because of its lack of disturbance to runway operations.

The ex situ treatment system construction and piping installation would be performed in accordance with standard industry practices. The treatment plant construction should be relatively easy to implement but the pipeline work will be complicated by the high number of utility lines located in the building area. Restrictions based on airfield safety and security requirements might complicate the planning and construction activities. To implement this alternative, extra time and effort will be required for coordination, LUCs, NPDES permitting, airfield construction waivers, security, anticipated delays due to air operations, utility clearances, Pathfinder escort procedures, and construction cleanup. It is also anticipated that the injection work would be scheduled for time periods with fewer active operations (such as weekends) to limit the impact on the airfield operations. The project team will need to work closely with base operations and the airfield groups impacted by the work to move injection locations, if necessary. Multiple lines of evidence will need to be utilized for the utility clearances, including the use of a private utility clearance

contractor, plus soft-dig procedures should be utilized for DPT and pipeline locations proposed near utility lines.

If the treatment plant building is installed outside Pathfinder, the project will be easier to implement because most of the routine maintenance work will be conducted outside the airfield operational area.

Groundwater performance monitoring associated with this alternative would also not be expected to impede airfield operations because none of the 23 indicator wells would be located on the active, paved portions of the taxiways or airfield.

5.5.7 Cost

The total NPW cost associated with Alternative 5 is estimated at $12,481,000 based on a 29-year project lifetime and the additional 3 years of monitoring and documentation required for Site Closure (**Table 5-5**). This total includes the capital costs for the drilling and/or installation of the extraction wells and construction of the treatment system building and components. Detailed cost estimates for all remedial alternatives are provided in **Appendix A**.

Table 5-5 Cost Analysis for
Alternative 5 – Groundwater Extraction and Treatment
Using Wells with In Situ Biodegradation and Land Use Controls

Total Project Lifetime	32 years (29+3)
Capital Cost	$ 5,147,100
Annual O&M Cost	$ 9,511,052
Periodic Cost	$ 568,316
Total Cost	$ 15,226,468
Total Present Worth	$ 12,481,000

6.0 COMPARATIVE ANALYSIS

In this section, the five remedial alternatives are evaluated in relation to one another based on each of the seven NCP criteria. The remedial alternatives were also evaluated in relation to one another based on their green and sustainable practices. The purpose of this analysis is to identify the relative advantages and disadvantages of each alternative. **Table 6-1** presents a summary of the comparative analysis of the five alternatives.

6.1 ALTERNATIVES – COMPARATIVE ANALYSIS

The five alternatives are compared or ranked in **Table 6-1** with respect to the degree to which each satisfies the two threshold criteria and the five balancing criteria. In addition, the five alternatives are compared in regards to their green or sustainable practices during the remedial implementation. In general, the distinguishing factors that result in ranking certain technologies more favorably than others are their estimated timeframes to achieve SRGs and their implementability and/or cost effectiveness. Because LUCs would be a component of all of the alternatives, aside from the No Action Alternative, they all provide a similar measure of protectiveness to human health because they prohibit the potable use of groundwater and limit the contact with groundwater until SRGs are achieved.

6.1.1 Threshold Criteria

Alternative 1 (No Action) does not meet the primary threshold criteria of protectiveness of human health and the environment because it contains no provision for LUCs. With excess risk present, this alternative was not retained for consideration as a preferred alternative because of its inability to meet the basic threshold criteria of protectiveness. Although Alternatives 2 through 5 meet the basic criteria of protectiveness (through LUCs), Alternative 2 would not likely achieve compliance with ARARs in a reasonable timeframe. Additionally, LUCs with MNA do not satisfy the USEPA preference for treatment at CERCLA sites where excess risk is present. Alternatives 3 (ISB/ISCR) and 4 (ISCO and ISB) are estimated to achieve ARARs in the shortest timeframes (within 20 years for both) of the active alternatives. Alternative 5 (Groundwater Extraction and Treatment) is estimated to achieve ARARs in 29 years.

6.1.2 Balancing Criteria

In general, Alternative 3 (ISB/ISCR) and Alternative 4 (ISCO and ISB) meet all of the balancing criteria to a high degree, whereas Alternative 5 (Groundwater Extraction and Treatment) meets all of the balancing criteria to a moderate to high degree. Alternative 2 (LUCs with MNA) meets many of the balancing criteria but, generally, to a low degree. Without active treatment, Alternative 2 does not meet the USEPA preference for treatment and the estimated timeframe to achieve SRGs may not be considered reasonable (i.e., 40 years or more).

6.1.2.1 Long-Term Effectiveness and Permanence

Alternative 3 (ISB/ISCR) and Alternative 4 (ISCO and ISB) provide a high level of long-term effectiveness and permanence because they would significantly degrade and/or destroy the groundwater contaminants and transform them into harmless compounds. Alternative 5 (Groundwater Extraction and Treatment) would meet this criterion to a moderate to high degree, significantly degrading and/or destroying the groundwater contaminants and likely achieving SRGs within 29 years. Alternative 2 would only satisfy this criterion to a low degree because of the uncertainty associated with natural attenuation processes and their ability to achieve SRGs in a reasonable timeframe (estimated as 40 or more years).

In Alternatives 2, 3, 4, and 5, the VOCs would be transformed into harmless compounds or the VOC concentrations would be reduced to levels that are protective of human health and the environment. The transformation processes associated with these alternatives are irreversible.

6.1.2.2 Reduction of TMV through Treatment

Alternatives 3 and 4 would satisfy the criterion of reducing TMV of contaminants through treatment to a high degree because these technologies would, through in situ biodegradation, chemical reduction, and chemical oxidation, achieve SRGs within 20 years, respectively, and prevent further migration through treatment. Alternative 5 would satisfy this criterion to a moderate degree because groundwater extraction would likely achieve SRGs within approximately 29 years. Alternative 2 would only satisfy this criterion to a low degree because it does not satisfy the preference for active treatment, natural attenuation processes at the site do not appear to be robust with less than optimal geochemical conditions (i.e., low ORP, low pH), and there is a potential for further migration of the contaminant plume.

In Alternative 5, toxicity of the contaminants would not change during the VOC removal from groundwater; however, if activated carbon is used to treat extracted gas (as opposed to direct release to the atmosphere), regeneration of activated carbon would transform contaminants to harmless compounds, thereby reducing the TMV of contaminants removed from the site groundwater.

6.1.2.3 Short-Term Effectiveness

Alternatives 2 through 5 are all relatively protective of site workers because adherence to airfield Pathfinder procedures, PAG requirements, and health and safety protocols would be administered during construction, injections, and performance monitoring activities. In addition, groundwater restrictions are in place and would continue to protect site personnel from contact with contaminated groundwater in the short term with the LUCs that are a part of Alternatives 2 through 5. Alternative 2 would pose the least risk to site workers because there would be no active construction or injection activities associated with this remedy, aside from performance monitoring. Alternative 5 would pose the most risk to workers because of the construction and O&M aspects of the remedy.

Alternatives 3, 4, and 5 could pose minimal short-term risks to workers during the injection phases when chemicals are mixed and injected underground on-site; however, the biological amendments are naturally occurring compounds, such as ZVI and food-grade, fibrous or liquid organic carbon, which would pose little if any exposure or handling risk to on-site workers. Sodium persulfate, used in Alternative 4 in the building region, is a strong oxidizer, and workers in the transportation and use of persulfate would need to follow proper industry practices to ensure its safe use. The sodium hydroxide, a strong alkali, used to activate the persulfate would also need to be handled carefully by trained injection workers. Normal industrial hygiene practices, which include the use of such protective equipment as chemical goggles, gloves, and work clothing that covers arms and legs as needed, would be established to minimize the risk of any such exposure. As an oxidant, sodium persulfate itself is non-combustible but will accelerate the burning of combustible materials. Therefore, contact with all combustible materials (e.g., wood and paper) and/or organic chemicals (e.g., jet fuel) would be avoided.

6.1.2.4 Implementability

Alternative 2 is easily implemented because it requires only periodic performance monitoring and relies on passive natural attenuation processes. Alternative 5 (Groundwater Extraction and Treatment), however, may be the most difficult remedy to implement, despite its proven track record. It is estimated that a total of 1,500 feet of piping would need to be installed underground, connecting the four proposed vertical extraction wells to the treatment plant. The pipe installation would be difficult to accomplish considering the density of other underground utilities in the area. In addition, building a treatment system structure and installing the associated components and piping would add to the construction time. Alternative 5 would also require additional permits, airfield construction approvals, and monthly O&M activities for the treatment plant.

Alternatives 3 and 4 are similar in terms of implementation complexity because they involve large-scale DP injections of engineered amendments or reagents. Although Alternative 5 does have a DP injection component, it would not cover as extensive an area as those covered by Alternatives 3 and 4. These types of DP injections have been successfully implemented previously at JBA. Technical expertise and reactive materials for implementation of the Alternatives 3, 4, and 5 injections are available from vendors who specialize in the design and injection of chemical and biological amendments. The injection points would be installed using standard DP injection equipment. Extra coordination and scheduling would be required for Alternatives 3 through 5 to gain access to the PAG to install injection points.

Implementation of groundwater well installation and LUCs has been successfully implemented at multiple sites at JBA and would be coordinated with various JBA offices plus state and local authorities. Alternatives 3, 4, and 5 injections would require extra time and effort for coordination with stakeholders (airfield operations, security, PAG), LUCs, permitting, airfield construction waivers, security, anticipated delays due to air operations, utility clearances, Pathfinder escort procedures, and construction cleanup.

It is also anticipated that the injection work affiliated with Alternatives 3, 4, and 5 would be scheduled for time periods with fewer active operations (such as weekends) to limit the impact on the airfield operations. The project team will need to work closely with base operations and the airfield groups impacted by the work to move injection locations, if necessary. Multiple lines of

evidence will need to be utilized for the utility clearances, including the use of a private utility clearance contractor, plus soft-dig procedures should be utilized for DPT and pipeline locations proposed near utility lines.

6.1.2.5 Costs

Alternative 2 would be the least costly to implement with an NPW of the 40-year cost of $3,157,000. Alternative 5 would be the most costly to implement with an NPW of the 32-year cost of $12,481,000. Of the two injection alternatives, Alternative 4 (ISCO and ISB) would be more costly to implement with an NPW of the 23-year cost of $5,630,000. The other injection alternative, Alternative 3 (ISB/ISCR), would be $5,033,000 (over 23 years). Although Alternatives 3 and 4 are both predicted to meet the SRGs over the same length of time, the main difference between the two costs is due to the number of injection events that are incorporated into the capital costs. The costs for Alternative 3 involve a total of three injection events. The costs for Alternative 4 involve a total of four injection events (two ISCO, two ISB/ISCR).

6.1.3 Green and Sustainable Practices

Of the active remedial alternatives, the implementation of Alternative 3 would provide the most sustainable practices during the project lifespan. Alternative 3 would enhance biological processes that occur naturally in the environment to degrade contaminants by using long-lasting biodegradable compounds (i.e., carbon substrates), requiring fewer rounds of treatment. Alternative 4 would also degrade the contaminants, but one of the key injection solutions to address the CTC-benzene plume in the building area would involve the use of harsher chemicals that are not natural to the environment (i.e., sodium persulfate and sodium hydroxide) and that, when handled improperly, could cause harm to workers. Sodium persulfate also does not last as long as the carbon substrate, so additional injection rounds could be required. No treatment wastes would be associated with Alternatives 3 or 4.

Alternative 5 is the least green and sustainable option. Although it includes in situ biological treatment for the downgradient portion of the plume, the main treatment method is through mechanical means (i.e., pumps, filters, chemicals) to treat the contaminated groundwater ex situ. Alternative 5 would also have air and water emission concerns that would require proper

permitting. This alternative would also yield the highest energy and O&M costs of all of the alternatives (i.e., pumps needed to extract the groundwater, power to run the treatment plant, personnel time to check and maintain equipment, personnel time to collect samples as required for permits, and trucks to handle treatment waste disposal).

6.1.4 Comparative Analysis Summary

The five remedial alternatives are evaluated in relation to one another based on each of the seven NCP criteria with the purpose of identifying the relative advantages and disadvantages of each alternative. As a result of the comparative analysis, the five alternatives were evaluated as satisfying the individual criteria to a high, moderate, or low/no (does not satisfy) degree.

The evaluation of the implementability of the five alternatives was based on the current conditions and preliminary understanding of the airfield operations being conducted at SS-28. Further discussions with the PAG will be required to determine the actual impact of each alternative on airfield operations. Additionally, missions and tenants change frequently at JBA so the implementability of these alternatives may change over time.

Based on the current understanding, Alternatives 3 (ISB/ISCR) and 4 (ISCO and ISB) were both judged to meet the RAOs and the CERCLA criteria to a high degree. The primary differences between these two injection alternatives are that Alternative 4 is expected to require one more injection event in order to reach SRGs than Alternative 3 (four events to three), and that Alternative 4 is expected to cost approximately $600,000 more than Alternative 3. **Table 6-2** presents the general evaluation for each of the five Alternatives.

6.2 CONCLUSIONS AND RECOMMENDATIONS

The selection of the recommended alternative as follows was dependent on the relative importance placed on the threshold criteria of protectiveness of human health and the environment, remedial timeframe, implementability within an active air operations area, and cost:

- **Alternative 1 – No Action**—Based on the evaluation of the remedial alternatives, the No Action Alternative was omitted as the recommended alternative because the threshold criteria for protection of human health and the environment were not met.

- **Alternative 2 – Monitored Natural Attenuation with Land Use Controls**—Omitted as the recommended alternative due to the unreasonably long remedial timeframe (greater than 40 years). Although biodegradation of contaminants appears to be occurring at SS-28, the groundwater system is fairly aerobic in nature and the pH is low, which are less than optimal conditions for natural biodegradation of chlorinated VOCs. This alternative is the least expensive of all of the active remedies ($3,157,000).
- **Alternative 4 – In Situ Chemical Oxidation and In Situ Biodegradation with Land Use Controls**—Not selected as the recommended alternative because of the higher costs ($5,630,000) than Alternative 3. Both alternatives have similar remedial timeframes and implementation requirements, so the higher costs were the deciding factor.
- **Alternative 5 – Groundwater Extraction and Treatment Using Wells with In Situ Biodegradation and Land Use Controls**—Omitted as the recommended alternative because of a combination of the longer remedial timeframe (29 years), higher costs as compared to the other injection alternatives ($12,481,000), and an implementability concern due to the high initial construction efforts necessary in order to install the piping to connect the extraction wells to the treatment facility.

Based on the evaluation of the remedial alternatives in this SS-28 FS, Alternative 3 – In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls, has been proposed as the recommended alternative. Alternative 3 has the shortest remedial timeframe (20 years to response complete, plus 3 years of monitoring and documentation required for site closure), the lowest cost ($5,033,000), and manageable implementation issues. The final selection of the preferred alternative will depend on input from USEPA, MDE, Prince George's County, and the public.

7.0 REFERENCES

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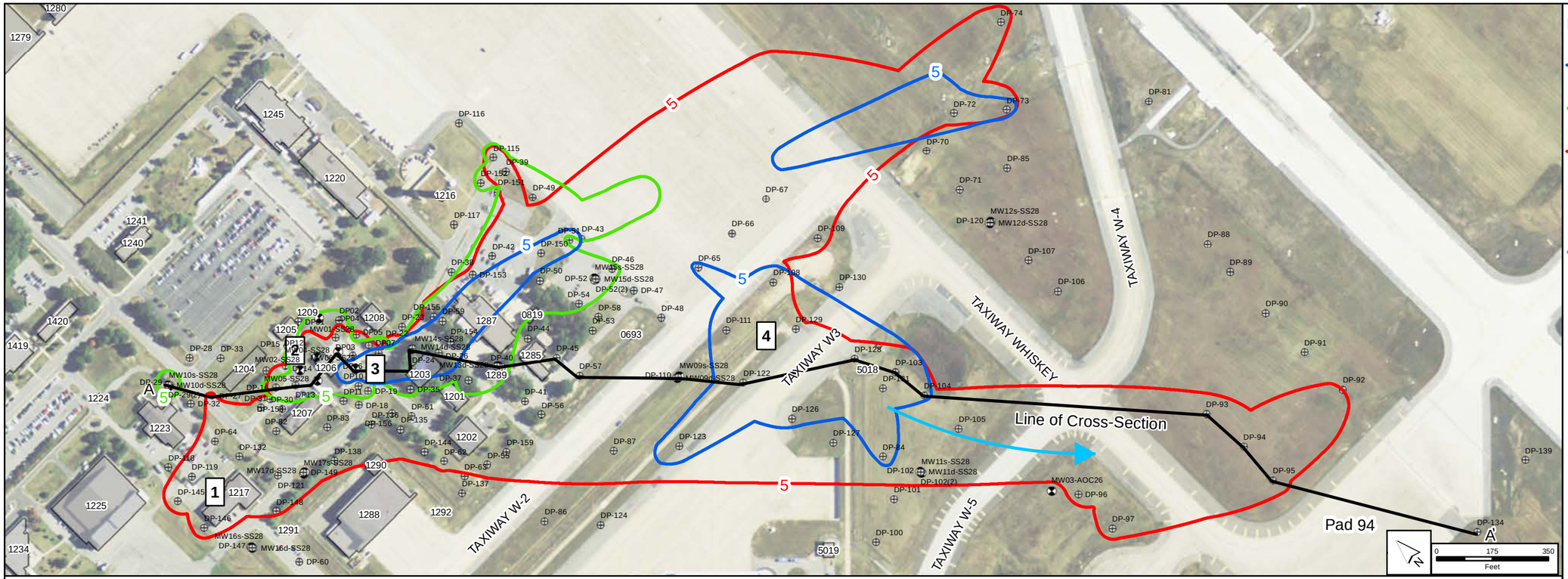
FIGURES

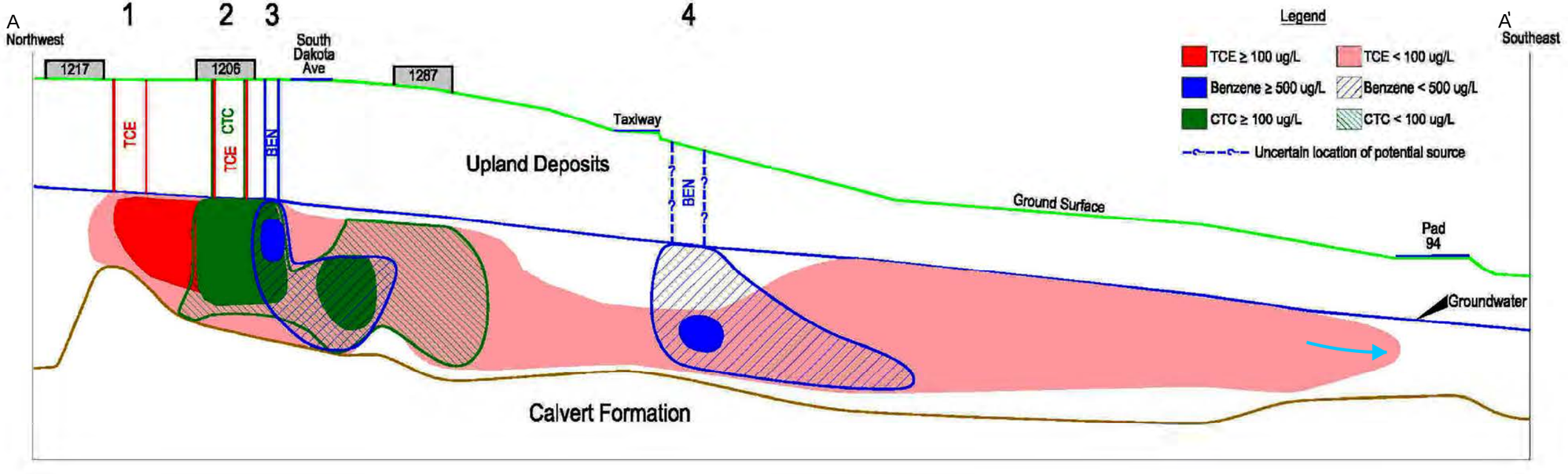


Legend

- Benzene Contour Line (Represents 5 µg/L = MCL)
- CTC Contour Line (Represents 5 µg/L = MCL)
- TCE Contour Line (Represents 5 µg/L = MCL)
- Direct Push Sample Locations
- Monitoring Well Locations
- Groundwater Flow Direction

Potential Contaminant Sources Areas

1 TCE
2 TCE + CTC
3 benzene
4 benzene



Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

Joint Base Andrews
SS-28 Site, Maryland

Figure ES-1
Nature and Extent of Contamination

Drafted: 3/4/2015
Modified:
User: johna

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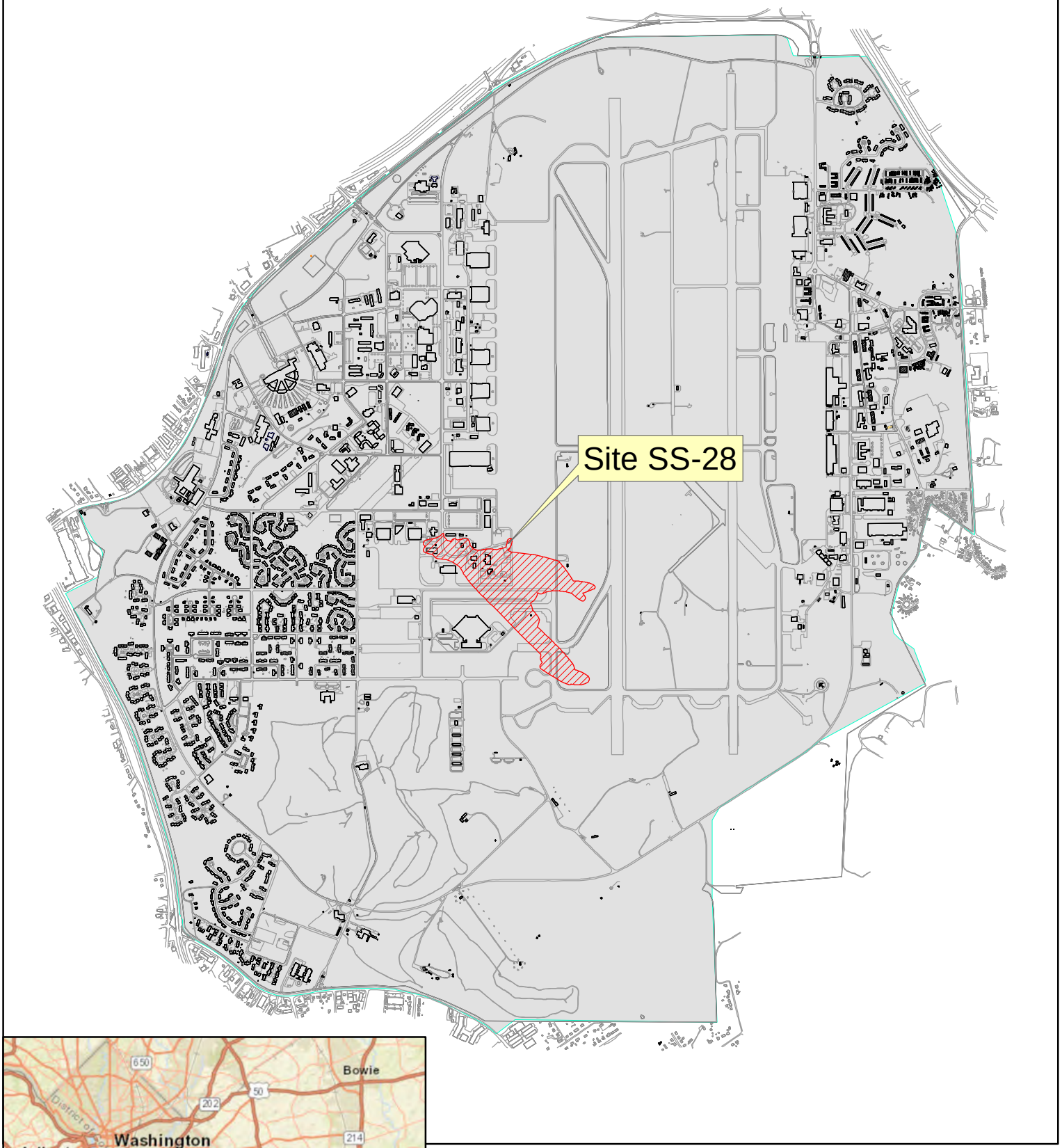

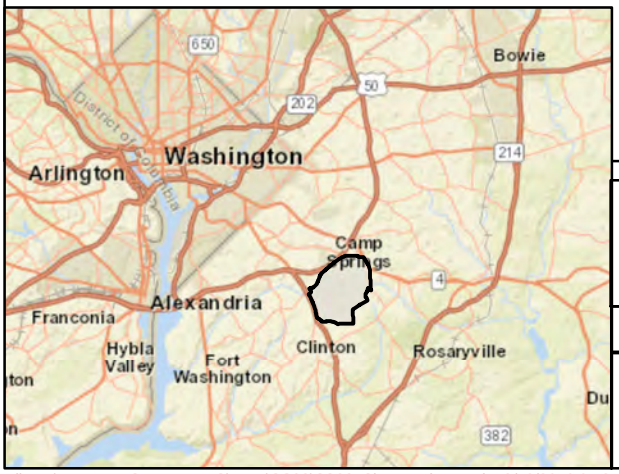

N

0 1,750 3,500

Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-1
Site Location
Site SS-28

Coordinate System:
State Plane Maryland FIPS 1900 *Linear Unit: Foot US*
Projection: Lambert Conformal Conic *Datum: D North American 1983 (NAD 83)*

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Former Hazardous Waste Storage (SWMU 40) and Waste Oil AST (SWMU 2) Area
Former Leaking Hydraulic Lifts
Fromer 1,000 Gal Fuel Oil UST
Former 6,000 Gal Diesel UST
Fuel Islands
Existing 25,000 Gal Gasoline UST
Existing 20,000 Gal Diesel UST
Former15,000 Gal Diesel UST
Taxiway W-2
Taxiway W-3
Taxiway W-4
Taxiway W-5
Taxiway Whiskey
Runway 1L/19R
Hot Pad
Pad 94

Legend
- Monitoring Well Locations
- Direct Push Sample Locations
- SS-28 100' Land Use Control Boundary

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 150 300
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-2
Site Layout Map

Drafted: 3/30/2017
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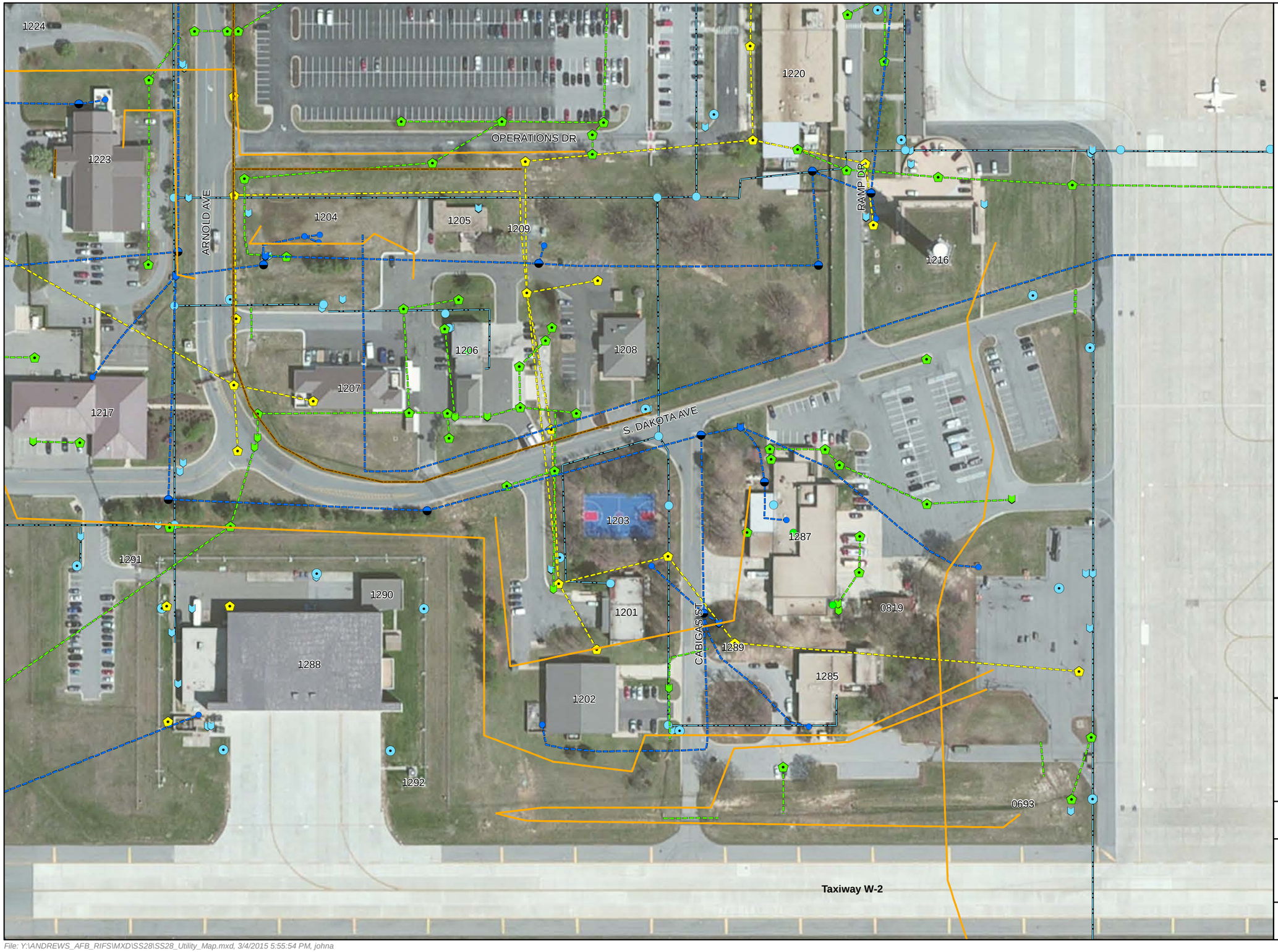

Legend

- Electrical Switching Point
- Electrical Junction Point
- Electrical Transformer
- Junction Point
- Sewer Inlet
- Oil/Water Separator
- Wastewater Junction Point
- Fire Connection/Hydrant
- Water Junction Point
- Water Valve Point
- Water Line
- Communications
- Natural Gas Line
- Electrical Lines
- Storm Sewer Line
- Wastewater Line

Source(s):
Imagery: TerraServer, 12/10/2011

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 50 100
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-3
Underground Utility Map

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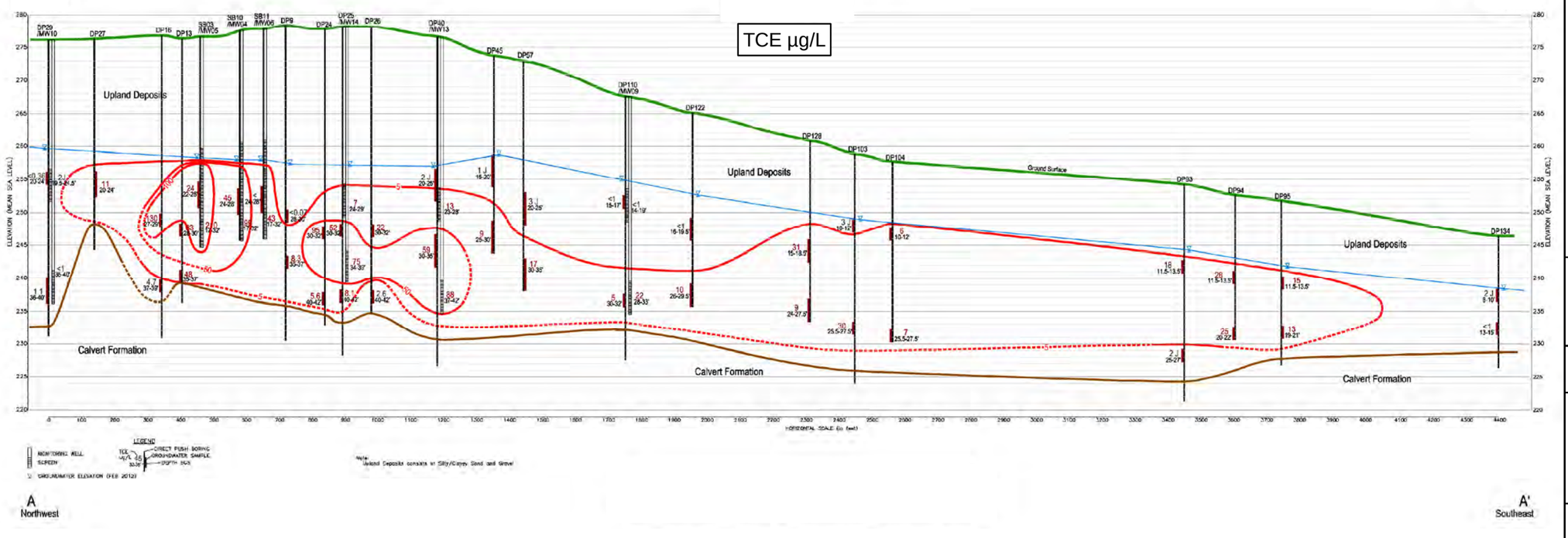
Legend

Groundwater Flow Direction



Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-4
Hydrogeologic Conceptual Site Model

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Legend

- Monitoring Well Locations
- Direct Push Sample Locations
- Calvert Elevation Contour Line (Above Mean Sea Level)
- SS-28 Boundary

Troughs in top of Calvert Formation stream channels with higher groundwater seepage velocity.

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 150 300
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-5
Top Elevation of
Calvert Formation

Drafted: 1/5/2015
Modified:
User: johna

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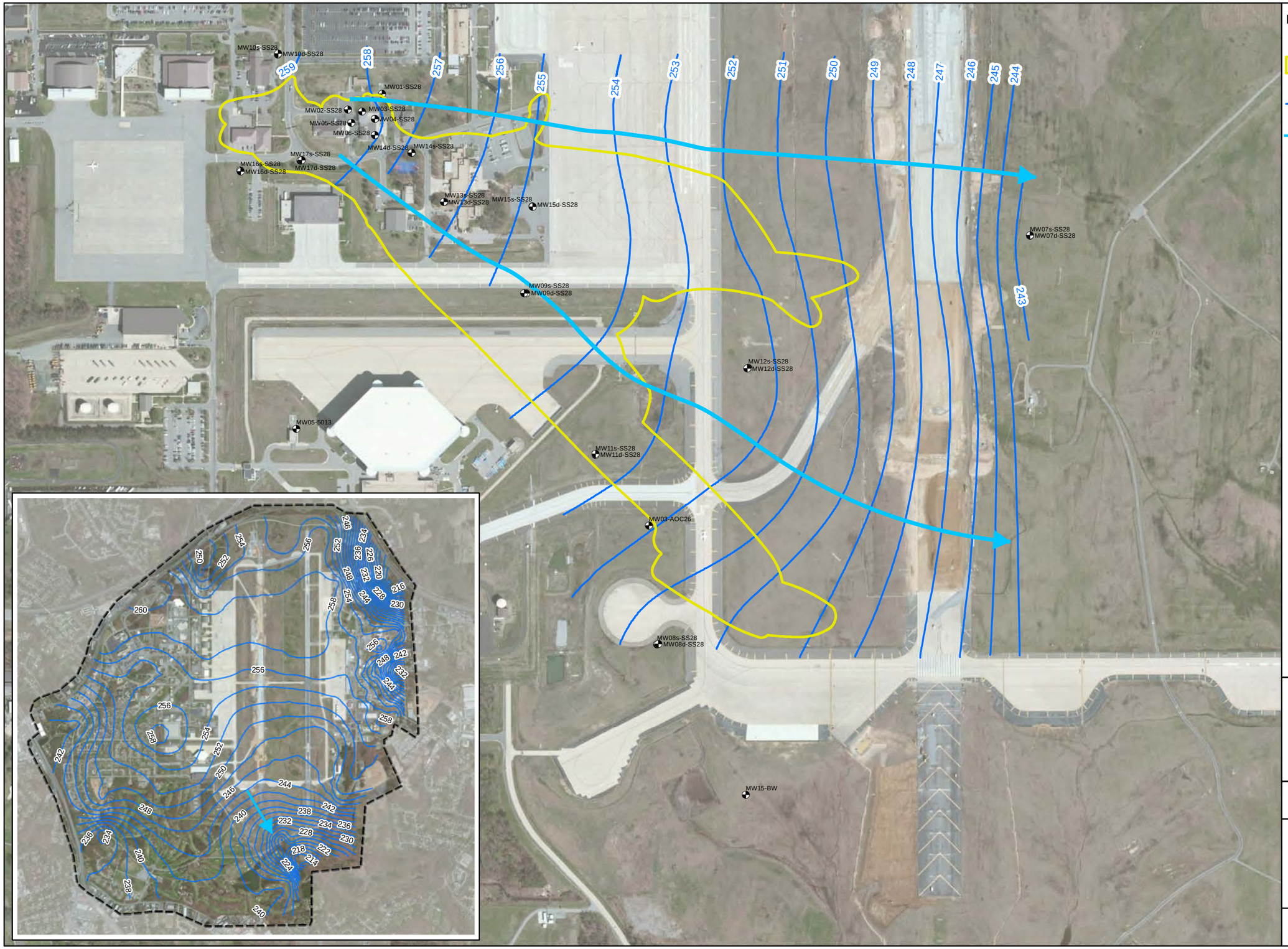

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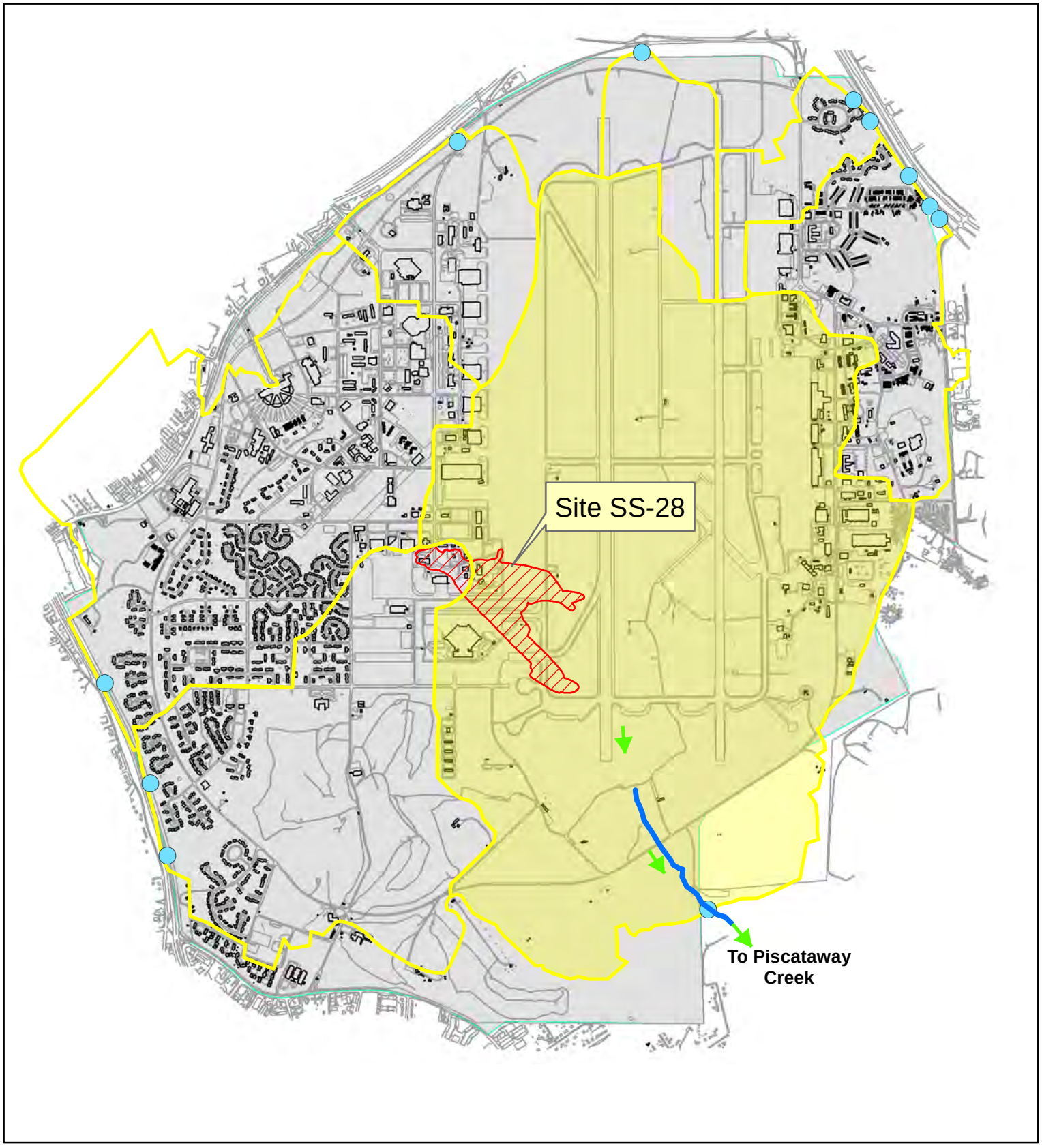

Legend

- NPDES Stormwater Monitoring Locations
- Watershed Boundary
- SS-28 Boundary
- Stream or Drainage Ditch
- Stormwater Drainage Path from SS-28

N

0 1,750 3,500

Feet

Joint Base Andrews
SS-28 Site, Maryland

WESTON SOLUTIONS

Figure 1-7
Ground Surface Elevation and Stormwater Drainage

Coordinate System:
State Plane Maryland FIPS 1900 *Linear Unit: Foot US*
Projection: Lambert Conformal Conic *Datum: D North American 1983 (NAD 83)*

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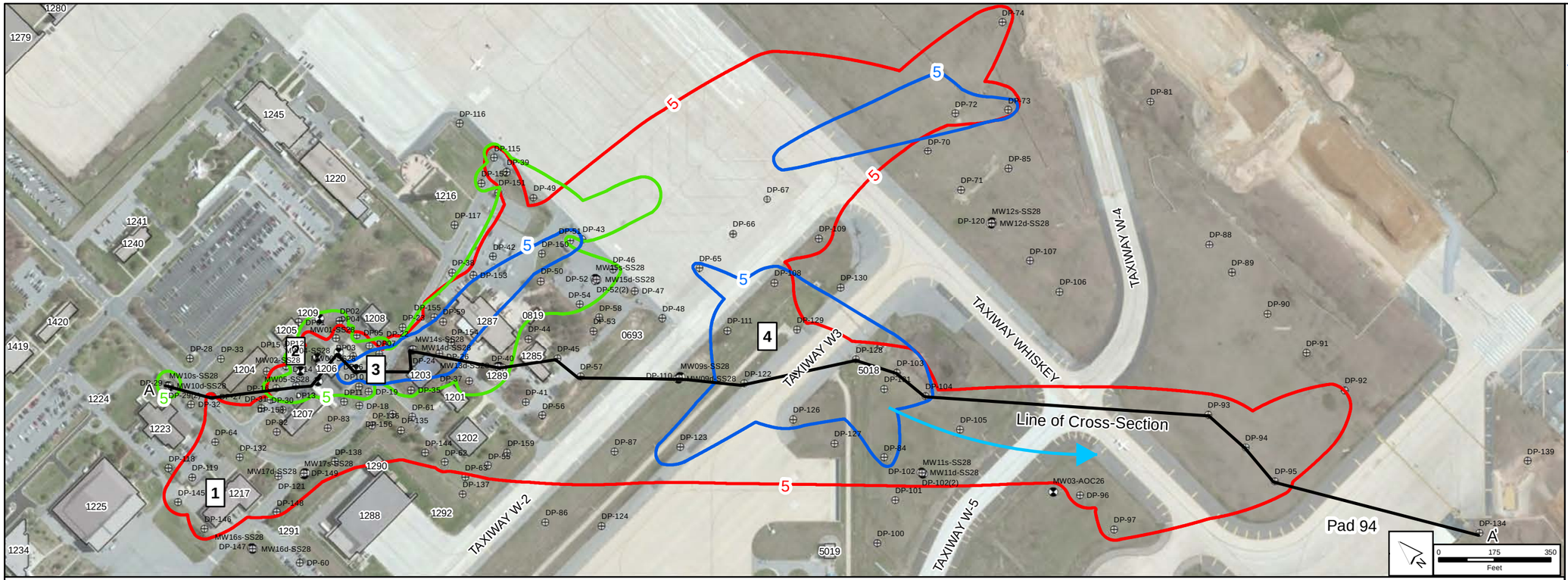
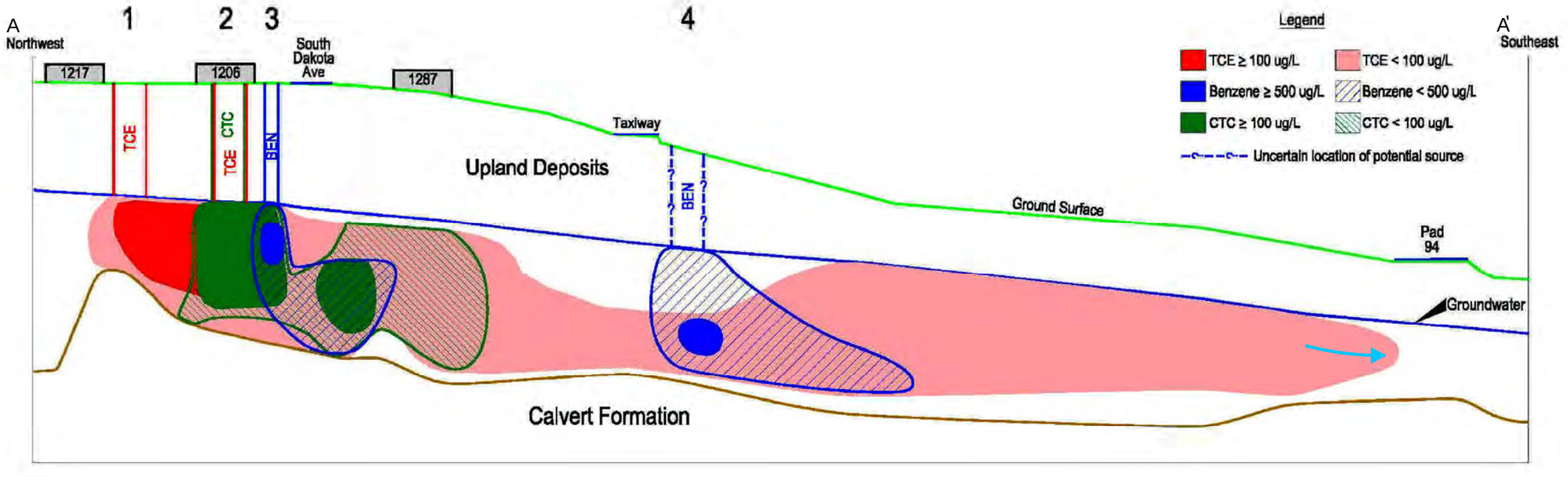


Legend

- Benzene Contour Line (Represents 5 µg/L = MCL)
- CTC Contour Line (Represents 5 µg/L = MCL)
- TCE Contour Line (Represents 5 µg/L = MCL)
- Direct Push Sample Locations
- Monitoring Well Locations
- Groundwater Flow Direction

Potential Contaminant Sources Areas

1 TCE
2 TCE + CTC
3 benzene
4 benzene



Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-8
Nature and Extent of Contamination

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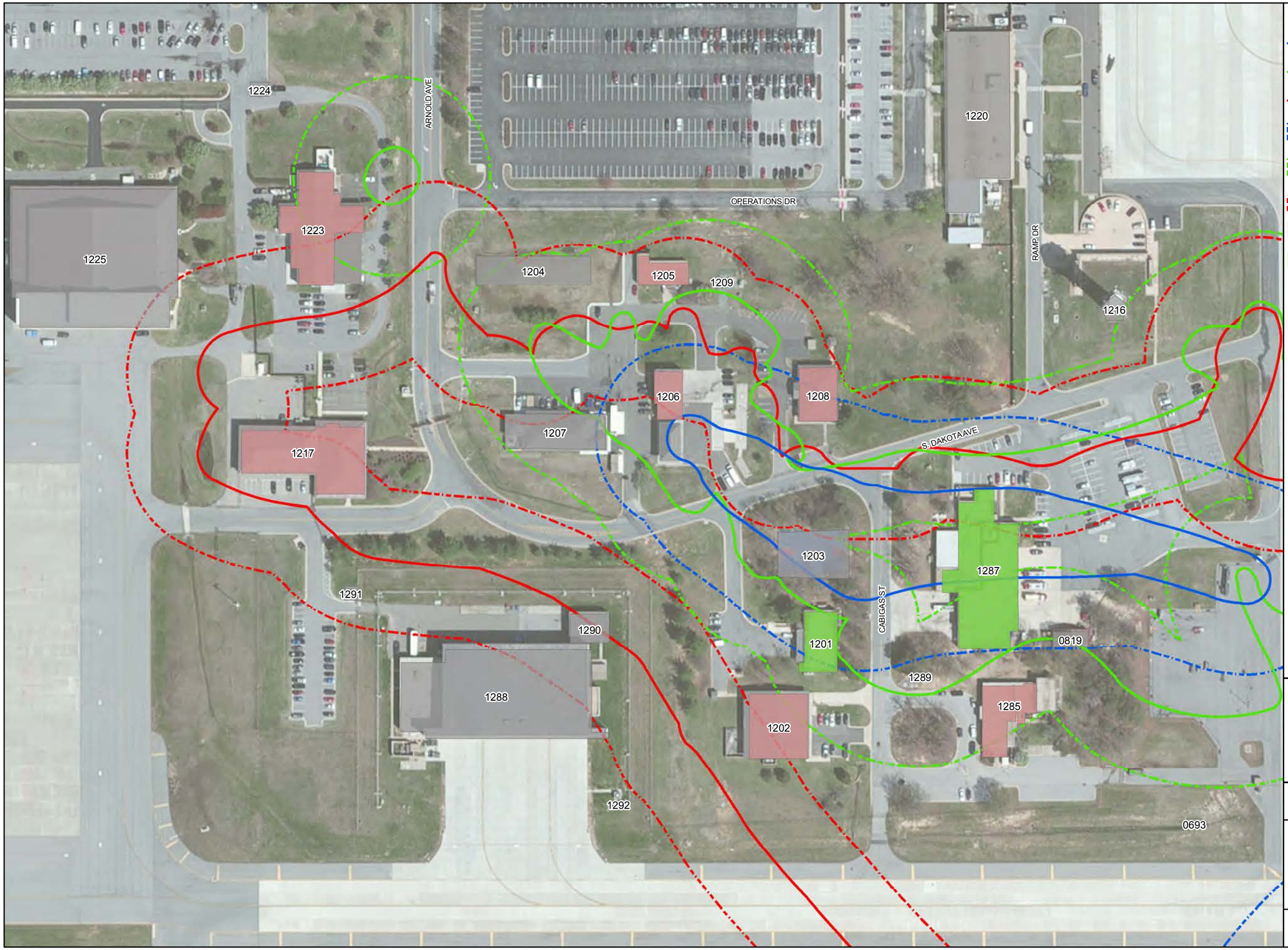

Legend

- Benzene 5 µg/L contour
- Carbon Tetrachloride 5 µg/L contour
- TCE 5 µg/L contour
- 100’ distance from Benzene Contour
- 100’ distance from Carbon Tetrachloride Contour
- 100’ distance from TCE Contour
- Vapor Samples Collected
- Indoor Vapor Samples above screening levels

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 65 130
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-9
Indoor Vapor Intrusion Locations

Drafted: 12/19/2016
Modified:
User: ricksc

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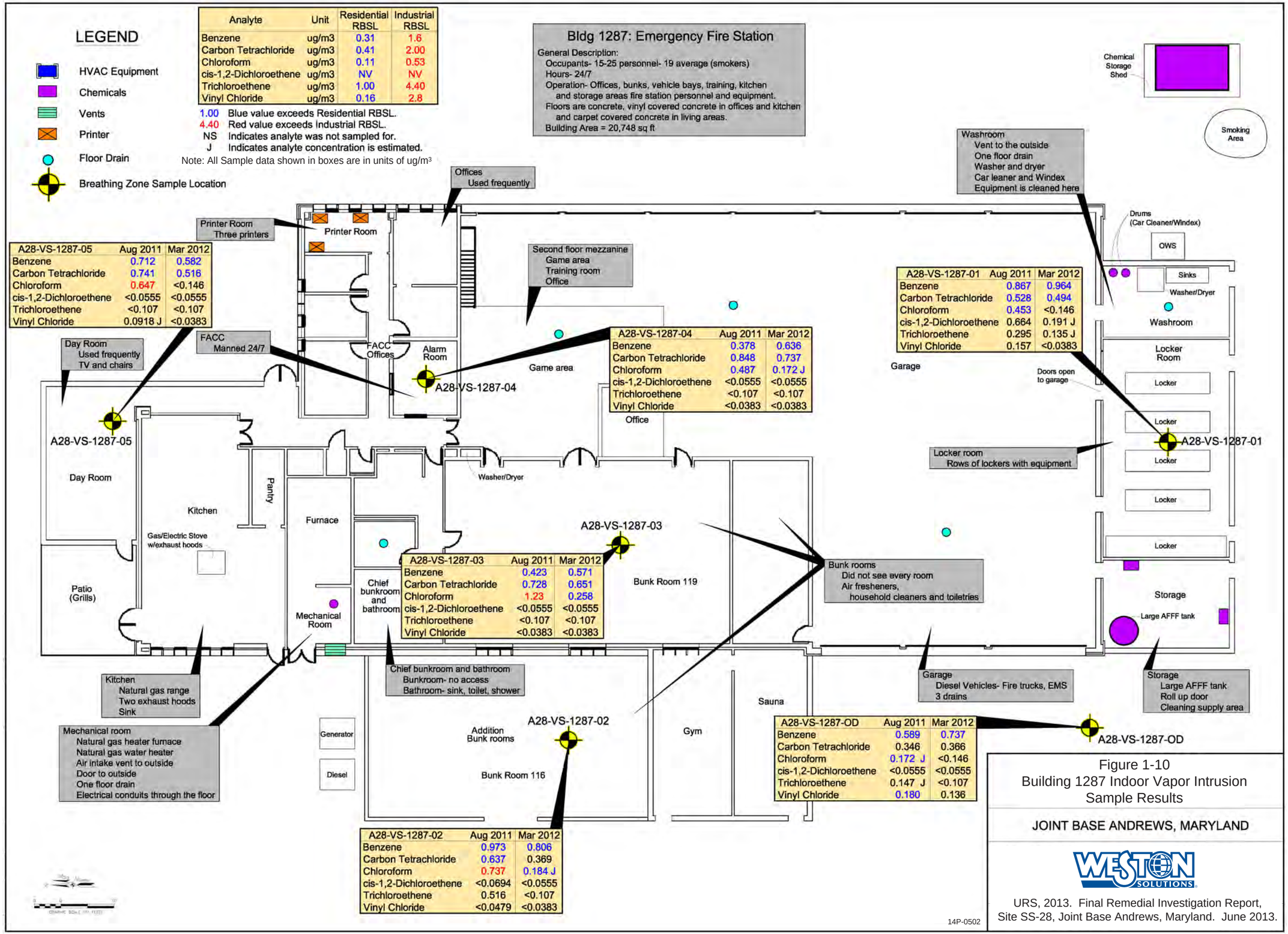


Analyte	Unit	Residential RBSL	Industrial RBSL
Benzene	ug/m3	0.31	1.6
Carbon Tetrachloride	ug/m3	0.41	2.00
Chloroform	ug/m3	0.11	0.53
cis-1,2-Dichloroethene	ug/m3	NV	NV
Trichloroethene	ug/m3	1.00	4.40
Vinyl Chloride	ug/m3	0.16	2.8

1.00 Blue value exceeds Residential RBSL.
4.40 Red value exceeds Industrial RBSL.
NS Indicates analyte was not sampled for.
J Indicates analyte concentration is estimated.
Note: All Sample data shown in boxes are in units of ug/m³

A28-VS-1287-05	Aug 2011	Mar 2012
Benzene	0.712	0.582
Carbon Tetrachloride	0.741	0.516
Chloroform	0.647	<0.146
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	0.0918 J	<0.0383

A28-VS-1287-04	Aug 2011	Mar 2012
Benzene	0.378	0.636
Carbon Tetrachloride	0.848	0.737
Chloroform	0.487	0.172 J
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	<0.0383	<0.0383

A28-VS-1287-01	Aug 2011	Mar 2012
Benzene	0.867	0.964
Carbon Tetrachloride	0.528	0.494
Chloroform	0.453	<0.146
cis-1,2-Dichloroethene	0.664	0.191 J
Trichloroethene	0.295	0.135 J
Vinyl Chloride	0.157	<0.0383

A28-VS-1287-03	Aug 2011	Mar 2012
Benzene	0.423	0.571
Carbon Tetrachloride	0.728	0.651
Chloroform	1.23	0.258
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	<0.0383	<0.0383

A28-VS-1287-02	Aug 2011	Mar 2012
Benzene	0.973	0.806
Carbon Tetrachloride	0.637	0.369
Chloroform	0.737	0.184 J
cis-1,2-Dichloroethene	<0.0694	<0.0555
Trichloroethene	0.516	<0.107
Vinyl Chloride	<0.0479	<0.0383

A28-VS-1287-OD	Aug 2011	Mar 2012
Benzene	0.589	0.737
Carbon Tetrachloride	0.346	0.366
Chloroform	0.172 J	<0.146
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	0.147 J	<0.107
Vinyl Chloride	0.180	0.136

Figure 1-10
Building 1287 Indoor Vapor Intrusion Sample Results

JOINT BASE ANDREWS, MARYLAND

WESTON SOLUTIONS

URS, 2013. Final Remedial Investigation Report, Site SS-28, Joint Base Andrews, Maryland. June 2013.

Dumpster

Bldg 1201: In-Flight Kitchen

General Description:
Occupants- 2 to 3 personnel (some smokers)
Hours- 24/7
Operation- Handle prepared foods, office work
Exposed concrete floor except tile in kitchen, bathrooms
Building Area = 3,896 sq ft

Notes:
Refrigerator/Freezer Rooms all excluded because of cold temperatures

Smoking Area

Ramp

LEGEND

- HVAC Equipment
- Chemicals
- Vents
- Printer
- Floor Drain
- Breathing Zone Sample Location

Analyte	Unit	Residential RBSL	Industrial RBSL
Benzene	ug/m3	0.31	1.6
Carbon Tetrachloride	ug/m3	0.41	2.00
Chloroform	ug/m3	0.11	0.53
cis-1,2-Dichloroethene	ug/m3	NV	NV
Trichloroethene	ug/m3	1.00	4.40
Vinyl Chloride	ug/m3	0.16	2.8

1.00 Blue value exceeds Residential RBSL.
4.40 Red value exceeds Industrial RBSL.
NS Indicates analyte was not sampled for.
J Indicates analyte concentration is estimated.
Note: All Sample data shown in boxes is in units of ug/m ^{3}

Mag. North

GRAPHIC SCALE (IN FEET)

Storage 1
Open to outdoors/loading dock area

Ice Maker Room
Used infrequently

Loading Dock

Storage 1

A28-VS-1201-03	Aug 2011	Mar 2012
Benzene	0.737	0.810
Carbon Tetrachloride	0.498	0.403
Chloroform	0.676	0.365
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	<0.0383	<0.0383

A28-VS-1201-03

Heat Exchange For Freezer

Freezer

Office 2

Ice Maker Room

Ice Maker

Storage 2
Outside door leads to loading dock and smoking area

Storage 2

Boiler Room
Door to outdoors
Large vent to outdoors

Boiler Room

A28-VS-1201-05	Aug 2011	Mar 2012
Benzene	0.495	0.741
Carbon Tetrachloride	0.557	0.423
Chloroform	0.922	0.795
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	0.495	<0.107
Vinyl Chloride	<0.0383	<0.0383

A28-VS-1201-04

Office 3

A28-VS-1201-05

Hall Area
One floor drain

Hall Area

A28-VS-1201-01

A28-VS-1201-01	Aug 2011	Mar 2012
Benzene	0.339	0.813
Carbon Tetrachloride	0.539	0.455
Chloroform	3.37	1.12
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	<0.0383	<0.0383

Kitchen

Office 2
Used frequently
One printer

Wash Sink/Cleaning Closet
Not enough space to sample and maintain staff access

#2 Fuel Oil

A28-VS-1201-02

Office 3
Used frequently
No printers
No outside doors

A28-VS-1201-04	Aug 2011	Mar 2012
Benzene	0.783	0.830
Carbon Tetrachloride	0.622	0.421
Chloroform	0.429	0.324
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	0.103 J	<0.0383

Closet

Men's BR

Women's BR

Women's Bathroom
Beauty supplies (body spray, soaps, hair spray) and air freshener
One floor drain

A28-VS-1201-02	Aug 2011	Mar 2012
Benzene	0.668	0.822
Carbon Tetrachloride	0.489	0.509
Chloroform	2.03	2.19
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	<0.107	<0.107
Vinyl Chloride	0.108 J	<0.0383

Office 1

Freezers

Freezers

Men's Bathroom
Air freshener and soaps located here

Elec. Oven

A28-VS-1201-OD

Kitchen
Door and window to outside
Used frequently by staff

Office 1
3 printers located here
Window (HVAC units outside)

A28-VS-1201-OD	Aug 2011	Mar 2012
Benzene	1.81	0.856
Carbon Tetrachloride	0.593	0.399
Chloroform	1.17	<0.146
cis-1,2-Dichloroethene	<0.0555	<0.0555
Trichloroethene	0.122 J	<0.107
Vinyl Chloride	1.11	0.108 J

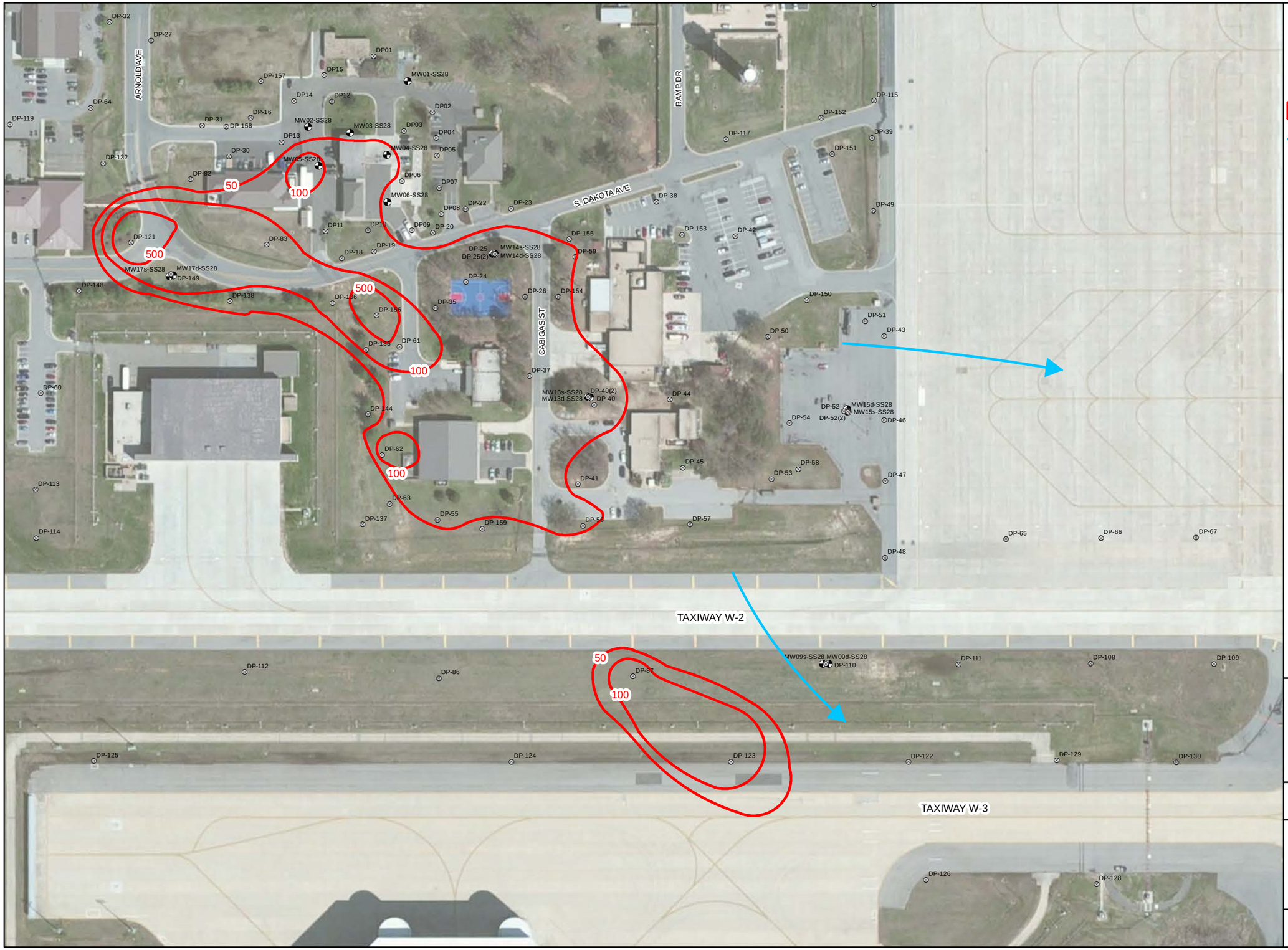
14P-0502-1

Figure 1-11
Building 1201 Indoor Vapor Intrusion Sample Results

JOINT BASE ANDREWS, MARYLAND

WESTON SOLUTIONS

URS, 2013. Final Remedial Investigation Report, Site SS-28, Joint Base Andrews, Maryland. June 2013.



Legend

- Monitoring Well Locations
- Direct Push Sample Locations
- Trichloroethene Plume Concentrations (ppb)
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-12
Trichloroethene
Groundwater Contamination
Plume

Drafted: 3/18/2015
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User: johna

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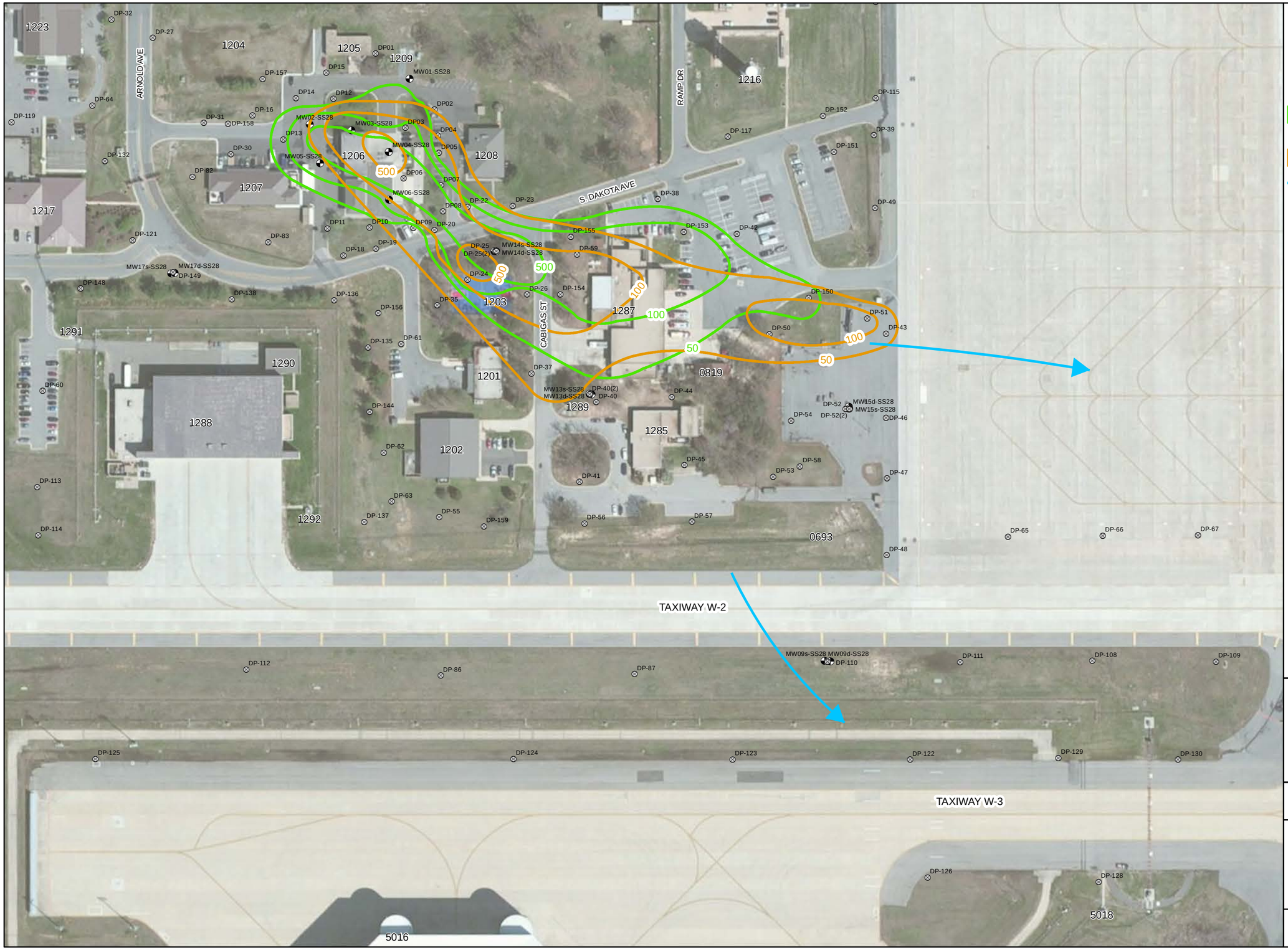

Legend

- Monitoring Well Locations
- Direct Push Sample Locations
- Carbon Tetrachloride Plume Concentrations (ppb)
- Chloroform Plume Concentrations (ppb)
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 1-13
Carbon Tetrachloride Groundwater Contamination Plume

Drafted: 3/18/2015
Modified:
User: johna

WESTON SOLUTIONS

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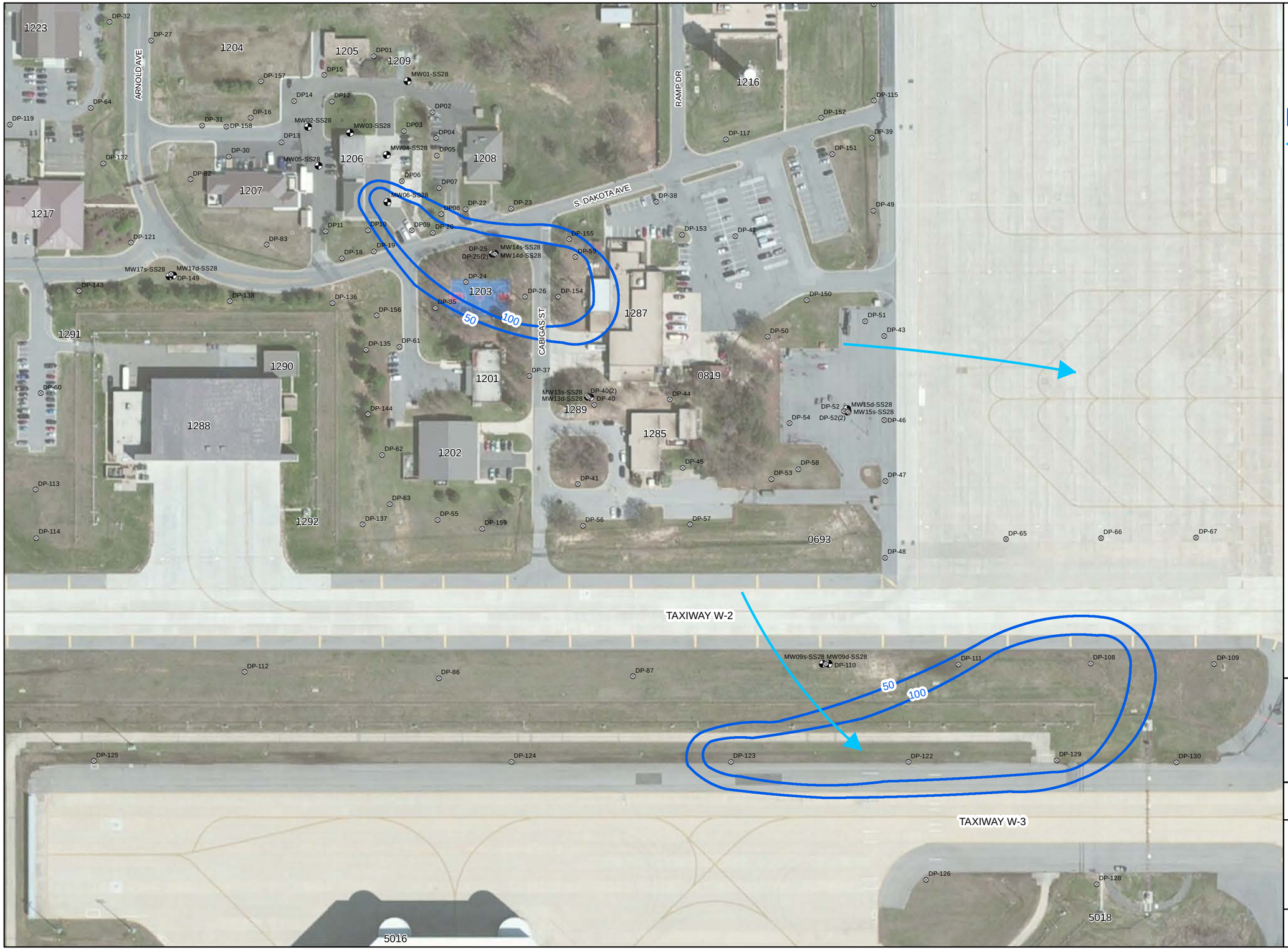


Legend

- Monitoring Well Locations
- Direct Push Sample Locations
- Benzene Plume Concentrations (ppb)
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150
Feet

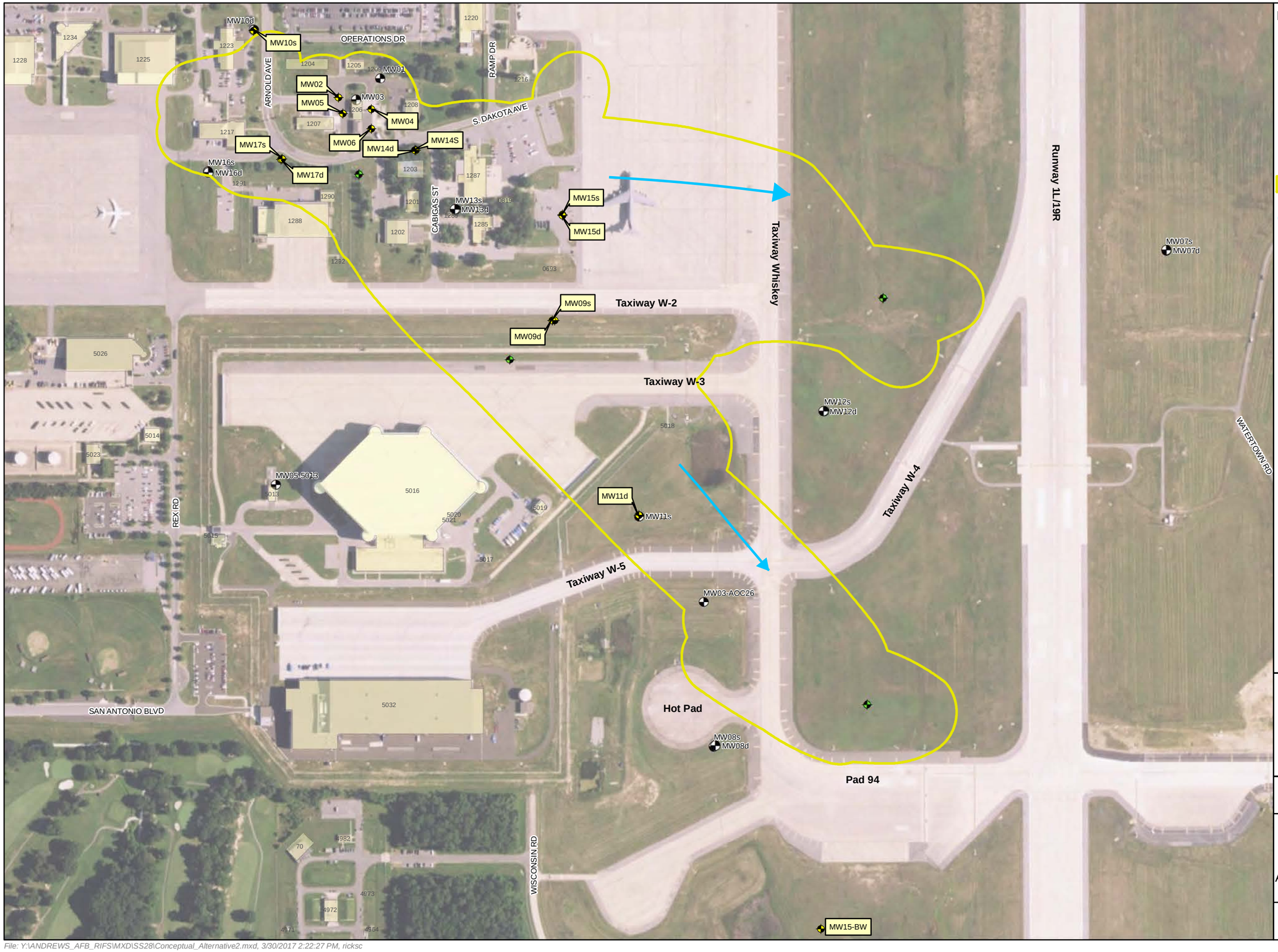
Joint Base Andrews
SS-28 Site, Maryland

Figure 1-14
Benzene
Groundwater Contamination
Plume

Drafted: 3/4/2015
Modified:
User: johna

WESTON SOLUTIONS

File: Y:\ANDREWS_AFB_RIFS\MXD\SS28\Benzene_GW_contamination_plume.mxd, 3/4/2015 5:53:33 PM, johna



Legend

- Monitoring Well Locations
- Indicator Wells Utilized in the Long-Term Monitoring Program
- Proposed New Indicator Well Location (part of Long-Term Monitoring Well Network)
- SS-28 100' Land Use Control Boundary
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 150 300
Feet

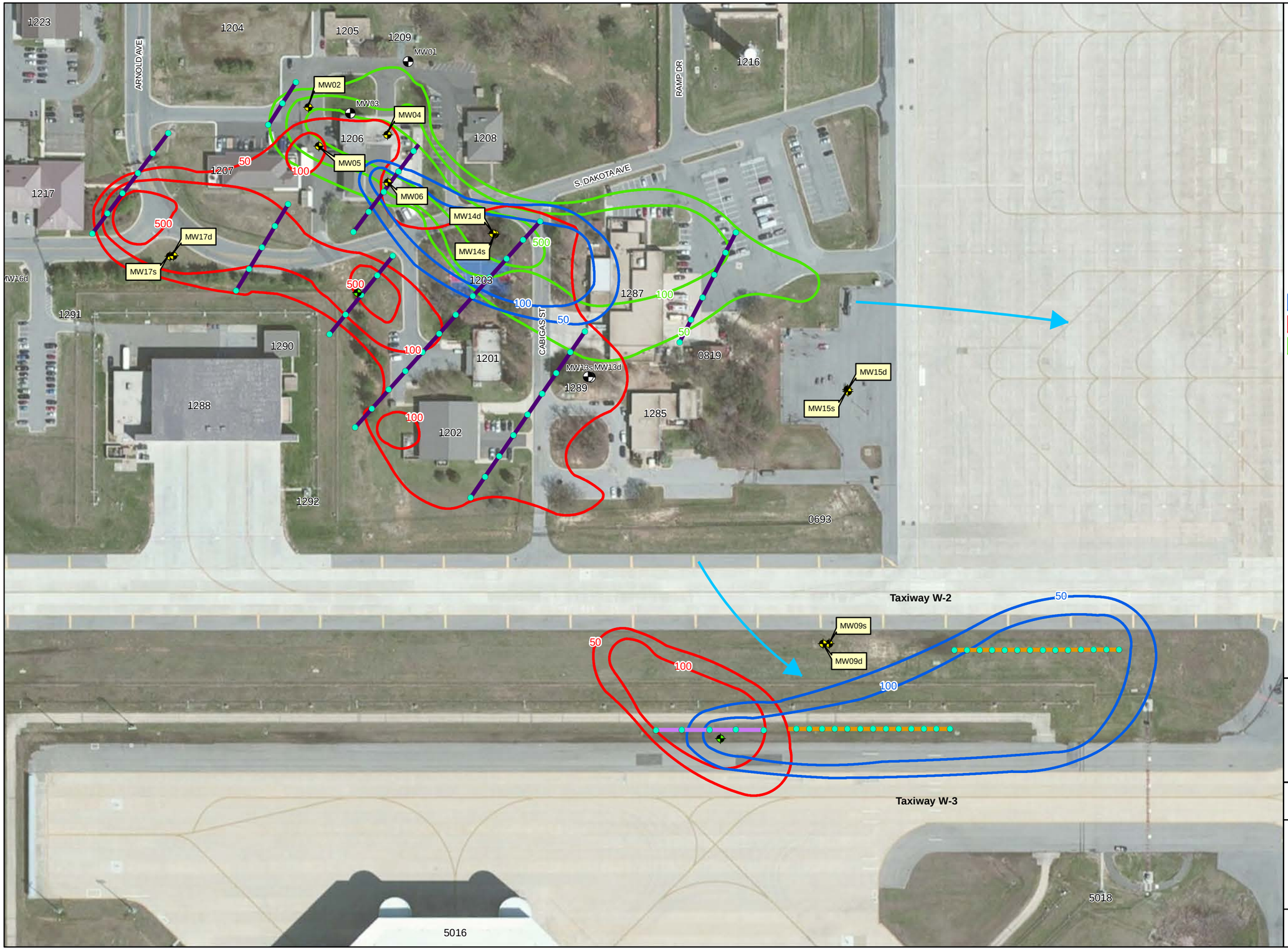
Joint Base Andrews
SS-28 Site, Maryland

Figure 4-1
Conceptual Layout Remedial Alternative 2: Monitored Natural Attenuation with Land Use Controls

Drafted: 3/30/2017
Modified:
User: ricksc

WESTON SOLUTIONS

File: Y:\ANDREWS_AFB_RIFS\MXD\SS28\Conceptual_Alternative2.mxd, 3/30/2017 2:22:27 PM, ricksc



Legend

- Monitoring Locations
- Indicator Wells Utilized in the Long-Term Monitoring Program
- Proposed New Indicator Well Location (part of Long-Term Monitoring Well Network)
- Injection Points
- 20 ft — Aerobic ISB Injection event row
- 50 ft — Anaerobic ISB Injection event row
- 40 ft — Anaerobic ISB/ISCR Injection event row
- Benzene
- TCE
- Carbon Tetrachloride
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 4-2
Conceptual Layout Remedial Alternative 3: In Situ Biodegradation and Chemical Reduction

Drafted: 7/16/2015
Modified:
User: johna

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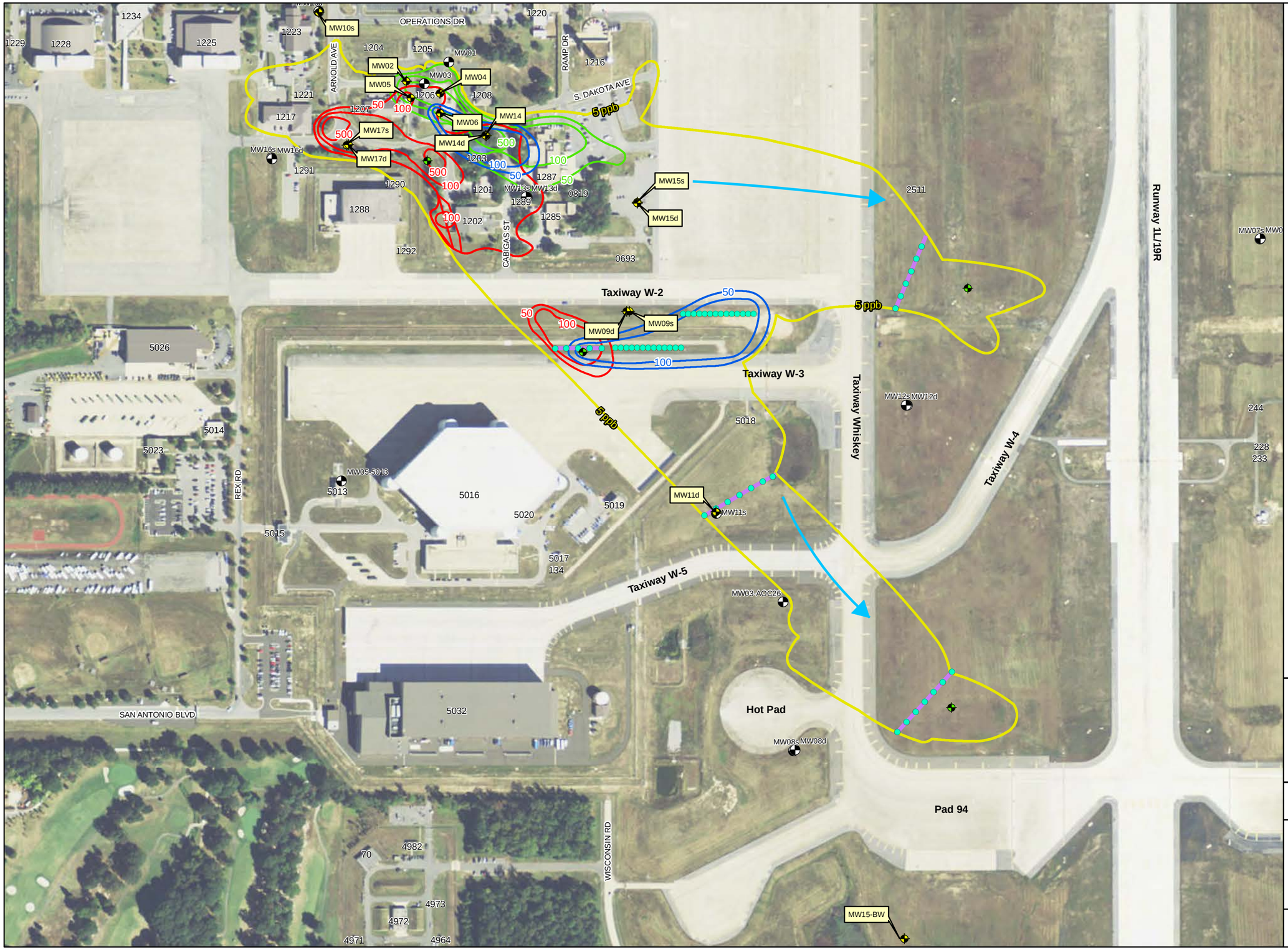

Legend

- Monitoring Locations
- Indicator Wells Utilized in the Long-Term Monitoring Program
- Proposed New Indicator Well Location (part of Long-Term Monitoring Well Network)
- Injection Points
- Aerobic ISB Injection event row (20 ft)
- Anaerobic ISB Injection event row (50 ft)
- Benzene
- TCE
- Carbon Tetrachloride
- SS-28 Boundary
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150 300
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 4-3
Conceptual Layout Remedial Alternatives 3, 4, 5: Downgradient In Situ Biodegradation

Drafted: 3/4/2015
Modified:
User: johna

WESTON SOLUTIONS

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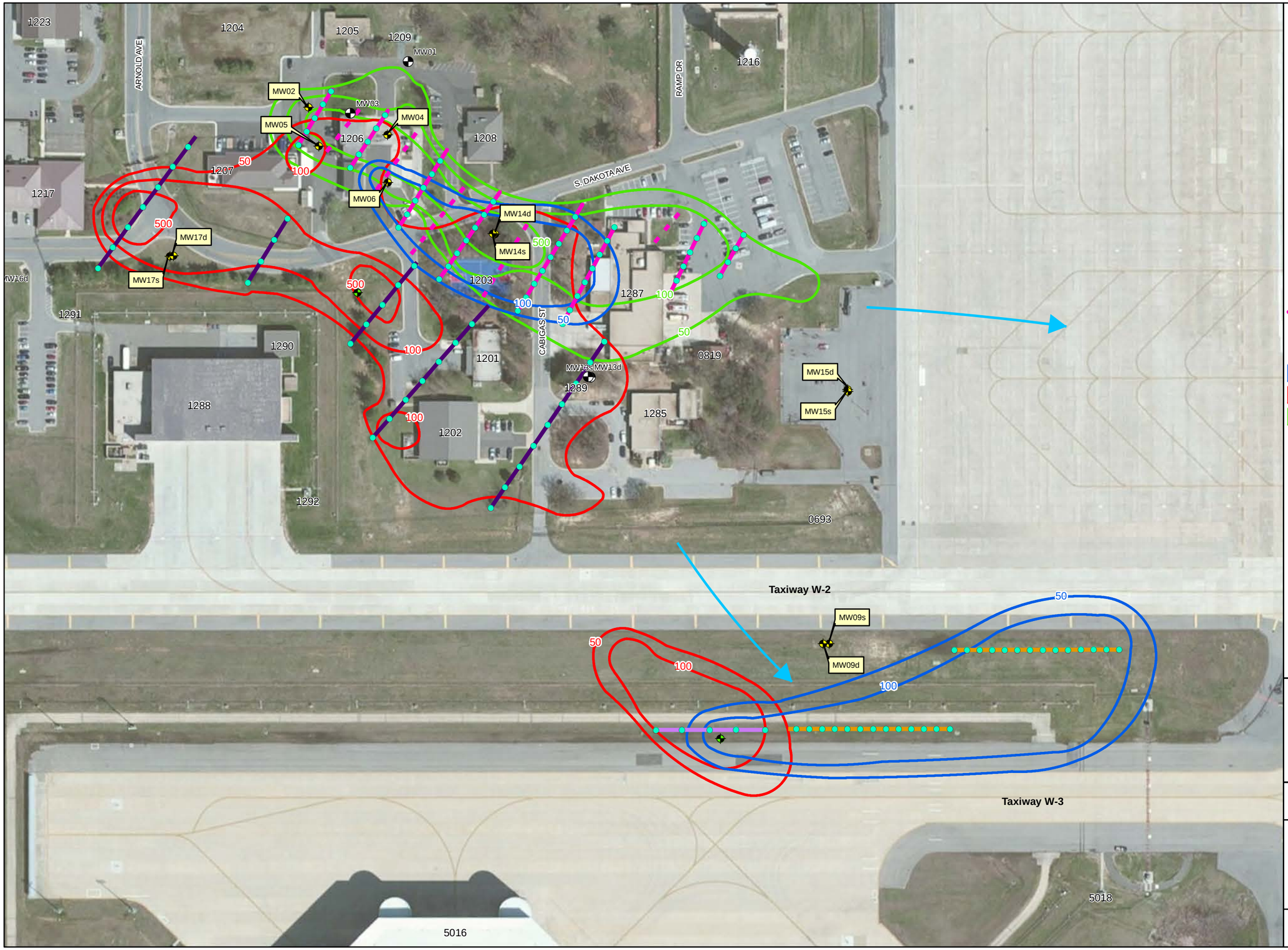

Legend

- Monitoring Locations
- Indicator Wells Utilized in the Long-Term Monitoring Program
- Proposed New Indicator Well Location (part of Long-Term Monitoring Well Network)
- Injection Points
- 20 ft — Aerobic ISB Injection event row
- 50 ft — Anaerobic ISB Injection event row
- 40 ft — Anaerobic ISB/ISCR Injection event row
- 25 ft — First ISCO injection event row
- Second ISCO injection event row
- Benzene
- TCE
- Carbon Tetrachloride
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 4-4
Conceptual Layout Remedial Alternative 4: In Situ Chemical Oxidation and In Situ Biodegradation

Drafted: 3/18/2015
Modified:
User: johna

WESTON SOLUTIONS

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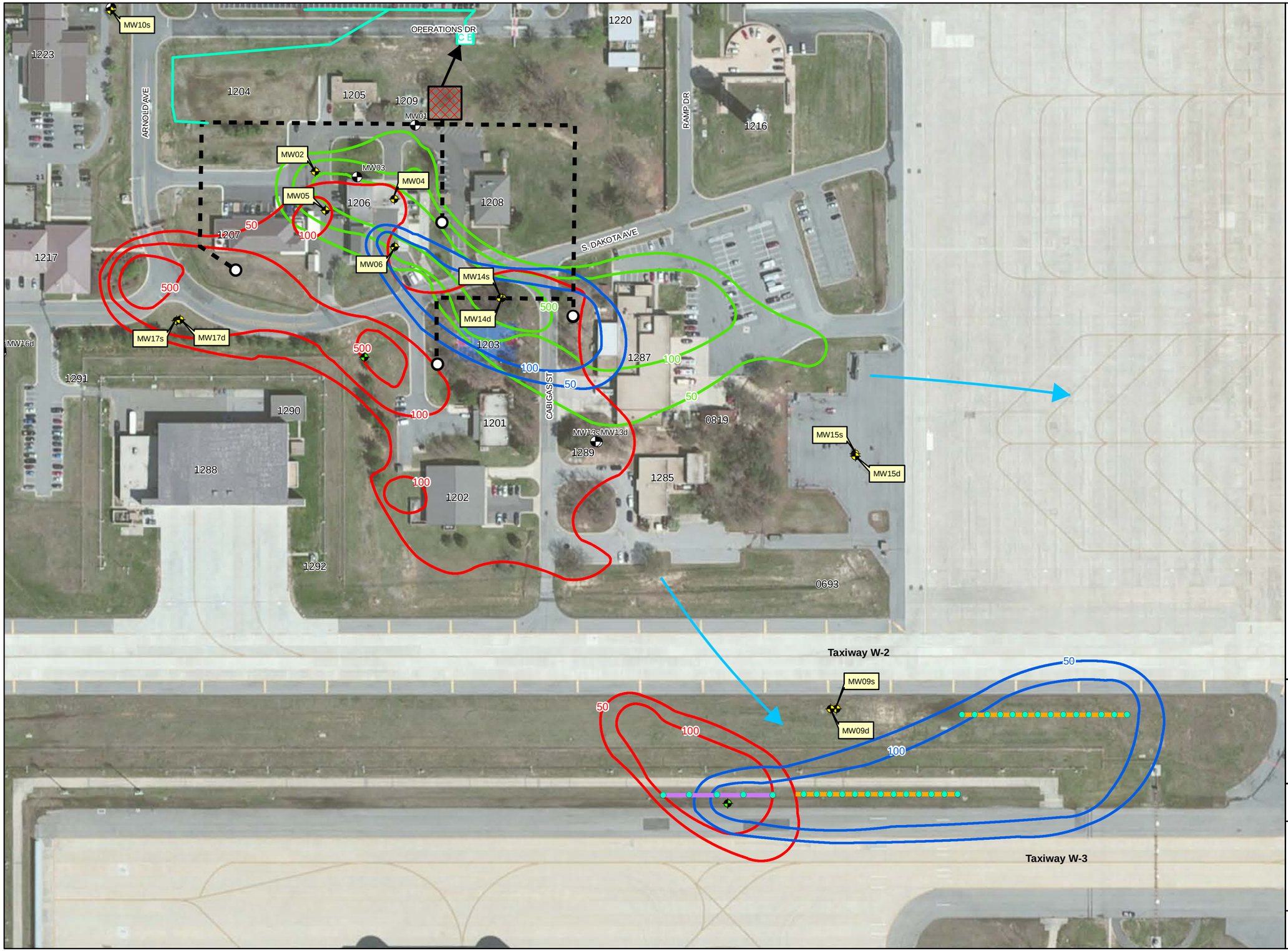


Legend

- Monitoring Locations
- Indicator Wells Utilized in the Long-Term Monitoring Program
- Proposed New Indicator Well Location (part of Long-Term Monitoring Well Network)
- Injection Points
- Vertical Groundwater Extraction Wells
- C B — Storm Sewer Curb Inlet
- Storm Sewer
- 20 ft — Aerobic ISB Injection event row
- 50 ft — Anaerobic ISB Injection event row
- Pumping Pipelines
- Benzene
- TCE
- Carbon Tetrachloride
- Groundwater Treatment Plant
- Groundwater Flow Direction

Coordinate System:
State Plane Maryland FIPS 1900
Projection: Lambert Conformal Conic

Linear Unit: Foot US
Datum: D North American 1983 (NAD 83)

N

0 75 150
Feet

Joint Base Andrews
SS-28 Site, Maryland

Figure 4-5
Conceptual Layout Remedial Alternative 5: Groundwater Extraction and Treatment Using Vertical Well Technology

Drafted: 3/18/2015
Modified:
User: johna

WESTON SOLUTIONS

File: Y:\ANDREWS_AFB_RIFS\MXD\SS28\Conceptual_Alternative5.mxd, 3/18/2015 2:18:05 PM, johna

TABLES

Table 1-1 Contaminants Detected Above Federal/State Contaminant Levels in Groundwater
SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Contaminant	USEPA Maximum Contaminant Level (µg/L)	Maximum Detected Concentration (µg/L)	Sampling Location	Number of Locations Exceeding Federal/State Standard	
				Monitoring Wells (24 total)	Direct-Push (157 total)
Benzene	5	270	MW06	2	22
		2,800	DP20		
Carbon Tetrachloride	5	2,200	MW04	14	37
		1,200	DP24		
Chloroform	80	610	MW04	6	16
		510	DP24		
1,2-DCA	5	9	MW14d	2	8
		63	DP20		
Naphthalene	0.65*	10	MW05-5013	1	19
		180	DP20		
PCE	5	13	MW07d	3	3
		24	DP115		
TCE	5	210	MW05	18	89
		1,200	DP121		

Notes:

DCA = dichloroethane.

PCE = tetrachloroethene.

TCE = trichloroethene.

USEPA = United States Environmental Protection Agency.

µg/L = microgram per liter.

MCL = maximum contaminant level

* - no USEPA MCL Standard.

Value shown is Maryland Department of the Environment Water Quality Standard for compound.

Table 1-2

SUMMARY OF RECEPTOR RISKS AND HAZARDS FOR COPCs

REASONABLE MAXIMUM EXPOSURE

Indoor Worker, Groundwater to Indoor Air

Joint Base Andrews, MD - SS-28

Scenario Timeframe:	Future
Receptor Population:	Indoor Worker
Receptor Age:	Adult

Medium	Exposure Medium	Exposure Point	Chemical of Potential Concern	Carcinogenic Risk					Non-Carcinogenic Hazard Quotient				
				Ingestion	Inhalation	Dermal	External (Radiation)	Exposure Routes Total	Primary Target Organ(s)	Ingestion	Inhalation	Dermal	Exposure Routes Total
Indoor Air	Indoor Air	Indoor Air at Site	**Volatile Organic Compounds**										
			Chloroform	--	4.E-06	--	--	4.E-06	liver	--	5.E-03	--	0.005
			Chemical Total	--	4.E-06	--	--	4.E-06		--	5.E-03	--	0.005
		Exposure Point Total						4.E-06					0.005
	Exposure Medium Total							4.E-06					0.005
Medium Total								4.E-06					0.005
Receptor Total							Receptor Risk Total	4.E-06				Receptor HI Total	0.005

Source: URS Corp. RI Report, 2013

Table 1-3

SUMMARY OF RECEPTOR RISKS AND HAZARDS FOR COPCs

REASONABLE MAXIMUM EXPOSURE

Adult Resident, Groundwater

Joint Base Andrews, MD - SS-28

Scenario Timeframe:	Future
Receptor Population:	Resident
Receptor Age:	Adult

Medium	Exposure Medium	Exposure Point	Chemical of Potential Concern	Carcinogenic Risk					Non-Carcinogenic Hazard Quotient				
				Ingestion	Inhalation	Dermal	External (Radiation)	Exposure Routes Total	Primary Target Organ(s)	Ingestion	Inhalation	Dermal	Exposure Routes Total
Groundwater	Groundwater	Groundwater at Site	**Volatile Organic Compounds**										
			1,2-Dichloroethane	7.E-06	--	3.E-07	--	7.E-06	kidney	0.04	--	0.001	0.04
			Benzene	3.E-05	--	3.E-06	--	3.E-05	blood/immun	0.4	--	0.05	0.4
			Carbon tetrachloride	7.E-04	--	1.E-04	--	0.E+00	liver	7	--	1	8
			Chloroform	9.E-05	--	6.E-06	--	9.E-05	liver	0.8	--	0.06	0.9
			cis-1,2-Dichloroethene	--	--	--	--	0.E+00	kidney	0.02	--	0.001	0.02
			Ethylbenzene	3.E-06	--	2.E-06	--	5.E-06	liver/kidney	0.009	--	0.004	0.01
			Methyl tert-butyl ether (MTBE)	1.E-07	--	4.E-09	--	1.E-07	NA	--	--	--	0
			Tetrachloroethene (PCE)	3.E-08	--	1.E-08	--	4.E-08	NS	0.006	--	0.003	0.009
			Trichloroethene (TCE) ADAF (0 - < 16 yrs)	2.E-05	--	2.E-06	--	2.E-05	thym/immun/heart	--	--	--	0
			Trichloroethene (TCE) ADAF (>16 - 70 yrs)	3.E-05	--	4.E-06	--	3.E-05	thym/immun/heart	--	--	--	0
			Trichloroethene (TCE)	--	--	--	--	0.E+00	thym/immun/heart	5	--	0.6	6
			Chemical Total	8.E-04	--	1.E-04	--	1.E-03		13	--	2	15
		Exposure Point Total						1.E-03					15
	Exposure Medium Total							1.E-03					15
	Air	Vapors While Showering	**Volatile Organic Compounds**										
			1,2-Dichloroethane	--	1.E-05	--	--	1.E-05	NS	--	0.2	--	0.2
			Benzene	--	3.E-05	--	--	3.E-05	blood	--	0.4	--	0.4
			Carbon tetrachloride	--	3.E-04	--	--	3.E-04	liver	--	2	--	2
			Chloroform	--	4.E-04	--	--	4.E-04	liver	--	0.5	--	0.5
			cis-1,2-Dichloroethene	--	--	--	--	0.E+00	NA	--	--	--	0
			Ethylbenzene	--	5.E-06	--	--	5.E-06	fetus	--	0.006	--	0.006
			Methyl tert-butyl ether (MTBE)	--	1.E-07	--	--	1.E-07	liver/kidney/eyes	--	0.0004	--	0.0004
			Tetrachloroethene (PCE)	--	2.E-08	--	--	2.E-08	NS	--	0.005	--	0.005
			Trichloroethene (TCE)	--	2.E-05	--	--	2.E-05	thym/immun/heart	--	8	--	8
			Chemical Total	--	8.E-04	--	--	8.E-04		--	10	--	10
		Exposure Point Total						8.E-04					10
	Exposure Medium Total							8.E-04					10
Medium Total								2.E-03					26
Receptor Total							Receptor Risk Total	2.E-03				Receptor HI Total	26

Source: URS Corp. RI Report, 2013

Total blood HI Across All Media =	1
Total eyes HI Across All Media =	0.0004
Total fetus HI Across All Media =	0.006
Total heart HI Across All Media =	13
Total immune system (immun) HI Across All Media =	14
Total kidney HI Across All Media =	0.07
Total liver HI Across All Media =	11
Total nervous system (NS) HI Across All Media =	0.2
Total thymus (thym) HI Across All Media =	13

Table 1-4

SUMMARY OF RECEPTOR RISKS AND HAZARDS FOR COPCs

REASONABLE MAXIMUM EXPOSURE

Child Resident, Groundwater

Joint Base Andrews, MD - SS-28

Scenario Timeframe:	Future
Receptor Population:	Resident
Receptor Age:	Child

Medium	Exposure Medium	Exposure Point	Chemical of Potential Concern	Carcinogenic Risk					Non-Carcinogenic Hazard Quotient				
				Ingestion	Inhalation	Dermal	External (Radiation)	Exposure Routes Total	Primary Target Organ(s)	Ingestion	Inhalation	Dermal	Exposure Routes Total
Groundwater	Groundwater	Groundwater at Site	**Volatile Organic Compounds**										
			1,2-Dichloroethane	4.E-06	--	1.E-07	--	4.E-06	kidney	0.09	--	0.003	0.09
			Benzene	2.E-05	--	2.E-06	--	2.E-05	blood/immun	0.9	--	0.09	1
			Carbon tetrachloride	4.E-04	--	7.E-05	--	4.E-04	liver	16	--	3	19
			Chloroform	5.E-05	--	3.E-06	--	5.E-05	liver	2	--	0.1	2
			cis-1,2-Dichloroethene	--	--	--	--	0.E+00	kidney	0.04	--	0.002	0.04
			Ethylbenzene	2.E-06	--	8.E-07	--	3.E-06	liver/kidney	0.02	--	0.008	0.03
			Methyl tert-butyl ether (MTBE)	6.E-08	--	2.E-09	--	6.E-08	NA	--	--	--	0
			Tetrachloroethene (PCE)	2.E-08	--	6.E-09	--	2.E-08	NS	0.02	--	0.006	0.02
			Trichloroethene (TCE) ADAF (0 - < 16 yrs)	3.E-05	--	2.E-06	--	3.E-05	thym/immun/heart	--	--	--	0
			Trichloroethene (TCE) ADAF (>16 - 70 yrs)	2.E-05	--	2.E-06	--	2.E-05	thym/immun/heart	--	--	--	0
			Trichloroethene (TCE)	--	--	--	--	0.E+00	thym/immun/heart	12	--	1	13
			Chemical Total	5.E-04	--	7.E-05	--	6.E-04		31	--	4	35
		Exposure Point Total						6.E-04					35
	Exposure Medium Total							6.E-04					35
Medium Total								6.E-04					35
Receptor Total							Receptor Risk Total	6.E-04				Receptor HI Total	35

Source: URS Corp. RI Report, 2013

Total blood HI Across All Media =	1
Total heart HI Across All Media =	13
Total immune system (immun) HI Across All Media =	14
Total kidney HI Across All Media =	0.2
Total liver HI Across All Media =	21
Total nervous system (NS) HI Across All Media =	0.02
Total thymus (thym) HI Across All Media =	13

Table 1-5

SUMMARY OF RECEPTOR RISKS AND HAZARDS FOR COPCs

REASONABLE MAXIMUM EXPOSURE

Adult and Child Resident, Groundwater

Joint Base Andrews, MD - SS-28

Scenario Timeframe:	Future
Receptor Population:	Resident
Receptor Age:	Child/Adult

Medium	Exposure Medium	Exposure Point	Chemical of Potential Concern	Carcinogenic Risk				
				Ingestion	Inhalation	Dermal	External (Radiation)	Exposure Routes Total
Groundwater	Groundwater	Groundwater at Site	**Volatile Organic Compounds**					
			1,2-Dichloroethane	1.E-05	--	4.E-07	--	1.E-05
			Benzene	5.E-05	--	5.E-06	--	5.E-05
			Carbon tetrachloride	1.E-03	--	2.E-04	--	1.E-03
			Chloroform	1.E-04	--	9.E-06	--	1.E-04
			cis-1,2-Dichloroethene	--	--	--	--	0.E+00
			Ethylbenzene	5.E-06	--	2.E-06	--	8.E-06
			Methyl tert-butyl ether (MTBE)	2.E-07	--	6.E-09	--	2.E-07
			Tetrachloroethene (PCE)	4.E-08	--	2.E-08	--	6.E-08
			Trichloroethene (TCE) ADAF (0 - < 16 yrs)	4.E-05	--	4.E-06	--	5.E-05
			Trichloroethene (TCE) ADAF (>16 - 70 yrs)	5.E-05	--	5.E-06	--	5.E-05
			Trichloroethene (TCE)	--	--	--	--	0.E+00
			Chemical Total	1.E-03	--	2.E-04	--	2.E-03
		Exposure Point Total						2.E-03
	Exposure Medium Total							2.E-03
	Air	Vapors While Showering	**Volatile Organic Compounds**					
			1,2-Dichloroethane	--	1.E-05	--	--	1.E-05
			Benzene	--	3.E-05	--	--	3.E-05
			Carbon tetrachloride	--	3.E-04	--	--	3.E-04
			Chloroform	--	4.E-04	--	--	4.E-04
			cis-1,2-Dichloroethene	--	--	--	--	0.E+00
			Ethylbenzene	--	5.E-06	--	--	5.E-06
			Methyl tert-butyl ether (MTBE)	--	1.E-07	--	--	1.E-07
			Tetrachloroethene (PCE)	--	2.E-08	--	--	2.E-08
			Trichloroethene (TCE)	--	2.E-05	--	--	2.E-05
			Chemical Total	--	8.E-04	--	--	8.E-04
		Exposure Point Total						8.E-04
	Exposure Medium Total							8.E-04
Medium Total								2.E-03
Receptor Total						Receptor Risk Total		2.E-03

NOTE: The cancer risk estimates for the adult resident (24 years) and child resident (6 years) are added together (30 years) to address lifetime exposure.

The non-cancer hazard evaluations are treated separately for the adult resident and child resident (See Adult Resident and Child Resident Tables). The shower pathway, however, is evaluated for the adult resident only; an exposure duration of 30 years is used in the calculation.

Source: URS Corp. RI Report, 2013

Table 2-1 Potential Chemical-Specific ARARs and TBCs for Groundwater Alternatives SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Federal or State Statute, Regulation or Guidance	Summary of Requirement	Type of ARAR	ARAR Category
Water			
40 CFR 122.26(a)(4) and 40 CFR125.3(a), (c) and (f)	Provides for the monitoring and limitation of pollutant discharges from point sources into waters of the United States.	RA	Chemical
40 CFR 141.61	Provides MCLs for the concentration of common contaminants in public drinking water supplies.	A	Chemical
COMAR 26.08.02.03-2A, E, and G(2)	Establishes numerical criteria for toxic substances in surface waters. Applicable for pump-and-treat remedial alternative discharge into open stormwater system.	RA	Chemical
MDE Cleanup Standards for Soil and Groundwater Interim Final Guidance (June 2008, Update 2.1), Table 1	Provides groundwater cleanup standards for any degradation compounds that do not have a federal MCL: chloromethane. Applicable for alternatives with enhanced bioremediation and natural attenuation	TBC	Chemical
Air			
COMAR 26.11.06.06B (1) (b)	Provides ambient air quality standards, general emissions standards, and restrictions for air emissions from construction activities, vents, and treatment technologies such as air strippers. Also includes nuisance and odor control. Applicable if an air stripper is used with the pump-and-treat remedial alternative.	A	Chemical

Notes:

A = Applicable.

ARAR = Applicable or relevant and appropriate requirement.

CFR = Code of Federal Regulations.

COMAR 26 = Code of Maryland Regulations Title 26, Department of the Environment (January 7, 2005).

MCL = Maximum Contaminant Level.

MDE = Maryland Department of the Environment

RA = Relevant and Appropriate.

TBC = To Be Considered.

Table 2-2 Potential Action-Specific ARARs and TBCs for Groundwater Alternatives SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Federal or State Statute, Regulation or Guidance	Summary of Requirement	Type of ARAR	ARAR Category
Hazardous Waste			
Standards applicable to generators of hazardous waste, 40 CFR Part 262 Subparts A, B, C, and D	General Facility Standards provide for hazardous waste determination, waste manifest preparation, handling requirements, recordkeeping and reporting.	RA	Action
Air			
Air Quality Regulations Pertaining to VOC Treatment, COMAR 26.11.06.01, .06, .08, and .09	Provides restrictions for air emissions from construction activities, vents, and treatment technologies such as air strippers (26.11.06.06). Also includes nuisance (26.11.06.08) and odor control (26.11.06.09). Applicable if air stripper is used with pump-and-treat remedial alternative.	RA	Action
Miscellaneous			
Maryland Underground Injection Control Program, COMAR 26.08.07.01	Prohibits any underground injection except as authorized by rule or permit. Applicable for the three injection alternatives.	A	Action
Well Construction Standards, COMAR 26.04.04.16 to .23 A(2), and .34	Provides specifications for well construction and abandonment.	RA	Action

Notes:

Action-specific ARARs are determined according to the specific technologies or activities taking place under an alternative.

A = Applicable.

ARAR = applicable or relevant and appropriate requirement.

CFR = Code of Federal Regulations.

COMAR 26 = Code of Maryland Regulations Title 26, Department of the Environment (January 7, 2005).

RA = Relevant and Appropriate.

TBC = To Be Considered.

Table 2-3 Potential Location-Specific ARARs and TBCs for Groundwater Alternatives SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Federal or State Statute, Regulation or Guidance	Summary of Requirement	Type of ARAR	ARAR Category
Miscellaneous			
No Location-Specific ARARs or TBCs were identified.	Not Applicable	Not Applicable	Not Applicable

Notes:

Location-specific ARARs are determined according to site-related characteristics such as geology, floodplains, wetlands, historic places, and federal regulation of air facilities.

TBC = To Be Considered.

ARAR = Applicable or relevant and appropriate requirement.

Table 2-4 Site Remediation Goals for Groundwater
SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Contaminant	Maximum Observed Concentration in Monitoring Wells (µg/L)	SRG (µg/L)	Basis of SRGs	Note
Benzene	270	5	MCL-based[1]	
Carbon tetrachloride (CTC)	2,200	5	MCL-based[1]	
Chloroform	610	80	MCL-based[1]	Degradation product of CTC; SRG based on trihalomethane total
1,2-Dichloroethane	9	5	MCL-based[1]	
Trichloroethene (TCE)	210	5	MCL-based[1]	

Notes:

[1]2006 Edition of the Drinking Water Standards and Health Advisories (United States Environmental Protection Agency [USEPA] 822-R-06-013).

MCL = maximum contaminant level.

MDE = Maryland Department of the Environment.

SRG = site remediation goal.

µg/L = microgram per liter.

Table 3-1 Groundwater Remediation, Treatment, and Disposal Technology Screening
SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Technology	Technology Description	Preliminary Screening
Monitored Natural Attenuation (MNA) with Land-Use Controls (LUCs)	Long-term monitoring of natural physical, chemical, or biological processes that act without human intervention to reduce the risks, toxicity, mobility, mass/volume, or concentration of contaminants. LUCs are maintained on-site through the base Master Plan to prevent the use/exposure to groundwater until cleanup levels are achieved.	**Retain for detailed analysis.**
Anaerobic In Situ Biodegradation (ISB) using Short-Lasting Carbon Substrate	Indigenous anaerobic microbes are stimulated by injection of a food grade, short-lasting (< 2 years) carbon substrate, such as sodium lactate, to degrade contaminants.	Omit from detailed analysis. The use of a short-lasting carbon substrate would require multiple injection events and many injection points, which would interfere with airfield operations.
Anaerobic In Situ Biodegradation (ISB) and Chemical Reduction (ISCR) using Long-Lasting Carbon Substrate	Indigenous anaerobic microbes are stimulated by injection of a food grade, long-lasting (>2 years) carbon substrate with zero valent iron (ZVI), such as EHC®, to degrade contaminants by biodegradation and chemical reduction. Microbial cultures of dechlorinating bacteria can also be injected into the subsurface to stimulate and augment the biological contaminant degradation.	**Retain for detailed analysis.**
Anaerobic In Situ Biodegradation (ISB) using Long-Lasting Carbon Substrate and Bioaugmentation	A long-lasting carbon substrate and microbial cultures of dechlorinating bacteria are injected into the subsurface to stimulate and augment the biological degradation of contaminants.	**Retain for detailed analysis.**

Table 3-1 Groundwater Remediation, Treatment and Disposal Technology Screening SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland (Continued)

Technology	Technology Description	Preliminary Screening
Aerobic In Situ Biodegradation (ISB) using an Oxygen Releasing Compound	Indigenous microbes are stimulated by introduction of oxygen to aerobically degrade contaminants.	**Retain for detailed analysis.**
Aerobic Cometabolic Biodegradation using iSOC/iMOX™ system	Aerobic biodegradation technique that is effective chlorinated volatile organic compounds (VOCs). Propane/methane/butane and oxygen infusion to degrade contaminants in groundwater through cometabolism.	Omit from detailed analysis. These devices depend on advection and diffusion to disperse a gaseous substrate in the subsurface. The limited zone of influence for iSOC devices would require a prohibitive number of wells across the site tarmac and storage hangers. In addition, frequent replacement of small gas canisters at each well would impede airfield operations. Large gas tanks cannot be stored on the airfield for safety reasons and piping the gas to the wells would require trenching and patching of large portions of the taxiway.
Anaerobic Biodegradation using iSOC™ system	Indigenous microbes are stimulated by introduction of hydrogen to anaerobically degrade contaminants.	
Chemical Oxidation using one of the following: Fenton's Reagent; Catalyzed Persulfate; Permanganate (sodium or potassium); Ozone	System of direct-push locations to inject long-lasting chemical oxidant to degrade contaminants.	**Retain Sodium Persulfate as an oxidant for benzene degradation for detailed analysis.**
Permeable Reactive Barrier (PRB) using one of the following: ZVI; or Bark Mulch Biowall	Chemical or biological treatment of chlorinated compounds by groundwater movement though a reactive treatment barrier (trench).	Omit from detailed analysis. Excavation of native material underneath the apron to install multiple PRBs is not feasible due to the need to minimize repairs of the apron surface. Placing of PRBs in the grassy areas west of the apron is feasible, but the depth to contaminated groundwater is over 20 feet deep and would require equipment that might be taller than an airfield would allow in these regions (up to 35 feet in height). In addition, multiple pore flushes would be required to remove all of the contaminants through the PRBs. Although the PRBs would theoretically prevent further contaminant migration beyond the downgradient site boundary, the contaminant plume itself would remain above cleanup standards within the site for an excessive period of time (>30 years).

Table 3-1 Groundwater Remediation, Treatment and Disposal Technology Screening SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland (Continued)

Technology	Technology Description	Preliminary Screening
Phytoremediation	Phytoremediation using fast-maturing trees such as poplars.	Omit from detailed analysis. Trees cannot be placed on the airfield because of safety and operational concerns.
Soil Heating (Electrical Resistance or Conductive Heating)	Heating of groundwater to remove VOCs by soil vapor extraction	Omit from detailed analysis. These thermal systems are maintenance intensive. Frequent visits to the site would disrupt site airfield operations.
Pump and Treat using Vertical Well Technology	Groundwater extraction by conventional pumping wells	**Retain for detailed analysis. Vertical well technology would not disrupt operations and is a viable alternative for groundwater plume.**
Air Sparging with Soil Vapor Extraction (SVE)	In situ air stripping of VOCs in groundwater and collection of vapors in SVE system.	Omit from detailed analysis. System is maintenance intensive. Frequent visits to the site and sparging points would disrupt airfield operations.
Groundwater Circulation Wells with SVE	In situ groundwater recirculation with air stripping and vapor extraction by vacuum applied to the upper well screen.	Omit from detailed analysis. System is maintenance intensive. Frequent visits to the site and new wells would disrupt airfield operations.
Dual-Phase Extraction (DPE)	Groundwater/soil vapor extraction by conventional pumping with vacuum applied to well casing	Omit from detailed analysis. DPE requires vertical wells and manifolds to extract vapor and groundwater, which would disrupt the airfield activities. Requires periodic operations and maintenance (O&M) both at the wellhead and for the treatment train equipment.
Air Stripping	Ex situ treatment by high volume air circulation to volatilize ("strip") VOCs from extracted groundwater	**Retain for detailed analysis.**
Carbon Adsorption	Ex situ treatment of extracted vapor- or liquid-phase VOCs through absorption in charcoal-filled canisters	**Retain for analysis for treatment of air stream discharge (pending review of state and local air regulations).**
Ultraviolet (UV) Oxidation	Ex situ treatment of extracted groundwater by exposure to ultraviolet radiation and a strong oxidizer.	Omit from detailed analysis because of high O&M costs and availability of more cost-effective treatment options.
Discharge by Reinjection	Discharge of treated water to nearby injection wells or infiltration gallery for return to aquifer.	Omit from detailed analysis because of high O&M costs and disruption of site mission operations if an infiltration gallery was installed.
Discharge to Surface Stream	Discharge of treated water to nearby	**Retain for detailed analysis.**

Table 3-1 Groundwater Remediation, Treatment and Disposal Technology Screening
SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland (Continued)

Technology	Technology Description	Preliminary Screening
through National Pollutant Discharge Elimination System (NPDES) Permit	drainage through a NPDES permit. Requires monthly sampling to ensure compliance with state and local surface water regulations.	
Discharge to Publicly Owned Treatment Works (POTW)	Discharge of treated water to POTW.	Omit from detailed analysis because local POTW does not accept treatment system discharge.

Table 6-1 Comparative Analysis of Remedial Alternatives
Site SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

	Overall Protection of Human Health and of the Environment	Compliance with ARARs	Long-Term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume (TMV) through Treatment	Short-Term Effectiveness	Implementability	Cost (Present Worth 2015)	Time to Response Complete*
Alternative 1 **No Action**	Does not satisfy preference for treatment - not protective of human health nor environment	Does Not Satisfy Preference for Treatment - without monitoring program, can't determine compliance with chemical-specific ARARs	Not effective in reducing the magnitude of risk associated with groundwater. Does not put institutional controls in place to protect human health.	Low Degree of Treatment - No reduction in TMV. Does not meet statutory preference for treatment as a principle element for TMV reduction.	No risk to workers during to implementation. Continued impact from existing conditions.	No construction or operation involved. May require ROD amendment if future problems arise. No monitoring involved; state of groundwater will not be known. No approval necessary. No equipment/materials required.	$0	40+ years
Alternative 2 **Monitored Natural Attenuation (MNA) with Land Use Controls**	Low Preference for Treatment - slow rate of natural attenuation - Protective of human health through land use controls (LUCs) by preventing use of groundwater. Not protective of environment.	Does Not Satisfy Preference for Treatment - will not comply with chemical-specific ARARs in a reasonable time frame	Not effective in reducing the magnitude of risk associated with groundwater in a reasonable timeframe. Adequacy and reliability of LUCs would be assessed through monitoring program. MNA required to track the rate of VOC decline.	Low Degree of Treatment - No reduction in TMV. Does not meet statutory preference for treatment as a principle element for TMV reduction.	Little to no risk to workers during implementation. LUCs are in-place so no impact to human health from existing conditions.	No construction or operation involved. May require ROD amendment if problems arise. Airfield LUCs may require special approvals from Joint Base Andrews. No special equipment/materials required. Monitoring equipment and personnel are readily available.	$3,157,000	40+ years
Alternative 3 **In Situ Biodegradation (ISB) and In Situ Chemical Reduction (ISCR) with Land Use Controls**	High Preference for Treatment - Protective of human health through LUCs by preventing use of groundwater. Potentially protective of environment.	High Preference for Treatment - meets compliance with all ARARs	Risk will be reduced due to the dechlorination or destruction of contaminant mass. Controls used for ISB/ISCR methods have been proven adequate and reliable over the years.	High Degree of Treatment - TMV will be reduced through anaerobic reductive dechlorination of VOCs to less toxic end products. Treatment by ISB and ISCR are irreversible. Incomplete dechlorination may result in the formation of toxic daughter products. Meets statutory preference for treatment.	Workers will be protected by implementation of land use controls (preventing use of VOC contaminated groundwater); no impact on workers due to implementing technology. No additional environmental impacts are expected due to implementation of technology; no adverse impacts to off-site water bodies - excess nutrients can be controlled by injection.	Moderate level of difficulty to construct and operate due to Air Force operations and security. Lab testing would be required to determine optimal electron donor and ability of geologic structure to maintain ISB and ISCR amendments within the plume. Can easily be expanded if required. Groundwater monitoring program will be in place to monitor effectiveness of ISB/ISCR processes. Amendments and experienced injection firms are commercially available.	$5,033,000	23 years (20 + 3)

Table 6-1 Comparative Analysis of Remedial Alternatives
Site SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland (Continued)

	Overall Protection of Human Health and of the Environment	Compliance with ARARs	Long-Term Effectiveness and Permanence	Reduction of Toxicity, Mobility, or Volume (TMV) through Treatment	Short-Term Effectiveness	Implementability	Cost (Present Worth 2015)	Time to Response Complete*
Alternative 4 **In Situ Chemical Oxidation (ISCO) and In Situ Biodegradation with Land Use Controls**	Moderate Preference for Treatment - Protective of human health through LUCs by preventing use of groundwater. Potentially protective of environment.	High Preference for Treatment - requires MNA for the edge of the plume - meets compliance with all ARARs	Risk will be reduced quickly due to the oxidation destruction of hotspot mass. Long-term monitoring required to track the degree of VOC rebound/decline in concentrations following treatment. Controls used for ISCO and ISB methods have been proven adequate and reliable over the years.	High Degree of Treatment - TMV will be reduced through chemical oxidation or destruction of VOCs - complete oxidation converts VOCs to harmless end products. ISB to treat remaining portions of the plume. Moderate potential for reduction in TMV due to MNA at edge of plume. Treatment by ISCO and ISB is irreversible. Incomplete oxidation or dechlorination may result in the formation of toxic daughter products. Meets statutory preference for treatment.	Workers will be protected by implementation of land use controls (preventing use of VOC contaminated groundwater); no impact on workers due to implementing technology. No additional environmental impacts are expected due to implementation of technology; no adverse impacts to off-site water bodies - excess nutrients can be controlled by injection. Workers need to handle oxidizers (persulfate, sodium hydroxide) carefully during implementation.	Moderate level of difficulty to construct and operate due to Air Force operations and security. Laboratory testing would be required to determine natural oxidant demand and ability of site geology to maintain ISCO amendments within the hotspots. Can easily be expanded if required. Groundwater monitoring program will be in place to monitor effectiveness of ISCO and ISB process. Amendments and experienced injection firms are commercially available.	$5,630,000	23 years (20 + 3)
Alternative 5 **Groundwater Extraction and Treatment Using Wells with In Situ Biodegradation and Land Use Controls**	Moderate Preference for Treatment - Protective of human health through LUCs by preventing use of groundwater. Potentially protective of environment.	Moderate Preference for Treatment - meets compliance with all ARARs. Slower compliance due to the need to pump multiple pore volumes to reach MCLs.	Risk may be reduced due to recovery/treatment of contaminants and partial capture of dissolved phase contaminants. Long-term monitoring required to track degree of VOC rebound/ decline following shutdown of pumping activities. Controls used for extraction and treatment methods have been proven adequate and reliable over the years.	Moderate Degree of Treatment - TMV will be reduced through removal and treatment of contaminated groundwater (i.e., air stripping and/or carbon treatment). Treatment methods such as air stripping and carbon filtration are irreversible. Groundwater expected to be treated to degree stated on NPDES permit at treatment plant effluent outflow.	Workers will be protected by implementation of land use controls (preventing use of VOC contaminated groundwater). Minimal protection needed against vapor inhalation and/or short-term skin contact with contaminated groundwater during construction, implementation, and monitoring activities. Increasing energy costs as a part of operation and maintenance (O&M) of this remedy. No additional environmental impacts are expected due to implementation of technology.	Most difficult to implement. The installation of multiple extraction wells and associated piping is invasive. Treatment system and piping construction is standard, but restricted due to airfield requirements and many utilities. Groundwater monitoring program will be in place to monitor effectiveness of pump-and-treat process. NPDES permit required to discharge treated water to storm sewer from treatment plant. Readily available equipment/ technology. Two technologies involved. High energy and O&M costs.	$12,481,000	32 years (29 + 3)

Note: An additional 3 years of monitoring and documentation will be required to achieve Site Closure. Details of the model are provided in Appendix B.

Table 6-2 List of Remedial Alternatives and the Degree to Which Each Meets the CERCLA Criteria
Site SS-28 Joint Base Andrews Naval Air Facility Washington, Maryland

Criterion	Alternative 1 No Action	Alternative 2 Monitored Natural Attenuation with Land Use Controls	Alternative 3 In Situ Biodegradation and In Situ Chemical Reduction with Land Use Controls	Alternative 4 In Situ Chemical Oxidation and In Situ Biodegradation with Land Use Controls	Alternative 5 Groundwater Extraction and Treatment with In Situ Biodegradation and Land Use Controls
Overall Protection of Human Health and of the Environment					
Human Health	○	◎	●	●	●
Environmental Protection	○	○	◎	◎	◎ ♻
Compliance with ARARs					
Potential Chemical-specific ARARs	○	○	● ♻	◎	◎
Potential Action-specific ARARs	NA	◎	●	●	◎
Potential Location-specific ARARs	NA	◎	●	●	◎
Long-Term Effectiveness and Permanence					
Magnitude of Residual Risk	○	○	● ♻	●	◎
Adequacy of Controls and Monitoring	NA	◎	●	●	●
Reduction of TMV through Treatment					
Reduction of TMV	○	○	● ♻	●	◎
Statutory Preference for Treatment	○	○	● ♻	●	●
Short-Term Effectiveness					
Community Protection	○	○	●	●	●
Worker Protection	○	○	● ♻	●	◎
Environmental Impacts	○	○	●	● ♻	◎
Time Until Response Complete	40+ years	40+ years	23 years (20 + 3)	23 years (20 + 3)	32 years (29 + 3)
Implementability					
Feasibility of Construction and Operation	NA	● ♻	◎	◎	◎
Reliability of Technology	○	○	●	●	●
Administrative Feasibility	●	●	◎	◎	○
Cost (Present Value 2015)*	$0	$3,157,000	$5,033,000	$5,630,000	$12,481,000
State/Supporting Agency Acceptance	To be determined	To be determined	To be determined	To be determined	To be determined
Community Acceptance	To be determined	To be determined	To be determined	To be determined	To be determined
Overall Ranking	○	○	●	◎	◎

Notes:

ARARs - applicable or relevant and appropriate requirement

NA - not applicable

TMV - toxicity, mobility, or volume

● - satisfies criterion to high degree in a timely manner

◎ - satisfies criterion to moderate degree in a timely manner

○ - satisfies criterion to low degree or does not satisfy criterion in a timely manner

♻ - most sustainable in each criterion

* - Cost (Present Value 2015) values are to Site Closure, including 3 years of long-term monitoring after the project reaches Response Complete

APPENDIX A
REMEDIAL ALTERNATIVES COSTING

APPENDIX A.1
REMEDIAL ALTERNATIVES BUDGET WORKSHEETS

Table A-1
Remedial Alternatives Costing Summary

Remedial Alternatives		Alternative Cost Duration (Years)	Total Capital Costs	Total Annual O&M Costs	Total Periodic Costs	Total Cost	Net Present Value
Alternative 1	No Action	40	$ -	$ -	$ -	$ -	$ -
Alternative 2	Monitored Natural Attenuation with Land Use Controls	40	$ 225,351	$ 3,808,910	$ 557,821	$ 4,592,082	$ 3,157,000
Alternative 3	In Situ Biodegradation and In Situ Chemical Reduction	23 (20+3)*	$ 3,084,782	$ 2,190,123	$ 430,306	$ 5,705,211	$ 5,033,000
Alternative 4	In Situ Chemical Oxidation with In Situ Biodegradation Barriers	23 (20+3)*	$ 3,749,396	$ 2,190,123	$ 430,306	$ 6,369,826	$ 5,630,000
Alternative 5	Groundwater Extraction and Treatment Using Wells With In Situ Biodegradation	32 (29+3)*	$ 5,147,100	$ 9,511,052	$ 568,316	$ 15,226,468	$ 12,481,000

Notes:

O&M - Operations and Maintenance

* Alternative Cost Duration is to Response Complete plus 3 years of monitoring and documentation required for Site Closure.

Groundwater Remedial Alternative No. 1
No Action
Site SS-28
Davidsonville Transmitter Area

CAPITAL COST:

Total Capital Cost	**$0**

ANNUAL O & M COST:

Total Annual O & M Cost	**$0**

PERIODIC COST:

	$0

PRESENT VALUE ANALYSIS:

Alternative Cost Duration: 40 yrs

Cost Type	Year	Total Cost	Total Cost Per Year	Discount Factor (2.0%)	Present Value
Total Capital Cost	0	$0	$0		$0
Total Annual O & M Cost	1 - 40	$0	$0		$0
Periodic Cost	1 - 40	$0	$0		$0
		$0			$0

Total Present Value of Alternative	**$0**

Notes:
EA = each, LS = lump sum, N/A = not applicable
Details on what is contained under task items can be found on page A.1-10

Groundwater Remedial Alternative No. 2
Long-Term Groundwater Monitoring with Land Use Controls
Site SS-28
Davidsonville Transmitter Area

CAPITAL COST:

	Description		QTY	Unit	Unit Cost	Total
0001	Logistics, Security, Base Coordination		1	LS	$12,110	$12,110
0002	Land Use Control (LUC) Plan		1	LS	$11,085	$11,085
0003	Implement Institutional Controls		1	LS	$16,565	$16,565
0004	Install New Monitoring Wells		8	LS	$18,900	$151,200
	Sub-Total					$178,850
	Contingency	20%				$35,770
	Sub-Total					$214,620
	Project Management	5%				$10,731
	Total Capital Cost					**$225,351**

ANNUAL O & M COST:

	Description		QTY	Unit	Unit Cost	Total
0005	Remedy Performance Monitoring - Groundwater & Vapor Intrusion		1	EA	$35,830	$35,830
0006	Data Management, Sampling Reports, & LUC Reports		1	EA	$33,172	$33,172
	Sub-Total					$69,002
	Contingency	20%				$13,800.40
	Sub-Total					$82,802
	Project Management	10%				$8,280
	Technical Support	5%				$4,140
	Annual O & M Cost					**$95,223**

PERIODIC COST:

	Description	Year	QTY	Unit	Unit Cost	Total
0007	Five Year Review - First Review	5	1	EA	$52,374	$52,374
0008	Five Year Review - Years 10,15,20,25,30,35,40	10 - 40	1	EA	$28,952	$28,952
0009	Update LUC Plan - Years 10,15,20,25,30,35,40	10 - 40	1	EA	$13,553	$13,553
0010	Site Close-Out (reports, sampling, well abandonment)	40	1	LS	$236,864	$236,864

PRESENT VALUE ANALYSIS:

Alternative Cost Duration: 40 yrs

Cost Type	Year	Total Cost	Total Cost Per Year	Discount Factor (2.0%)	Present Value
Total Capital Cost	0	$225,351	$225,351	1	$225,351
Total Annual O & M Cost	1 - 40	$3,808,910	$95,223	27.355	$2,604,864
Periodic Cost	5	$52,374	$52,374	0.906	$47,437
Periodic Cost	10	$42,505	$42,505	0.820	$34,869
Periodic Cost	15	$42,505	$42,505	0.743	$31,582
Periodic Cost	20	$42,505	$42,505	0.673	$28,605
Periodic Cost	25	$42,505	$42,505	0.610	$25,908
Periodic Cost	30	$42,505	$42,505	0.552	$23,466
Periodic Cost	35	$42,505	$42,505	0.500	$21,254
Periodic Cost (Site Closeout)	40	$250,417	$250,417	0.453	$113,411
		$4,592,082			$3,156,746
Total Present Value of Alternative					**$3,156,746**

Notes:
EA = each, LS = lump sum, N/A = not applicable
Details on what is contained under task items can be found on page A.1-10

Groundwater Remedial Alternative No. 3
In Situ Biodegradation and In Situ Chemical Reduction
Site SS-28
Davidsonville Transmitter Area

CAPITAL COST:

	Description		QTY	Unit	Unit Cost	Total
	Mobilization / Demobilization (All Injection Events)					
0001	Logistics, Security, Base Coordination		3	EA	$12,110	$36,330
0002	Construction Equipment & Facilities		3	EA	$7,000	$21,000
0003	Plans & RA-O Reports		3	EA	$52,374	$157,122
0004	Temporary Facilities & Utilities		3	EA	$4,000	$12,000
0005	Install Injection Points		3	LS	$90,000	$270,000
0006	Injection Point Abandonment & Restoration		3	EA	$1,000	$3,000
0007	Post Injection Monitoring Events		3	EA	$62,571	$187,713
	Sub-Total				$229,055	$687,165
	Injection Event 1 (ISB/ISCR w/BA)					
0008	Baseline Groundwater Monitoring		1	LS	$62,571	$62,571
0009	Install New Monitoring Wells		8	LS	$18,900	$151,200
0010	ISB/ISCR Injection & BA - 1 (labor)		1	LS	$206,698	$206,698
0011	ISB/ISCR Injection & BA - 1 (amendment)		1	LS	$295,532	$295,532
0012	Downgradient Suite Injection & BA - 1 (labor)		1	LS	$105,164	$105,164
0013	Downgradient Suite Injection & BA - 1 (amendment)		1	LS	$170,394	$170,394
						$991,560
	Injection Event 2 (ISB/ISCR)					
0014	ISB/ISCR Injection - 2 (labor)		1	LS	$103,349	$103,349
0015	ISB/ISCR Injection - 2 (amendment)		1	LS	$148,546	$148,546
0016	Downgradient Suite Injection - 2 (labor)		1	LS	$52,582	$52,582
0017	Downgradient Suite Injection - 2 (amendment)		1	LS	$66,683	$66,683
						$371,160
	Injection Event 3 (ISB/ISCR)					
0018	ISB/ISCR Injection -3 (labor)		1	LS	$51,675	$51,675
0019	ISB/ISCR Injection -3 (amendment)		1	LS	$57,432	$57,432
0020	Downgradient Suite Injection - 3 (labor)		1	LS	$26,291	$26,291
0021	Downgradient Suite Injection - 3 (amendment)		1	LS	$35,291	$35,291
						$109,106
	Sub-Total					$1,471,826
	Contingency	20%				$431,798
	Project Management	10%				$259,079
	Remedial Design	8%				$207,263
	Land Use Controls					
0022	Land Use Control (LUC) Plan		1	EA	$11,085	$11,085
0023	Implement Institutional Controls		1	LS	$16,565	$16,565
	Total Capital Cost					**$3,084,782**

ANNUAL O & M COST:

	Description	QTY	Unit	Unit Cost	Total
0024	Remedy Performance Monitoring - Groundwater & Vapor Intrusion	1	EA	$35,830	$35,830
0025	Data Management, Sampling Reports, & LUC Reports	1	EA	$33,172	$33,172
	Sub-Total				$69,002
	Contingency 20%				$13,800.40
	Sub-Total				$82,802
	Project Management 10%				$8,280
	Technical Support 5%				$4,140
	Annual O & M Cost				**$95,223**

PERIODIC COST:

	Description	Year	QTY	Unit	Unit Cost	Total
0026	Five Year Review - First Review	5	1	EA	$52,374	$52,374
0027	Five Year Review - Years 10, 15, 20	10 - 20	1	EA	$28,952	$28,952
0028	Update LUC Plan - Years 10,15,20 & 23	10 - 23	1	EA	$13,553	$13,553
0029	Site Close-Out (reports, sampling, well abandonment)	23	1	LS	$236,864	$236,864

PRESENT VALUE ANALYSIS:

Alternative Cost Duration: 23 yrs

Cost Type	Year	Total Cost	Total Cost Per Year	Discount Factor (2.0%)	Present Value
Capital Cost - Injection Event 1	0	$2,146,405	$2,146,405	1	$2,146,405
Capital Cost - Injection Event 2	4	$600,215	$600,215	0.924	$554,506
Capital Cost - Injection Event 3	8	$338,161	$338,161	0.853	$288,618
Total Annual O & M Cost	1-22	$2,190,123	$95,223	18.292	$1,741,834
Periodic Cost	5	$52,374	$52,374	0.906	$47,437
Periodic Cost	10	$42,505	$42,505	0.820	$34,869
Periodic Cost	15	$42,505	$42,505	0.743	$31,582
Periodic Cost	20	$42,505	$42,505	0.673	$28,605
Periodic Cost (Site Closeout)	23	$250,417	$250,417	0.634	$158,803
		$5,705,211			$5,032,658
Total Present Value of Alternative					**$5,032,658**

Notes:
EA = each, LS = lump sum, N/A = not applicable
Details on what is contained under task items can be found on page A.1-10

Groundwater Remedial Alternative No. 4
In Situ Chemical Oxidation with Downgradient Biodegradation Barriers
Site SS-28
Davidsonville Transmitter Area

CAPITAL COST:

	Description		QTY	Unit	Unit Cost	Total
	Mobilization / Demobilization					
0001	Logistics, Security, Base Coordination		4	EA	$12,110	$48,440
0002	Construction Equipment & Facilities		4	EA	$7,000	$28,000
0003	Plans & RA-O Reports		4	EA	$52,374	$209,496
0004	Temporary Facilities & Utilities		4	EA	$4,000	$16,000
0005	Install Injection Points		4	LS	$90,000	$360,000
0006	Injection Point Abandonment & Restoration		4	EA	$1,000	$4,000
0007	Post Injection Monitoring Events		3	EA	$62,571	$187,713
	Sub-Total				$229,055	$853,649
	Injection Event 1 (ISCO)					
0008	Baseline Groundwater Monitoring		1	LS	$50,390	$50,390
0009	Install New Monitoring Wells		8	LS	$18,900	$151,200
0010	ISCO Persulfate Injection - 1 (labor)		1	LS	$247,738	$247,738
0011	ISCO Persulfate Injection - 1 (amendment)		1	LS	$59,946	$59,946
						$509,274
	Injection Event 2 (ISCO)					
0014	ISCO Persulfate Injection - 2 (labor)		1	LS	$247,738	$247,738
0015	ISCO Persulfate Injection - 2 (amendment)		1	LS	$59,946	$59,946
						$307,684
	Injection Event 3 (ISB/ISCR w/BA)					
0016	ISB/ISCR Injection & BA - 1 (labor)		1	LS	$140,949	$140,949
0017	ISB/ISCR Injection & BA - 1 (amendment)		1	LS	$202,788	$202,788
0018	Downgradient Suite Injection - 1 (labor)		1	LS	$105,164	$105,164
0019	Downgradient Suite Injection - 1 (amendment)		1	LS	$170,394	$170,394
						$619,296
	Injection Event 4 (ISB/ISCR)					
0020	ISB/ISCR Injection - 2 (labor)		1	LS	$191,209	$191,209
0021	ISB/ISCR Injection - 2 (amendment)		1	LS	$103,052	$103,052
0022	Downgradient Suite Injection - 2 (labor)		1	LS	$105,164	$105,164
0023	Downgradient Suite Injection - 2 (amendment)		1	LS	$66,683	$66,683
						$294,261
	Sub-Total					$1,730,514
	Contingency	20%				$516,833
	Project Management	10%				$310,100
	Remedial Design	8%				$248,080
	Land Use Controls					
0024	Land Use Control (LUC) Plan		1	EA	$11,085	$11,085
0025	Implement Institutional Controls		1	LS	$16,565	$16,565
	Total Capital Cost					**$3,686,825**

ANNUAL O & M COST:

	Description		QTY	Unit	Unit Cost	Total
0026	Remedy Performance Monitoring - Groundwater & Vapor Intrusion		1	EA	$35,830	$35,830
0027	Data Management, Sampling Reports, & LUC Reports		1	EA	$33,172	$33,172
	Sub-Total					$69,002
	Contingency	20%				$13,800.40
	Sub-Total					$82,802
	Project Management	10%				$8,280.24
	Technical Support	5%				$4,140.12
	Annual O & M Cost					**$95,223**

PERIODIC COST:

	Description	Year	QTY	Unit	Unit Cost	Total
0028	Five Year Review - First Review	5	1	EA	$52,374	$52,374
0029	Five Year Review - Years 10,15,20	10 - 20	1	EA	$28,952	$28,952
0030	Update LUC Plan - Years 10,15,20,23	10 - 23	1	EA	$13,553	$13,553
0031	Site Close-Out (reports, sampling, well abandonment)	23	1	LS	$236,864	$236,864

PRESENT VALUE ANALYSIS:

Alternative Cost Duration: 23 yrs

	Cost Type	Year	Total Cost	Total Cost Per Year	Discount Factor (2.0%)	Present Value
	Capital Cost - Injection Event 1	0	$1,840,991	$1,840,991	1	$1,840,991
	Capital Cost - Injection Event 2	2	$536,739	$536,739	0.961	$515,897
	Capital Cost - Injection Event 3	4	$848,351	$848,351	0.924	$783,745
	Capital Cost - Injection Event 4	8	$523,316	$523,316	0.853	$446,645
	Total Annual O & M Cost	1-22	$2,190,123	$95,223	18.292	$1,741,834
	Periodic Cost	5	$52,374	$52,374	0.906	$47,437
	Periodic Cost	10	$42,505	$42,505	0.820	$34,869
	Periodic Cost	15	$42,505	$42,505	0.743	$31,582
	Periodic Cost	20	$42,505	$42,505	0.673	$28,605
	Periodic Cost (Site Closeout)	23	$250,417	$250,417	0.634	$158,803
			$6,369,826			$5,630,407
	Total Present Value of Alternative					**$5,630,407**

Notes:
EA = each, LS = lump sum, N/A = not applicable
Details on what is contained under task items can be found on page A.1-9

Groundwater Remedial Alternative No. 5
Groundwater Extraction and Treatment Using Wells With In Situ Biodegradation
Site SS-28
Joint Base Andrews Naval Air Facility Washington

CAPITAL COST:

	Description	QTY	Unit	Unit Cost	Total
	Mobilization / Demobilization - Treatment Plant				
0001	Logistics, Security, Base Coordination	1	EA	$12,110	$12,110
0002	Construction Equipment & Facilities	1	EA	$7,500	$7,500
0003	Remedial Design Work Plan	1	LS	$52,374	$52,374
0004	Site Restoration - Landscaping	1	EA	$5,000	$5,000
	Sub-Total				$76,984
	Mobilization / Demobilization - Downgradient Injections				
0005	Logistics, Security, Base Coordination	3	EA	$12,110	$36,330
0006	Construction Equipment & Facilities	3	EA	$7,000	$21,000
0007	Plans & RA-O Reports	3	EA	$52,374	$157,122
0008	Temporary Facilities & Utilities	3	EA	$4,000	$12,000
0009	Install Injection Points	3	LS	$90,000	$270,000
0010	Injection Point Abandonment & Restoration	3	EA	$1,000	$3,000
0011	Post Injection Monitoring Events	3	EA	$62,571	$187,713
	Sub-Total			$229,055	$226,452
	Well Installation and Testing - Treatment Plant				
0012	Vertical Well Installation	4	EA	$335,000	$1,340,000
0013	Pump Test New Wells	4	EA	$12,500	$50,000
0014	Install Well Pumps	4	EA	$8,000	$32,000
	Sub-Total				$1,422,000
	Groundwater Treatment Plant				
0015	NEPA Process (Environmental Assessment)	1	EA	$50,000	$50,000
0016	Facility (building, fencing, support areas, influent/effluent lines)	1	EA	$222,750	$222,750
0017	Groundwater Treatment Plant Equipment, Installed	1	EA	$197,120	$197,120
0018	Facility & Yard Piping (20% of installed equipment)	1	EA	$39,424	$39,424
0019	Facility & Yard Elect. (15% of installed equipment)	1	EA	$29,568	$29,568
0020	Instrumentation (15% of installed equipment)	1	EA	$29,568	$29,568
0021	Site Work	1	EA	$20,160	$20,160
0022	Engineering and Legal				$80,000
	Sub-Total				$668,590
	System Setup & Monitoring				
0023	Startup and Testing	1	EA	$51,520	$51,520
0024	Install Monitoring Wells	8	LS	$18,900	$151,200
0025	Baseline & Post Startup GW Monitoring	4	EA	$62,571	$250,284
0026	NPDES Permit Setup	1	EA	$5,600	$5,600
					$458,604
	Remediation Injections & Monitoring				
0027	Downgradient Suite Injection & BA - 1 (labor)	1	LS	$105,164	$105,164
0028	Downgradient Suite Injection & BA - 1 (amendment)	1	LS	$170,394	$170,394
0029	Downgradient Suite Injection - 2 (labor)	1	LS	$105,164	$105,164
0030	Downgradient Suite Injection - 2 (amendment)	1	LS	$66,683	$66,683
0031	Downgradient Suite Injection - 3 (labor)	1	LS	$105,164	$105,164
0032	Downgradient Suite Injection - 3 (amendment)	1	LS	$35,291	$35,291
					$587,861
	Sub-Total				$3,440,491
	Contingency	20%			$688,098
	Sub-Total				$4,128,589
	Project Management	10%			$412,859
	Remedial Design	8%			$330,287
	Construction Management	6%			$247,715
	Land Use Controls				
0033	Land Use Control (LUC) Plan	1.00	LS	$11,085	$11,085
0034	Implement Institutional Controls	1.00	LS	$16,565	$16,565
	Total Capital Cost				**$5,147,100**

Groundwater Remedial Alternative No. 5
Groundwater Extraction and Treatment Using Wells With In Situ Biodegradation
Site SS-28
Joint Base Andrews Naval Air Facility Washington

ANNUAL O & M COST:

	Description		QTY	Unit	Unit Cost	Total
0035	Remedy Performance Monitoring - Groundwater & Vapor Intrusion		1	LS	$35,830	$35,830
0036	Data Management, Sampling Reports, & LUC Reports		1	EA	$33,172	$33,172
	Sub-Total					$69,002
	Groundwater Treatment Plant					
0037	Labor		1	EA	$45,920	$45,920
0038	Chemicals and Supplies		1	EA	$30,240	$30,240
0039	Utilities		1	EA	$28,000	$28,000
0040	Waste Disposal		1	EA	$1,120	$1,120
0041	Effluent Monitoring		1	EA	$20,160	$20,160
0042	Equipment Maintenance		1	EA	$3,360	$3,360
0043	NPDES Permit Monitoring, Management, Reporting, Fees		1	EA	$8,960	$8,960
	Sub-Total					$137,760
	Contingency	25%				$51,691
	Sub-Total					$258,453
	Project Management	10%				$25,845
	Technical Support	5%				$12,923
	Total Annual O & M Cost					**$297,220**

PERIODIC COST:

	Description	Year	QTY	Unit	Unit Cost	Total
0044	Five Year Review - First Review	5	1	EA	$52,374	$52,374
0045	NPDES Permit Renewal - Year 5	5	1	EA	$5,000	$5,000
	Sub-Total					$57,374
0046	Five Year Review - Years 10,15,20,25,30	10 - 30	1	EA	$28,952	$28,952
0047	Update LUC Plan - Years 10,15,20,25,30,32	10 - 32	1	EA	$13,553	$13,553
0048	NPDES Permit Renewal - Years 10,15,20,25,30	10 - 30	1	EA	$5,000	$5,000
0049	Site Close-Out (reports, sampling, well abandonment)	32	1	EA	$236,864	$236,864
0050	Treatment Plant Dismantling/Salvaging	32	1	EA	$23,000	$23,000
	Sub-Total					$307,369
0051	Equipment Replacement Costs	20	1	EA	$115,000	$115,000
	Contingency of Equipment Replacement 25%					$28,750
	Total Periodic Costs					**$508,493**

PRESENT VALUE ANALYSIS:

Alternative Cost Duration: 32 yrs

Cost Type	Year	Total Cost	Total Cost Per Year	Discount Factor (2.0%)	Present Value
Capitol Cost	0	$5,147,100	$5,147,100	1	$5,147,100
Annual O & M Cost	1-18	$9,511,052	$297,220	23.468	$6,975,267
Periodic Cost	5	$57,374	$57,374	0.906	$51,965
Periodic Cost	10	$47,505	$47,505	0.820	$38,971
Periodic Cost	15	$47,505	$47,505	0.743	$35,297
Periodic Cost	20	$47,505	$47,505	0.673	$31,970
Periodic Cost	25	$47,505	$47,505	0.610	$28,956
Periodic Cost	30	$47,505	$47,505	0.552	$26,226
Periodic Cost (Site Closeout)	32	$273,417	$273,417	0.531	$145,084
		$15,226,468			$12,480,836
Value of Alternative					**$12,480,836**

Notes:
EA = each, LS = lump sum, N/A = not applicable
Details on what is contained under task items can be found on page A.1-10

Explanation of Alternative Sub-Tasks:

Sub-Task 0001 "Logistics, Security, Base Coordination":

This sub-task include (but not limited to) the time for completion of the following items: FAA Form 7460-1, Temporary Airfield Construction Waiver, local permits from Terrapin Utility Services for potable water access from fire hydrants (as needed), airfield utility clearance(s), planning and coordination with the security/appropriate JBA personnel, and necessary training for all field and security personnel.

Mobilization/Demobilization Sub-Tasks:

The value of "quantity/QTY" is equal to the number of remediation rounds needed for the remedial alternative to reach "Site Closeout". For Alternatives 3 – 5, this equals the number of injection rounds.

For all of the injection alternatives, the "Temporary Facilities and Utilities" include (but not limited to) time and equipment for setting/dismantling up the staging area, any decontamination stations, collecting potable water to help mix the injection solutions, and defining/repairing work areas (surveying and marking locations, work area perimeters, noting any preexisting conditions or change in conditions within work area).

Injection Sub-Tasks:

Injection amendment costs were based from amendment supplier quotes, which include amendment value and shipping costs. Quotes are shown in Appendix A-2.

For Alternatives 3, bioaugmentation is only included in the initial injections in order to boost the native microorganism population initially. None of the other injection rounds included bioaugmentation costs. For the second injection event, the amendment volumes used in the both the building region and downgradient suite injections are half of the volume used in the initial injection. The third injection event assumes only a quarter of the original amendments and pH buffer volumes will be needed. The same shipping costs were used across all injection events.

For Alternative 4, it is assumed that the same volume of ISCO amendment would be used for both ISCO injection events. ISB/ISCR injection and the downgradient suite injections would take place during the third and fourth injection events. Bioaugmentation is only considered for the initial ISB/ISCR injection event (third injection event overall) in order to boost the native populations that were originally depleted as a result of the previous ISCO injections. The second ISB/ISCR injection assumes the half volume of substrate and pH buffer will be injected compared to the first round. The shipping costs will be the same for all of the injections. A full breakdown of amendment cost components is shown in the table on page A.1-10.

“Install Injection Points” is based on the actual costs for the FT-02 injection in 2013, which includes equipment, labor, and their personal mobilization costs.

All “Injection – (labor)” task line items include the costs for labor, travel, and field supplies for 3 WESTON field personnel (all with Pathfinder clearance) for preparations, field work, and closeout, and flat costs for equipment rentals needed by the WESTON personnel during the field work.

The “Post-Injection Monitoring Events” are semi-annual groundwater sampling events that will take place in between the “Long-Term Annual Groundwater Sampling” events.

Remedial Alternatives - Cost Buildup
SS-28 Feasibility Study

ISB/ISCR Amendments (Alternative 3)

Item	Quantity	Unit	Rate	Total
EHC (Peroxychem) - source area > 500ppb	49,140	lbs.	$1.48	$72,727
SRS-SD (TSI) - source area	20,180	lbs.	$9.71	$195,947
KMnO4 pH Buffer (Peroxychem)	975	lbs.	$2.50	$2,438
NaHCO3 pH Buffer (TSI)	23,679	lbs.	$0.60	$14,207
CaCO3 pH Buffer (TSI)	6,622	lbs.	$0.60	$3,973
DHC Culture (Peroxychem)	26	liters	$90.00	$2,340
Shipping (Peroxychem) - ISCR	1	each	$3,900.00	$3,900

TOTAL $ 295,532

ISCO Persulfate & ISB/ISCR Amendments (Alternative 4)

Item	Quantity	Unit	Rate	Total
Klozur Persulfate (Peroxychem)	331	lbs.	$1.59	$526
FeEDTA Activation (Peroxychem)	12,223	lbs.	$4.00	$48,893
NaOH activator (Peroxychem)	393	lbs.	$0.39	$153
H2O2 Activator (Peroxychem)	1,335	lbs.	$0.28	$374
Shipping (Peroxychem) - ISCO	1	each	$10,000	$10,000
EHC (Peroxychem) - source area > 500ppb	30,927	lbs.	$1.48	$45,772
SRS-SD (TSI) - source area	33,709	lbs.	$9.71	$327,311
KMnO4 pH Buffer (Peroxychem)	614	lbs.	$2.50	$1,534
NaHCO3 pH Buffer (TSI)	28,639	lbs.	$0.60	$17,183
CaCO3 pH Buffer (TSI)	8,009	lbs.	$0.60	$4,806
DHC Culture (Peroxychem)	13	liters	$90	$1,170
Shipping (Peroxychem) - ISCR	1	each	$3,900	$3,900

TOTAL $ 461,623

Downgradient Suite Amendments (Alternatives 3 - 5)

Item	Quantity	Unit	Rate	Total
Aerobic ISB				
PermeOx (Peroxychem)	5,650	lbs.	$ 6.50	$36,725
Shipping (Peroxychem)	1	each	$ 463.59	$464
Anaerobic ISB				
SRS-SD (TSI)	12,024	gal	$ 9.71	$116,753
Calcium Bicarbonate pH Buffer (TSI)	11,478	lbs.	$ 0.60	$6,887
Lime pH Buffer (TSI)	3,210	lbs.	$ 0.60	$1,926
DHC Culture (TSI)	34	liters	$ 110	$3,740
Shipping (TSI)	1	each	$ 3,900	$3,900

TOTAL $ 170,394

APPENDIX A.2
REMEDIAL ALTERNATIVES BUDGET SUPPORT DOCUMENTS

EHC AMENDMENT
IN SITU CHEMICAL REDUCTION

EHC-L® Liquid ISCR Reagent Demand Calculations

14-Jan-2015

Customer:	**Weston Solutions**	**Prepared by:**	
Contact:	**Mary Boggs**	**Fayaz Lakhwala, PhD**	
Site Location:	**Camp Springs, MD, Site 1 -Area**	**1-908-230-9567**	
Proposal Number:	**PeroxyChem-OPP-02766-98317**	**Fayaz.Lakhwala@peroxychem.com**	

PRODUCT OVERVIEW

EHC-L® is a cold-water soluble formulation of EHC® that is specially designed for injection via existing wells or hydraulic injection networks for the treatment of a wide range of groundwater contaminants. The base composition is controlled-release organic carbon with an organo-iron compound (both food-grade).

Packaging:

EHC-L is delivered in 2 parts and mixed together with water in the field.

Part 1: Liquid emulsion delivered in 55-USG drums, filled with 50 USG / 420 lbs per drum.
Part 2: Water soluble powder with the organo-iron compound and other additives delivered in 24.6 lb bags.

SITE INFORMATION / ASSUMPTIONS

	Value	Unit	Comment
Treatment Area Dimensions:			
Width of targeted zone (perpendicular to gw flow)	500	ft	customer supplied
Length of targeted zone (parallel to gw flow)	20	ft	customer supplied
Depth to top of treatment zone	25	ft bgs	customer supplied
Treatment zone thickness	15	ft	customer supplied
Treatment volume	150,000	ft3	calculated value
Total Porosity	30	%	default value
Groundwater volume	45,000	ft3	calculated value
Soil bulk density	90	lbs/ft3	default value
Soil mass	6,750	ton	calculated value
Transport characteristics:			
Treatment time / design life for one application	3	years	default value
Linear groundwater flow velocity	53	ft/year	calculated value
Distance of inflowing gw over design life	158	ft	calculated value
Effective porosity for groundwater flow	30	%	default value
Volume of water passing region over design life	356012	ft3	calculated value
Soil type	medium		customer supplied

Fraction organic carbon in soil, foc	0.005	estimated value

CONTAMINANTS OF CONCERN (COCs)

Constituent	GW (mg/L)	Soil* (mg/kg)	Total COI Mass** (lb)
TCE	0.25	0.13375	8.1
CT	0.5	0.275	16.2
CF	0.2	0.034	5.5

*Unless provided, sorbed concentrations were roughly estimated based on expected groundwater concentrations, foc and Koc values. For a more refined estimate, it is recommended that actual values be verified via direct sampling of the targeted treatment interval.

**The total COI mass was estimated based on concentrations in soil and groundwater within the targeted area plus expected contributions from inflowing groundwater over the projected design life.

GEOCHEMICAL DATA

Competing Electron Acceptors	GW (mg/L)	
Dissolved oxygen	5.44	customer provided
Nitrate (as N)	1	customer provided
Manganese (estimated conc. Mn(II) generated)*	10	default value
Iron (estimated conc. Fe(II) generated)*	10	default value
Sulfate	12	customer provided

*An estimated projection of dissolved concentrations of Mn and Fe following ERD/ISCR were used to estimate H demand from the reduction of oxidized Fe and Mn minerals (typically only a portion of actual soil concentrations will be reduced).

ORP (mV)	249	
pH	4.88	Note: It is recommended to inject a pH buffer together with the EHC-L to adjust the pH to around 7

STOICHIOMETRIC DEMAND CALCULATIONS

	GW (mg/L)	Soil (mg/kg)
H2 Demand from COIs	0.05	0.02
H2 Demand from Competing Electron Acceptors	2.53	0.00
Total H2 Demand	2.58	0.02
H2 Demand from Soil within Targeted Area	0.30	lb
H2 Demand from GW within Targeted Area	7.25	lb
H2 Demand from Influx over Design Life	57.37	lb
Total Estimated H2 Demand	64.92	lb

EHC-L DEMAND CALCULATIONS

The Stoichiometric demand for the targeted area was calculated using available data presented above, noting that the Stoichiometric demand represents minimum requirements and require a complete geochemical data set to be calculated accurately. Therefore, the resulting EHC dosing required to meet the estimated Stoichiometric demand was compared to our minimum guidelines for the selected type of application, selecting the higher number.

Application type: Hot-Spot Treatment

	Value	Unit
Concentration EHC-L in GW to meet H2 demand	264.7	mg/L
Minimum target conc. TOC in pore water*	2,000	mg/L
Recommended conc. of EHC-L in pore water	8,000	mg/L
Mass of EHC-L required	22,478	lbs
Mass EHC-L per container	420	lbs
Number of Containers / Bags of Mix	54	containers
Mass EHC-L (rounded up based on container size)	22,680	lbs
Mass of EHC-L Mix (dry component)	1,330	lbs

*Our general recommended minimum guideline for the proposed application exceeds the dose rate required based on hydrogen demand calculations and was therefore used for the purpose of this dosing calculation.

OPTIONAL pH BUFFER

If groundwater pH is below 6.5 or inoculants are to be applied together with the EHC-L, we recommend that the EHC-L injection solution be pH buffered to create optimal conditions for microbial growth. Based on laboratory tests, potassium bicarbonate, a fully soluble buffer, applied at a rate of 25 lbs / 11 kg per drum (420 lb) of EHC-L will buffer the pH of the injectate solution to circum-neutral. If baseline pH conditions were to be below 6, additional pH buffer will be needed to raise the pH of the groundwater to 7. The amount of buffer required to raise the pH of the groundwater to 7 will depend on the site-specific buffering capacity of the soil and will have to be determined by conducting a pH titration test.

Total $KHCO_3$ demand = amount $KHCO_3$ to neutralize EHC-L solution + amount needed to raise ground water / soil to a pH of 7

Soil buffering amount = KHCO3 for ground water / soil pH adjustment, which can be determined in the laboratory via titration.

	Value	Unit	
Mass $KHCO_3$ to neutralize EHC-L solution	2,700	lbs	default value
Estimated soil buffering amount	0	lbs	estimated value
Total $KHCO_3$ demand	2,700	lbs	

OPTIONAL DHC INOCULANT

Although not typically required for ISCR, DHC inoculants have shown to improve removal kinetics, in particular for potential daughter products such as cis-DCE and VC. The DHC will be added after EHC-L application, once favorable redox conditions (ORP < -75 mV, DO <0.2 mg/L, pH between 6 and 8.5) have been attained. The DHC inoculant will contain at least 5 x10E10 cfu/L of live bacteria including high numbers of dehalococcoides species with known abilities to biodegrade DCE. The target density of DHC cells in the treated aquifer is 1x10E6 cfu/L.

	Value	Unit
Dechlorinating consortium concentration in inoculant	5.00E+10	DHC/L
Design final concentration after dilution in aquifer	1.00E+06	DHC/L
Volume of Inoculant Required	26	L

COST ESTIMATE

Item	Quantity	Unit	Price	Cost
EHC-L [1, 2]	22,680	lbs	$1.58	$35,834
Shipping Estimate [3]	1	lump sum	TBD	TBD
Sub Total Cost				**$35,834**
Optional items:				
pH Buffer ($KHCO_3$) [4]	2,700	lbs	$2.50	$6,750
DHC Inoculum (incl. minimum) [4]	26	L	$90	$2,340
TOTAL COST [5]				**$44,924**

1) Price valid for 90 days from date at top of document. Terms: net 30 days.

2) Any applicable taxes not included. Please provide a copy of your tax exempt certificate or resale tax number when placing your order. In accordance with the law, applicable state and local taxes will be applied at the time of invoicing if PeroxyChem has not been presented with your fully executed tax exemption documentation.

3) Shipping rate provided is an estimate. Standard delivery time can vary from 1-3 weeks from time of order, depending upon volume. Expedited transport can be arranged at extra cost. Unless requested otherwise, costs assume standard ground transport via truck, with no need for a lift gate or pallet jack.

4) Price excludes shipping.

5) All sales are per PeroxyChem's Terms and Conditions.

Disclaimer:

The estimated dosage and recommended application methodology described in this document are based on the site information provided to us, but are not meant to constitute a guaranty of performance or a predictor of the speed at which a given site is remediated. The calculations in the Cost Estimate regarding the amount of product to be used in your project are based on stoichiometry or default minimum guideline values, and do not take into account the kinetics, or speed of the reaction. Note that the Stoichiometric mass represents the minimum anticipated amount needed to address the constituents of concern (COCs). As a result, these calculations should be used as a general approximation for purposes of an initial economic assessment. PeroxyChem recommends that you or your consultants complete a comprehensive remedial design that takes into consideration the precise nature of the COC impact and actual site conditions.

INSTALLATION

The EHC-L will be delivered as two components, which will be mixed together in the field. The first component, a 25% liquid emulsion of carbon substrate, will be provided in 55-USG drums, with 50 USG/190 litres per drum. The second component is the EHC-L mix which contains the ferrous iron powder, and is delivered as a dry powder and added to the liquid component in the field. The EHC-L mix is proportioned so that one bag (24.5 lbs / 11.1 kg) of EHC L mix is added per drum.

Depending on the application method, between 10% and 100% of the effective porosity is normally targeted during EHC-L injection, with a higher percent pore fill normally targeted during low-flow injections into wells and injection networks. This is in contrast to applications via direct push technology (DPT) where normally around 10 to 15% is targeted. To facilitate the desired injection volume, the EHC-L components will be diluted in the field.

The below table shows examples of mixing recipes for a 55-USG drum of EHC-L and the resulting total injection volume and percent pore fill. Alternative packaging options are available upon request and the below mixing recipe may be scaled depending on mix batch and packaging size.

EHC-L Mixing Recipe (per 50 USG drum)

Dilution:	**3-fold**	**10-fold**	**25-fold**
Volume EHC-L emulsion per drum (USG)	50	50	50
Mass EHC-L mix (lbs)	24.6	24.6	24.6
Volume water (USG)	100	450	1,200
Resulting total volume (USG)	150	500	1,250
Resulting EHC-L conc. (organic carbon + Fe mix)	9.7%	2.9%	1.2%
Total volume water (USG)	5,400	24,300	64,800
Total injection volume (USG)	8,100	27,000	67,500
Resulting injection volume to total pore volume	2.4%	8.0%	20.0%

Injection recommendations (can be altered):

The EHC-L solution could be injected via fixed wells or using direct push. The injection spacing would be determined based on the radius of influence achieved for the specific implementation method and lithology.

	Value	**Unit**	**Comment**
Dilution of EHC-L emulsion (can be altered)	10		can be altered
Total volume of water required	24,446	U.S. gallons	calculated value
Approximate volume of solution to inject	27,162	U.S. gallons	calculated value

Injection spacing	20	ft	customer provided
Number of injection points	25	locations	calculated value
Injection volume per point	1,086	U.S. gallons	calculated value
Injection volume per vertical foot	72	U.S. gallons	calculated value
Injection volume to total pore space volume	8	percent	calculated value

Note that the construction estimates presented above can be readily modified in the field or per recommendations from the injection contractor as required (for example, the concentration of the EHC-L solution could be changed to modify the total injection volume or the injections spacing could be altered based on installation technology).

SRS® AMENDMENT
IN SITU BIODEGRADATION

Terra Systems
INCORPORATED

Offering Bioremediation Solutions to Environmental Problems

United States Patent# RE40448 Emulsified Vegetable Oil Substrate

130 Hickman Road, Suite 1, Claymont, Delaware 19703
http://www.terrasystems.net/
Email: **mfree@terrasystems.net** - Telephone: 302-798-9553 - Fax: 302-798-9554

JBA SS-28				
Row	**Length ft**	**60 % SRS®-SD pounds**	**60% SRS®-SD gallons**	**TSI-DCL**
1	225	30,340	3,750	21.3
2	75	10,113	1,250	7.1
3	180	24,272	3,000	17.1
4	200	26,969	3,334	19.0
5	150	20,227	2,500	14.3
6	525	70,793	8,751	49.9
7	360	48,544	6,000	34.2
8	180	24,272	3,000	17.1
Sum	**1,895**	**255,530**	**31,586**	**180**

Terra Systems
INCORPORATED

Offering Bioremediation Solutions to Environmental Problems

United States Patent# RE40448 Emulsified Vegetable Oil Substrate

130 Hickman Road, Suite 1, Claymont, Delaware 19703
http://www.terrasystems.net/
Email: **mfree@terrasystems.net** - Telephone: 302-798-9553 - Fax: 302-798-9554

Downgradient Barrier				
Row	**Length ft**	**60 % SRS® -SD pounds**	**60 % SRS® -SD gallons**	**TSI-DC L**
A	125	12,384	1,531	4.2
B	250	24,769	3,062	8.5
C	325	32,199	3,980	11.0
D	300	27,922	3,451	10.2
Sum	**1,000**	**97,274**	**12,024**	**34**

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

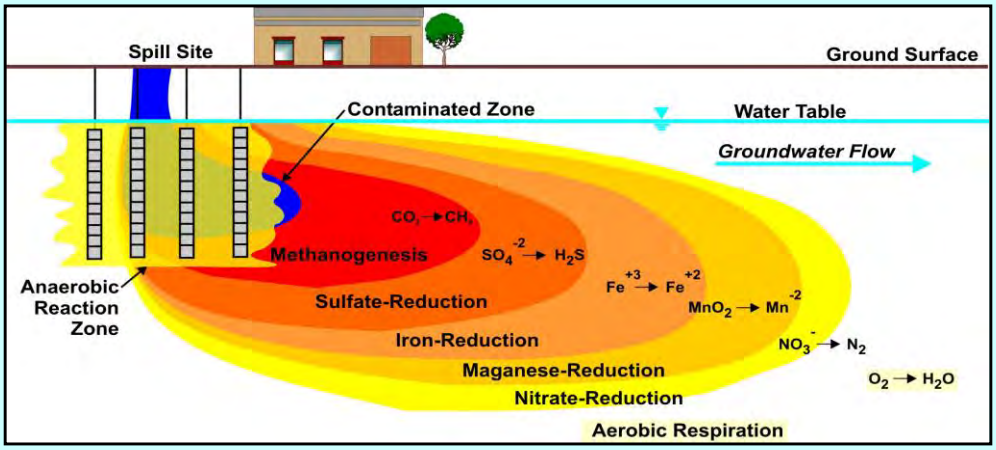
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 8

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	180	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	5040	--	ft^2	
Treatment Zone Volume	201,600	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	452,511	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	452,511	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	596,665	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 8

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	180	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	5040	--	ft^2
Treatment Zone Volume	201,600	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	452,511	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	596,665	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	5.29	7.94	0.67	4
Nitrate (denitrification)	1.1	4.15	12.30	0.34	5
Sulfate	6.32	23.86	11.91	2.00	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	37.76	1.99	18.97	8
Soluble Competing Electron Acceptor Demand (lb.)				**21.98**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	10.19	27.25	0.37	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	23.45	55.41	0.42	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.80**	

C. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.05	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.79	21.73	0.04	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.02	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	8.31	19.08	0.44	8
Trichloromethane (or chloroform) (CF)	0.610	2.30	19.74	0.12	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.02	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.07	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.03	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.60**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)

	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.04	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.24	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	5.27	19.08	0.28	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.41	19.74	0.02	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.02	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.31**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	6.97	7.94	0.88	4
Nitrate (denitrification)	1.1	5.48	10.25	0.53	5
Sulfate	6.32	31.47	11.91	2.64	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	49.79	1.99	25.02	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**29.1**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.06	20.57	0.00	8
Trichloroethene (TCE)	0.210	1.05	21.73	0.05	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.03	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	10.95	19.08	0.57	8
Trichloromethane (or chloroform) (CF)	0.610	3.04	19.74	0.15	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.03	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.10	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.04	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.79**	

Initial Hydrogen Requirement First Year (lb)	**53.6**
Total Life-Cycle Hydrogen Requirement (lb)	**143.1**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**1,674.7**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	37,415	37,415	1.70E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	37,415	77,624	1.70E+10	1,579
Molasses (assuming 6 0	11.7	35,544	59,239	1.61E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	37,423	46,779	1.70E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	19,135	23,919	8.68E+09	808
Whey (assuming 100% lactose)	11.7	25,827	36,896	1.17E+10	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	28,362	28,362	1.29E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	14,563	14,563	6.61E+09	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	14,563	24,272	6.61E+09	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 8

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	180	feet	55	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

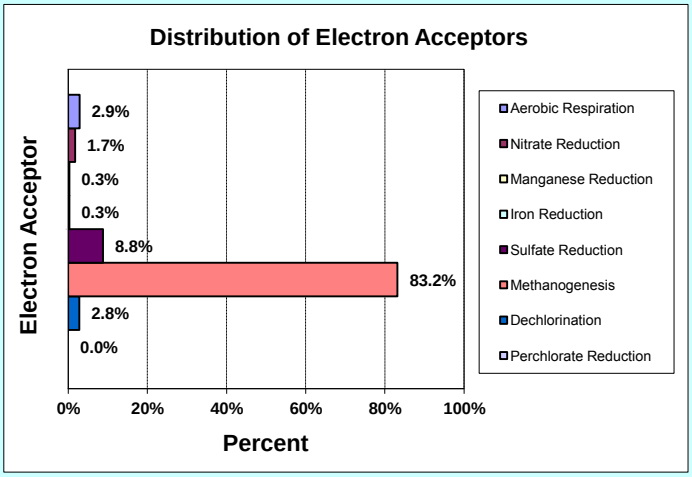
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	452,511	gallons	1,712,894	liters
Groundwater Flux (per year)	596,665	gallons/year	2,258,558	liters/year
Total Groundwater Volume Treated (over entire design period)	2,839,169	gallons total	10,747,125	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	4.177
Nitrate Reduction	1.7%	2.475
Sulfate Reduction	8.8%	12.572
Manganese Reduction	0.3%	0.374
Iron Reduction	0.3%	0.423
Methanogenesis	83.2%	119.053
Dechlorination	2.8%	4.061
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**143.14**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	77,624	7,057	1,579	as lactic acid
2. Molasses Product	59,239	4,937	1,500	as sucrose
3. Fructose Product	46,779	4,177	1,580	as fructose
4. Ethanol Product	23,919	3,467	808	as ethanol
5. Sweet Dry Whey (lactose)	36,896	sold by pound	1,090	as lactose
6. HRC®	28,362	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	14,563	1,867	615	as soybean oil
8. Emulsified Vegetable Oil	24,272	3,112	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

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Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

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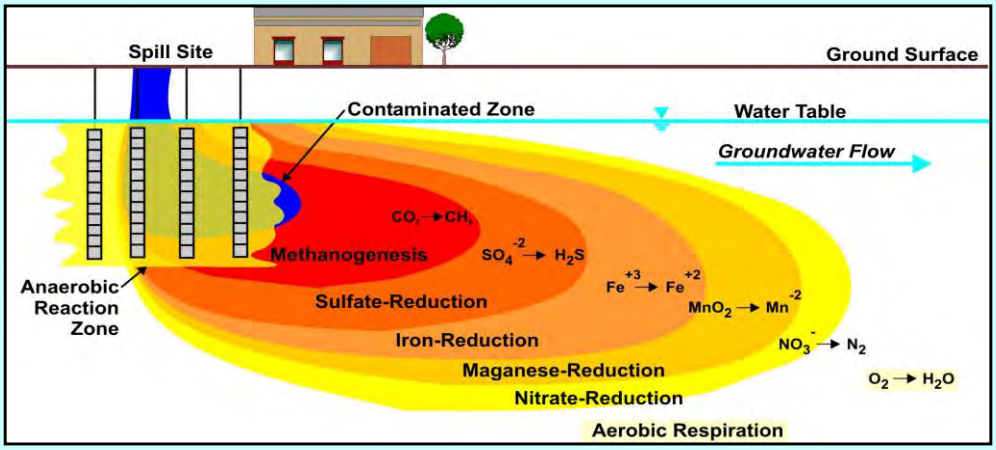

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Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 7

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	360	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	10080	--	ft^2	
Treatment Zone Volume	403,200	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	905,023	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	905,023	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	1,193,329	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 7

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	360	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	10080	--	ft^2
Treatment Zone Volume	403,200	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	905,023	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	1,193,329	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	10.57	7.94	1.33	4
Nitrate (denitrification)	1.1	8.31	12.30	0.68	5
Sulfate	6.32	47.73	11.91	4.01	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	75.52	1.99	37.95	8
Soluble Competing Electron Acceptor Demand (lb.)				**43.96**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	20.37	27.25	0.75	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	46.91	55.41	0.85	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**1.59**	

C. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.10	20.57	0.00	8
Trichloroethene (TCE)	0.210	1.59	21.73	0.07	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.05	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	16.61	19.08	0.87	8
Trichloromethane (or chloroform) (CF)	0.610	4.61	19.74	0.23	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.05	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.15	22.06	0.01	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.07	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**1.20**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)

	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.07	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.48	21.73	0.02	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.01	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	10.55	19.08	0.55	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.82	19.74	0.04	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.04	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.01	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.62**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	13.94	7.94	1.76	4
Nitrate (denitrification)	1.1	10.95	10.25	1.07	5
Sulfate	6.32	62.93	11.91	5.28	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	99.58	1.99	50.04	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**58.1**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.13	20.57	0.01	8
Trichloroethene (TCE)	0.210	2.09	21.73	0.10	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.06	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	21.91	19.08	1.15	8
Trichloromethane (or chloroform) (CF)	0.610	6.07	19.74	0.31	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.06	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.19	22.06	0.01	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.09	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**1.58**	

Initial Hydrogen Requirement First Year (lb)	**107.1**
Total Life-Cycle Hydrogen Requirement (lb)	**286.3**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**3,349.4**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	74,829	74,829	3.39E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	74,829	155,248	3.39E+10	1,579
Molasses (assuming 6 0	11.7	71,087	118,478	3.22E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	74,846	93,557	3.40E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	38,270	47,838	1.74E+10	808
Whey (assuming 100% lactose)	11.7	51,654	73,792	2.34E+10	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	56,725	56,725	2.57E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	29,126	29,126	1.32E+10	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	29,126	48,544	1.32E+10	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 7

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	360	feet	110	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

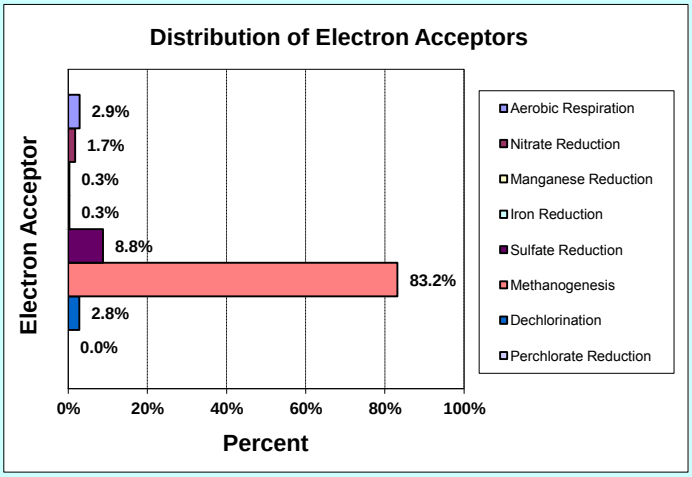
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	905,023	gallons	3,425,788	liters
Groundwater Flux (per year)	1,193,329	gallons/year	4,517,116	liters/year
Total Groundwater Volume Treated (over entire design period)	5,678,339	gallons total	21,494,250	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	8.355
Nitrate Reduction	1.7%	4.950
Sulfate Reduction	8.8%	25.144
Manganese Reduction	0.3%	0.748
Iron Reduction	0.3%	0.847
Methanogenesis	83.2%	238.106
Dechlorination	2.8%	8.123
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**286.27**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	155,248	14,113	1,579	as lactic acid
2. Molasses Product	118,478	9,873	1,500	as sucrose
3. Fructose Product	93,557	8,353	1,580	as fructose
4. Ethanol Product	47,838	6,933	808	as ethanol
5. Sweet Dry Whey (lactose)	73,792	sold by pound	1,090	as lactose
6. HRC®	56,725	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	29,126	3,734	615	as soybean oil
8. Emulsified Vegetable Oil	48,544	6,224	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

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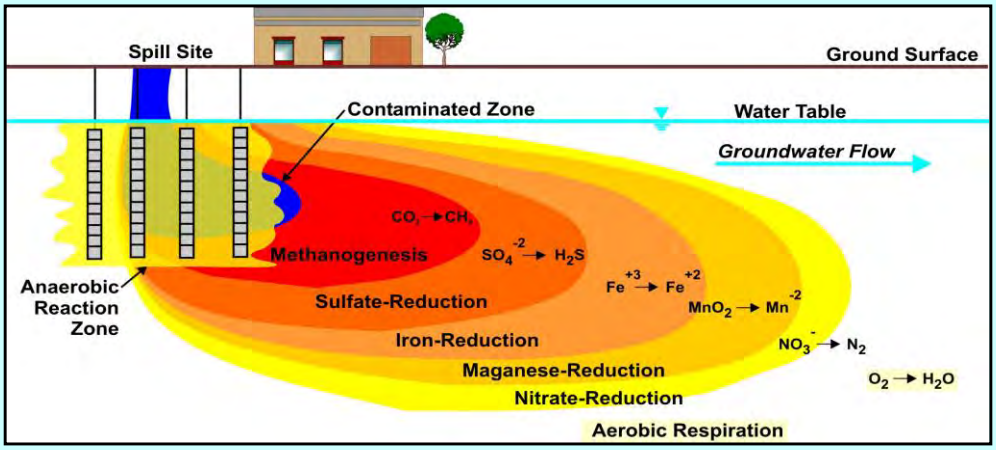
PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 6

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	525	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	14700	--	ft^2	
Treatment Zone Volume	588,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	1,319,825	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	1,319,825	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	1,740,271	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 6

RETURN TO COVER PAGE

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	525	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	14700	--	ft^2
Treatment Zone Volume	588,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	1,319,825	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	1,740,271	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	15.42	7.94	1.94	4
Nitrate (denitrification)	1.1	12.11	12.30	0.98	5
Sulfate	6.32	69.60	11.91	5.84	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	110.13	1.99	55.34	8
Soluble Competing Electron Acceptor Demand (lb.)				**64.11**	

B. Solid-Phase Native Electron Acceptors

(Based on manganese and iron produced)

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	29.71	27.25	1.09	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	68.41	55.41	1.23	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**2.32**	

C. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.14	20.57	0.01	8
Trichloroethene (TCE)	0.210	2.31	21.73	0.11	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.07	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	24.23	19.08	1.27	8
Trichloromethane (or chloroform) (CF)	0.610	6.72	19.74	0.34	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.07	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.21	22.06	0.01	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.10	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**1.74**	

D. Sorbed Contaminant Electron Acceptors

(Soil Concentration = Koc x foc x Cgw)

	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.11	20.57	0.01	8
Trichloroethene (TCE)	107	0.01	0.70	21.73	0.03	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.01	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	15.38	19.08	0.81	8
Trichloromethane (or chloroform) (CF)	63	0.02	1.20	19.74	0.06	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.01	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.06	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.01	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.91**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	20.33	7.94	2.56	4
Nitrate (denitrification)	1.1	15.97	10.25	1.56	5
Sulfate	6.32	91.78	11.91	7.71	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	145.22	1.99	72.97	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**84.8**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.19	20.57	0.01	8
Trichloroethene (TCE)	0.210	3.05	21.73	0.14	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.09	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	31.95	19.08	1.67	8
Trichloromethane (or chloroform) (CF)	0.610	8.86	19.74	0.45	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.09	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.28	22.06	0.01	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.13	24.55	0.01	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**2.30**	

Initial Hydrogen Requirement First Year (lb)	**156.2**
Total Life-Cycle Hydrogen Requirement (lb)	**417.5**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**4,884.5**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	109,126	109,126	4.95E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	109,126	226,403	4.95E+10	1,579
Molasses (assuming 6 0	11.7	103,669	172,781	4.70E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	109,150	136,438	4.95E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	55,811	69,764	2.53E+10	808
Whey (assuming 100% lactose)	11.7	75,329	107,613	3.42E+10	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	82,724	82,724	3.75E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	42,476	42,476	1.93E+10	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	42,476	70,793	1.93E+10	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 6

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	525	feet	160	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

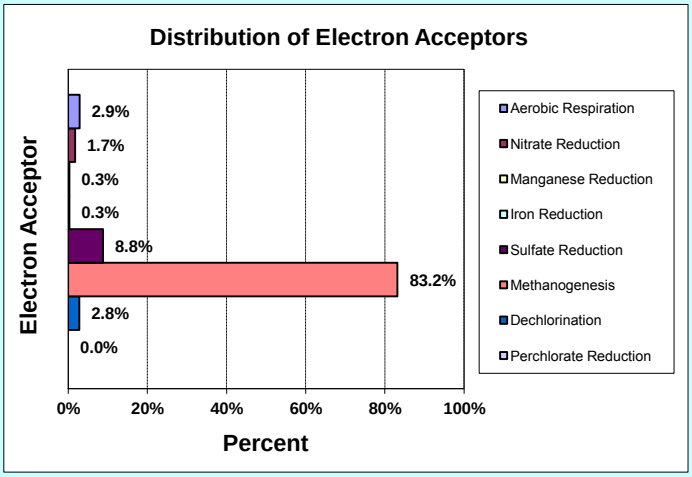
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	1,319,825	gallons	4,995,941	liters
Groundwater Flux (per year)	1,740,271	gallons/year	6,587,460	liters/year
Total Groundwater Volume Treated (over entire design period)	8,280,911	gallons total	31,345,781	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	12.184
Nitrate Reduction	1.7%	7.219
Sulfate Reduction	8.8%	36.668
Manganese Reduction	0.3%	1.090
Iron Reduction	0.3%	1.235
Methanogenesis	83.2%	347.238
Dechlorination	2.8%	11.846
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**417.48**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	226,403	20,582	1,579	as lactic acid
2. Molasses Product	172,781	14,398	1,500	as sucrose
3. Fructose Product	136,438	12,182	1,580	as fructose
4. Ethanol Product	69,764	10,111	808	as ethanol
5. Sweet Dry Whey (lactose)	107,613	sold by pound	1,090	as lactose
6. HRC®	82,724	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	42,476	5,446	615	as soybean oil
8. Emulsified Vegetable Oil	70,793	9,076	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

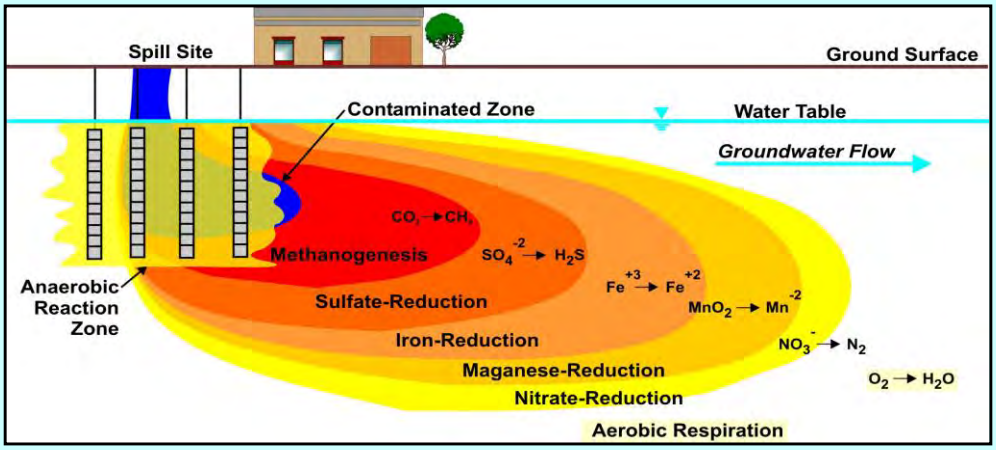
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 5

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	150	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	4200	--	ft^2	
Treatment Zone Volume	168,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	377,093	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	377,093	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	497,220	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 5

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	150	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	4200	--	ft^2
Treatment Zone Volume	168,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	377,093	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	497,220	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	4.41	7.94	0.55	4
Nitrate (denitrification)	1.1	3.46	12.30	0.28	5
Sulfate	6.32	19.89	11.91	1.67	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	31.47	1.99	15.81	8
Soluble Competing Electron Acceptor Demand (lb.)				**18.32**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	8.49	27.25	0.31	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	19.55	55.41	0.35	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.66**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.04	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.66	21.73	0.03	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.02	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	6.92	19.08	0.36	8
Trichloromethane (or chloroform) (CF)	0.610	1.92	19.74	0.10	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.02	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.06	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.03	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.50**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.03	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.20	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	4.39	19.08	0.23	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.34	19.74	0.02	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.02	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.26**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	5.81	7.94	0.73	4
Nitrate (denitrification)	1.1	4.56	10.25	0.45	5
Sulfate	6.32	26.22	11.91	2.20	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	41.49	1.99	20.85	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**24.2**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.05	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.87	21.73	0.04	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.02	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	9.13	19.08	0.48	8
Trichloromethane (or chloroform) (CF)	0.610	2.53	19.74	0.13	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.02	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.08	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.04	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.66**	

Initial Hydrogen Requirement First Year (lb)	**44.6**
Total Life-Cycle Hydrogen Requirement (lb)	**119.3**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**1,395.6**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	31,179	31,179	1.41E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	31,179	64,687	1.41E+10	1,579
Molasses (assuming 6 0	11.7	29,620	49,366	1.34E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	31,186	38,982	1.41E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	15,946	19,932	7.23E+09	808
Whey (assuming 100% lactose)	11.7	21,523	30,747	9.76E+09	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	23,635	23,635	1.07E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	12,136	12,136	5.50E+09	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	12,136	20,227	5.50E+09	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 5

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	150	feet	46	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

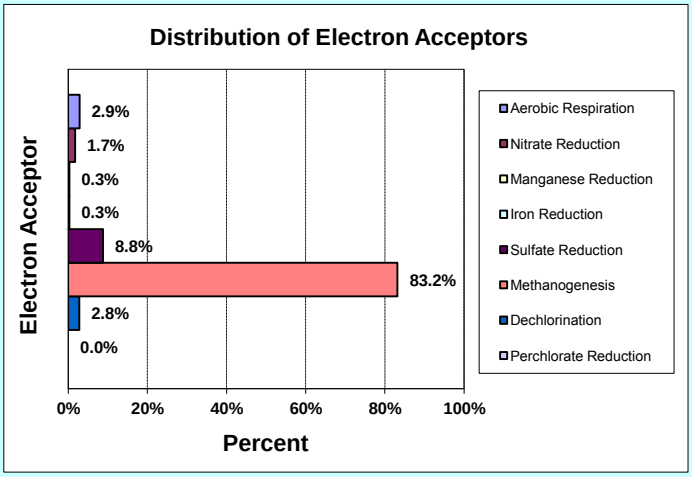
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	377,093	gallons	1,427,412	liters
Groundwater Flux (per year)	497,220	gallons/year	1,882,131	liters/year
Total Groundwater Volume Treated (over entire design period)	2,365,975	gallons total	8,955,937	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	3.481
Nitrate Reduction	1.7%	2.062
Sulfate Reduction	8.8%	10.477
Manganese Reduction	0.3%	0.312
Iron Reduction	0.3%	0.353
Methanogenesis	83.2%	99.211
Dechlorination	2.8%	3.385
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**119.28**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	64,687	5,881	1,579	as lactic acid
2. Molasses Product	49,366	4,114	1,500	as sucrose
3. Fructose Product	38,982	3,481	1,580	as fructose
4. Ethanol Product	19,932	2,889	808	as ethanol
5. Sweet Dry Whey (lactose)	30,747	sold by pound	1,090	as lactose
6. HRC®	23,635	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	12,136	1,556	615	as soybean oil
8. Emulsified Vegetable Oil	20,227	2,593	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

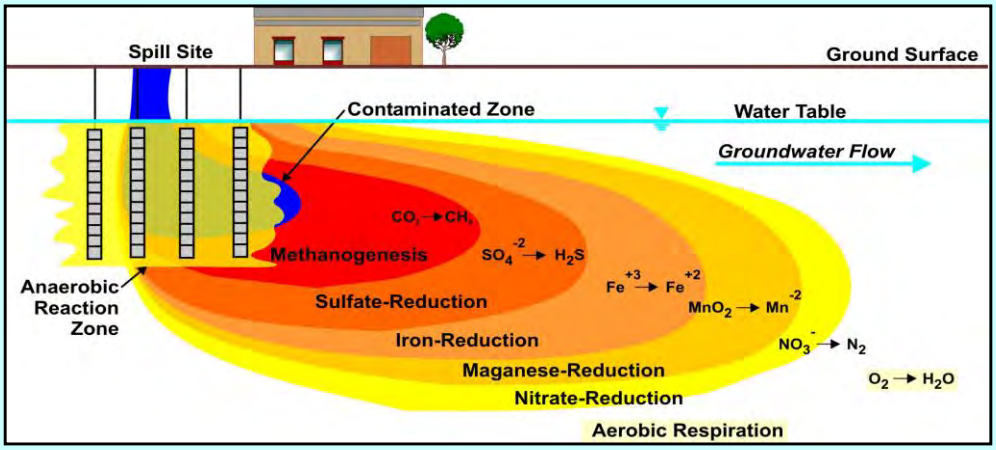
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 4

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	200	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	5600	--	ft^2	
Treatment Zone Volume	224,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	502,790	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	502,790	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	662,961	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 4

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	200	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	5600	--	ft^2
Treatment Zone Volume	224,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	502,790	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	662,961	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	5.87	7.94	0.74	4
Nitrate (denitrification)	1.1	4.62	12.30	0.38	5
Sulfate	6.32	26.52	11.91	2.23	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	41.96	1.99	21.08	8
Soluble Competing Electron Acceptor Demand (lb.)				**24.42**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	11.32	27.25	0.42	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	26.06	55.41	0.47	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.89**	

C. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.05	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.88	21.73	0.04	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.03	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	9.23	19.08	0.48	8
Trichloromethane (or chloroform) (CF)	0.610	2.56	19.74	0.13	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.03	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.08	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.04	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.66**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)

	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.04	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.27	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	5.86	19.08	0.31	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.46	19.74	0.02	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.02	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.35**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	7.74	7.94	0.98	4
Nitrate (denitrification)	1.1	6.09	10.25	0.59	5
Sulfate	6.32	34.96	11.91	2.94	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	55.32	1.99	27.80	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**32.3**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.07	20.57	0.00	8
Trichloroethene (TCE)	0.210	1.16	21.73	0.05	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.03	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	12.17	19.08	0.64	8
Trichloromethane (or chloroform) (CF)	0.610	3.37	19.74	0.17	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.03	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.11	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.05	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.88**	

Initial Hydrogen Requirement First Year (lb)	**59.5**
Total Life-Cycle Hydrogen Requirement (lb)	**159.0**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**1,860.8**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	41,572	41,572	1.89E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	41,572	86,249	1.89E+10	1,579
Molasses (assuming 6 0	11.7	39,493	65,821	1.79E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	41,581	51,976	1.89E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	21,261	26,577	9.64E+09	808
Whey (assuming 100% lactose)	11.7	28,697	40,996	1.30E+10	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	31,514	31,514	1.43E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	16,181	16,181	7.34E+09	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	16,181	26,969	7.34E+09	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 4

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	200	feet	61	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

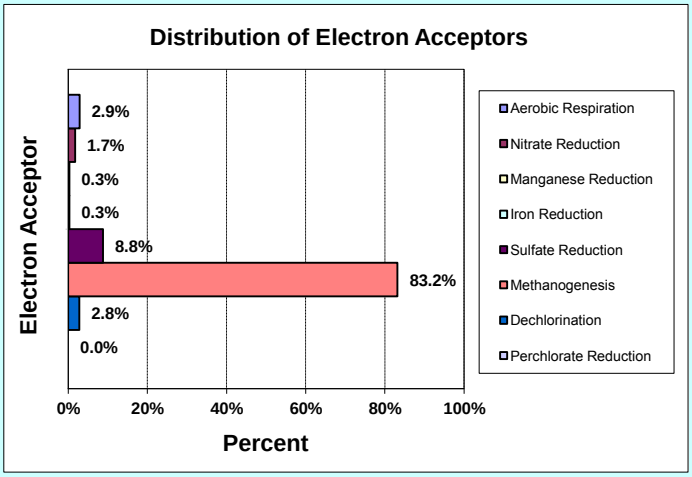
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	502,790	gallons	1,903,216	liters
Groundwater Flux (per year)	662,961	gallons/year	2,509,509	liters/year
Total Groundwater Volume Treated (over entire design period)	3,154,633	gallons total	11,941,250	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	4.642
Nitrate Reduction	1.7%	2.750
Sulfate Reduction	8.8%	13.969
Manganese Reduction	0.3%	0.415
Iron Reduction	0.3%	0.470
Methanogenesis	83.2%	132.281
Dechlorination	2.8%	4.513
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**159.04**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	86,249	7,841	1,579	as lactic acid
2. Molasses Product	65,821	5,485	1,500	as sucrose
3. Fructose Product	51,976	4,641	1,580	as fructose
4. Ethanol Product	26,577	3,852	808	as ethanol
5. Sweet Dry Whey (lactose)	40,996	sold by pound	1,090	as lactose
6. HRC®	31,514	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	16,181	2,075	615	as soybean oil
8. Emulsified Vegetable Oil	26,969	3,458	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

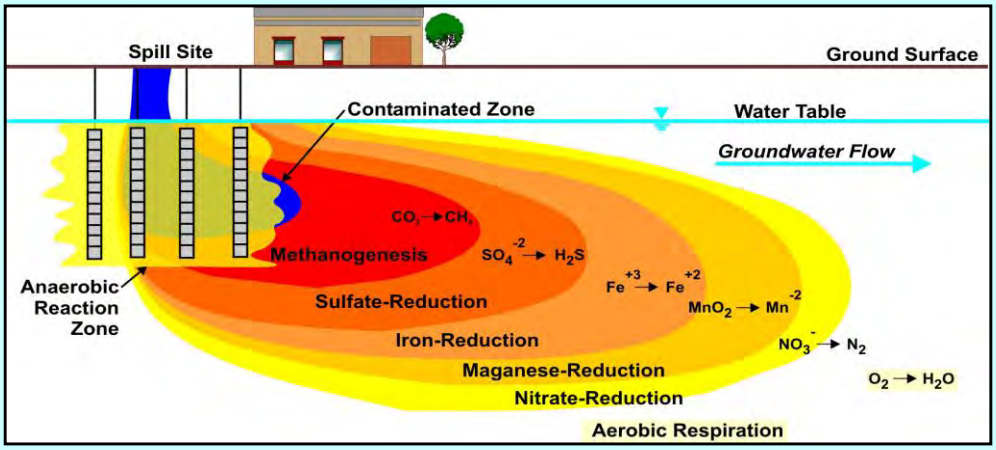
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 3

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	180	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	5040	--	ft^2	
Treatment Zone Volume	201,600	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	452,511	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	452,511	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	596,665	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 3

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	180	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	5040	--	ft^2
Treatment Zone Volume	201,600	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	452,511	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	596,665	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	5.29	7.94	0.67	4
Nitrate (denitrification)	1.1	4.15	12.30	0.34	5
Sulfate	6.32	23.86	11.91	2.00	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	37.76	1.99	18.97	8
Soluble Competing Electron Acceptor Demand (lb.)				**21.98**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	10.19	27.25	0.37	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	23.45	55.41	0.42	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.80**	

C. Soluble Contaminant Electron Acceptors

	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.05	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.79	21.73	0.04	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.02	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	8.31	19.08	0.44	8
Trichloromethane (or chloroform) (CF)	0.610	2.30	19.74	0.12	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.02	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.07	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.03	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.60**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)

	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.04	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.24	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	5.27	19.08	0.28	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.41	19.74	0.02	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.02	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.31**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	6.97	7.94	0.88	4
Nitrate (denitrification)	1.1	5.48	10.25	0.53	5
Sulfate	6.32	31.47	11.91	2.64	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	49.79	1.99	25.02	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**29.1**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.06	20.57	0.00	8
Trichloroethene (TCE)	0.210	1.05	21.73	0.05	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.03	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	10.95	19.08	0.57	8
Trichloromethane (or chloroform) (CF)	0.610	3.04	19.74	0.15	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.03	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.10	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.04	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.79**	

Initial Hydrogen Requirement First Year (lb)	**53.6**
Total Life-Cycle Hydrogen Requirement (lb)	**143.1**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**1,674.7**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	37,415	37,415	1.70E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	37,415	77,624	1.70E+10	1,579
Molasses (assuming 6 0	11.7	35,544	59,239	1.61E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	37,423	46,779	1.70E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	19,135	23,919	8.68E+09	808
Whey (assuming 100% lactose)	11.7	25,827	36,896	1.17E+10	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	28,362	28,362	1.29E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	14,563	14,563	6.61E+09	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	14,563	24,272	6.61E+09	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 3

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	180	feet	55	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

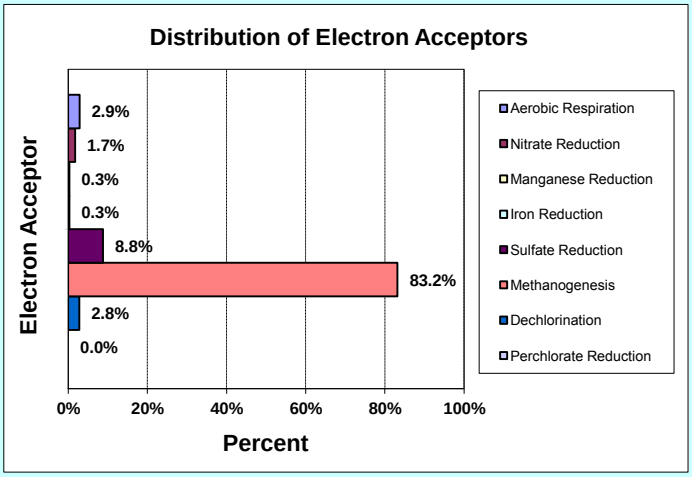
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	452,511	gallons	1,712,894	liters
Groundwater Flux (per year)	596,665	gallons/year	2,258,558	liters/year
Total Groundwater Volume Treated (over entire design period)	2,839,169	gallons total	10,747,125	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	4.177
Nitrate Reduction	1.7%	2.475
Sulfate Reduction	8.8%	12.572
Manganese Reduction	0.3%	0.374
Iron Reduction	0.3%	0.423
Methanogenesis	83.2%	119.053
Dechlorination	2.8%	4.061
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**143.14**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	77,624	7,057	1,579	as lactic acid
2. Molasses Product	59,239	4,937	1,500	as sucrose
3. Fructose Product	46,779	4,177	1,580	as fructose
4. Ethanol Product	23,919	3,467	808	as ethanol
5. Sweet Dry Whey (lactose)	36,896	sold by pound	1,090	as lactose
6. HRC®	28,362	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	14,563	1,867	615	as soybean oil
8. Emulsified Vegetable Oil	24,272	3,112	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

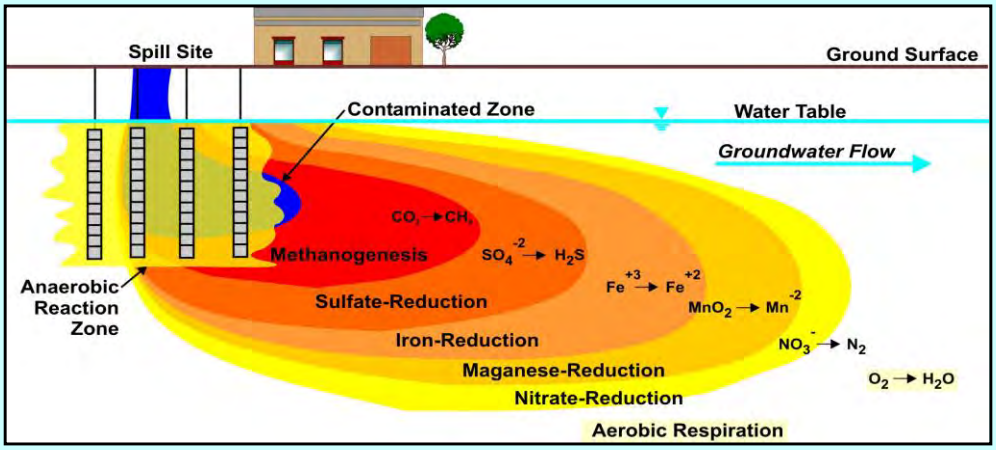
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 2

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	75	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	2100	--	ft^2	
Treatment Zone Volume	84,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	188,546	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	188,546	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	248,610	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 2

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	75	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	2100	--	ft^2
Treatment Zone Volume	84,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	188,546	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	248,610	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	2.20	7.94	0.28	4
Nitrate (denitrification)	1.1	1.73	12.30	0.14	5
Sulfate	6.32	9.94	11.91	0.83	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	15.73	1.99	7.91	8
Soluble Competing Electron Acceptor Demand (lb.)				**9.16**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	4.24	27.25	0.16	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	9.77	55.41	0.18	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.33**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.02	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.33	21.73	0.02	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.01	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	3.46	19.08	0.18	8
Trichloromethane (or chloroform) (CF)	0.610	0.96	19.74	0.05	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.01	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.03	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.01	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.25**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.02	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.10	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	2.20	19.08	0.12	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.17	19.74	0.01	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.01	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.13**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	2.90	7.94	0.37	4
Nitrate (denitrification)	1.1	2.28	10.25	0.22	5
Sulfate	6.32	13.11	11.91	1.10	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	20.75	1.99	10.42	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**12.1**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.03	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.44	21.73	0.02	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.01	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	4.56	19.08	0.24	8
Trichloromethane (or chloroform) (CF)	0.610	1.27	19.74	0.06	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.01	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.04	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.02	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.33**	

Initial Hydrogen Requirement First Year (lb)	**22.3**
Total Life-Cycle Hydrogen Requirement (lb)	**59.6**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**697.8**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

RETURN TO COVER PAGE

Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	15,589	15,589	7.07E+09	1,579
Sodium Lactate Product (60 percent solution)	11.7	15,589	32,343	7.07E+09	1,579
Molasses (assuming 6 0	11.7	14,810	24,683	6.72E+09	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	15,593	19,491	7.07E+09	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	7,973	9,966	3.62E+09	808
Whey (assuming 100% lactose)	11.7	10,761	15,373	4.88E+09	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	11,818	11,818	5.36E+09	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	6,068	6,068	2.75E+09	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	6,068	10,113	2.75E+09	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 2

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	75	feet	23	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

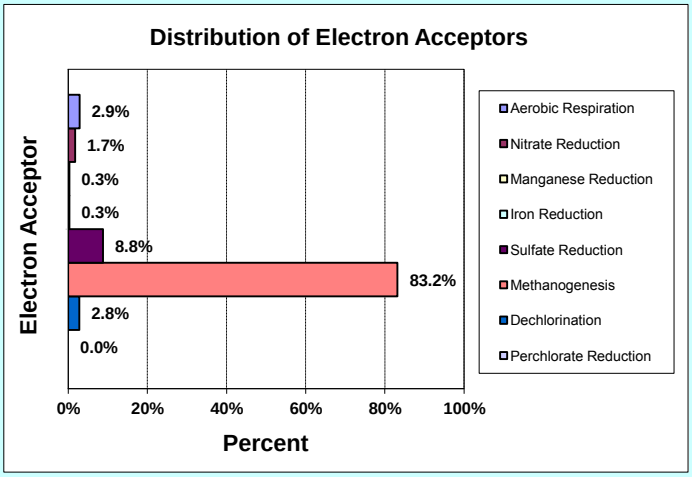
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	188,546	gallons	713,706	liters
Groundwater Flux (per year)	248,610	gallons/year	941,066	liters/year
Total Groundwater Volume Treated (over entire design period)	1,182,987	gallons total	4,477,969	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	1.741
Nitrate Reduction	1.7%	1.031
Sulfate Reduction	8.8%	5.238
Manganese Reduction	0.3%	0.156
Iron Reduction	0.3%	0.176
Methanogenesis	83.2%	49.605
Dechlorination	2.8%	1.692
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**59.64**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	32,343	2,940	1,579	as lactic acid
2. Molasses Product	24,683	2,057	1,500	as sucrose
3. Fructose Product	19,491	1,740	1,580	as fructose
4. Ethanol Product	9,966	1,444	808	as ethanol
5. Sweet Dry Whey (lactose)	15,373	sold by pound	1,090	as lactose
6. HRC®	11,818	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	6,068	778	615	as soybean oil
8. Emulsified Vegetable Oil	10,113	1,297	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

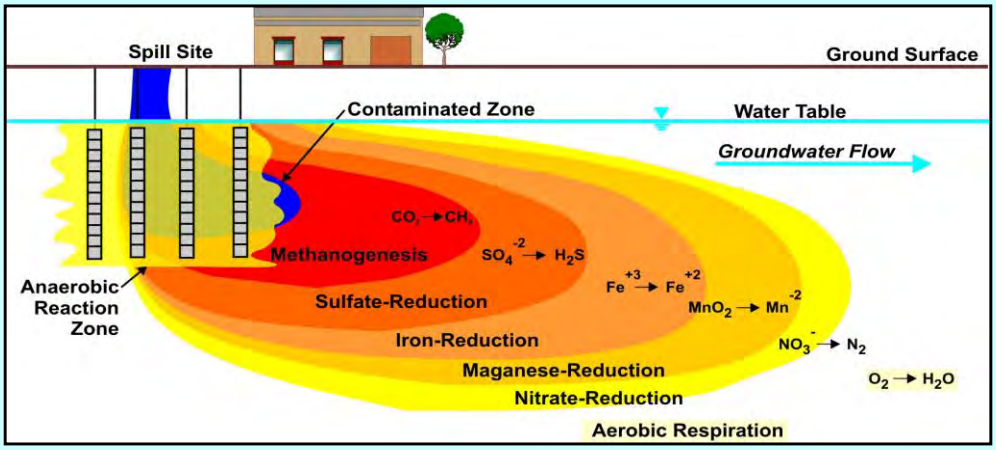
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 1

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	225	1-10,000	feet	based on TCE 50ppb in building region - overlaps CT
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	based on TCE 50ppb in building region - overlaps CT
Saturated Thickness	28	1-100	feet	ranges from 25 to 30 ft
Treatment Zone Cross Sectional Area	6300	--	ft^2	
Treatment Zone Volume	252,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	565,639	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	565,639	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	745,831	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.10	0.1 to- 20	mg/L	average
Sulfate	6	10 to 5,000	mg/L	average
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.013	--	mg/L	region max
Trichloroethene (TCE)	0.210	--	mg/L	region max
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	--	mg/L	region max
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	2.200	--	mg/L	region max
Trichloromethane (or chloroform) (CF)	0.610	--	mg/L	region max
Dichloromethane (or methylene chloride) (MC)	0.006	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	--	mg/L	region max
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	--	mg/L	region max
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	ºC	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	6	10 to 1,000	mg/L	site average
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	73	10 to 10,000	mg/L	average
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 1

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	225	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	28	1-100	feet
Treatment Zone Cross Sectional Area	6300	--	ft^2
Treatment Zone Volume	252,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	565,639	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	14.45	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.14	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	52.7	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	745,831	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	6.61	7.94	0.83	4
Nitrate (denitrification)	1.1	5.19	12.30	0.42	5
Sulfate	6.32	29.83	11.91	2.50	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	47.20	1.99	23.72	8
Soluble Competing Electron Acceptor Demand (lb.)				**27.48**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	12.73	27.25	0.47	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	29.32	55.41	0.53	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**1.00**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.06	20.57	0.00	8
Trichloroethene (TCE)	0.210	0.99	21.73	0.05	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.03	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	10.38	19.08	0.54	8
Trichloromethane (or chloroform) (CF)	0.610	2.88	19.74	0.15	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.03	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.09	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.04	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.75**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.05	20.57	0.00	8
Trichloroethene (TCE)	107	0.01	0.30	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.25	6.59	19.08	0.35	8
Trichloromethane (or chloroform) (CF)	63	0.02	0.51	19.74	0.03	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.03	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.39**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	8.71	7.94	1.10	4
Nitrate (denitrification)	1.1	6.85	10.25	0.67	5
Sulfate	6.32	39.33	11.91	3.30	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	62.24	1.99	31.27	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**36.3**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.013	0.08	20.57	0.00	8
Trichloroethene (TCE)	0.210	1.31	21.73	0.06	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.006	0.04	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	2.200	13.69	19.08	0.72	8
Trichloromethane (or chloroform) (CF)	0.610	3.80	19.74	0.19	6
Dichloromethane (or methylene chloride) (MC)	0.006	0.04	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.020	0.12	22.06	0.01	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.009	0.06	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.99**	

Initial Hydrogen Requirement First Year (lb)	**66.9**
Total Life-Cycle Hydrogen Requirement (lb)	**178.9**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**2,093.4**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	46,768	46,768	2.12E+10	1,579
Sodium Lactate Product (60 percent solution)	11.7	46,768	97,030	2.12E+10	1,579
Molasses (assuming 6 0	11.7	44,429	74,049	2.02E+10	1,500
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	46,779	58,473	2.12E+10	1,580
Ethanol Product (assuming 80% ethanol by weight)	11.7	23,919	29,899	1.08E+10	808
Whey (assuming 100% lactose)	11.7	32,284	46,120	1.46E+10	1,090
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	35,453	35,453	1.61E+10	958
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	18,204	18,204	8.26E+09	615
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	18,204	30,340	8.26E+09	615

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row 1

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	225	feet	69	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	28	feet	8.5	meters
Design Period of Performance	4	years	4	years

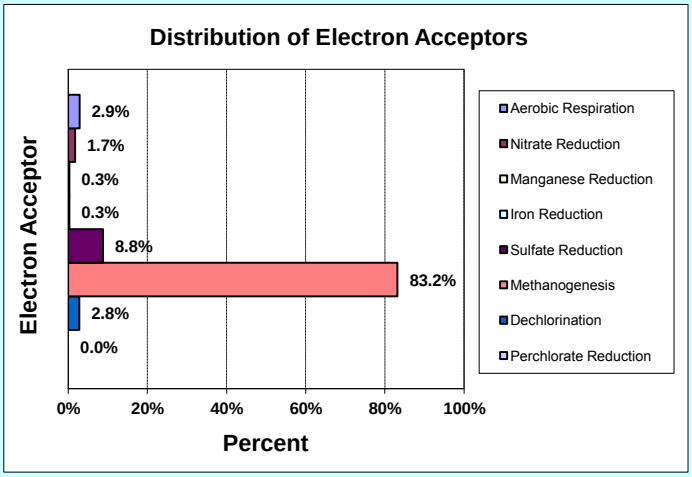
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	14.45	ft/day	5.1E-03	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.14	ft/day	4.4E+00	cm/day
Average Groundwater Seepage Velocity	53	ft/yr	16.1	m/yr
Total Treatment Zone Pore Volume	565,639	gallons	2,141,117	liters
Groundwater Flux (per year)	745,831	gallons/year	2,823,197	liters/year
Total Groundwater Volume Treated (over entire design period)	3,548,962	gallons total	13,433,906	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.9%	5.222
Nitrate Reduction	1.7%	3.094
Sulfate Reduction	8.8%	15.715
Manganese Reduction	0.3%	0.467
Iron Reduction	0.3%	0.529
Methanogenesis	83.2%	148.816
Dechlorination	2.8%	5.077
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**178.92**

Hydrogen demand in pounds/gallon:	5.04E-05
Hydrogen demand in grams per liter:	6.04E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	97,030	8,821	1,579	as lactic acid
2. Molasses Product	74,049	6,171	1,500	as sucrose
3. Fructose Product	58,473	5,221	1,580	as fructose
4. Ethanol Product	29,899	4,333	808	as ethanol
5. Sweet Dry Whey (lactose)	46,120	sold by pound	1,090	as lactose
6. HRC®	35,453	sold by pound	958	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	18,204	2,334	615	as soybean oil
8. Emulsified Vegetable Oil	30,340	3,890	615	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE

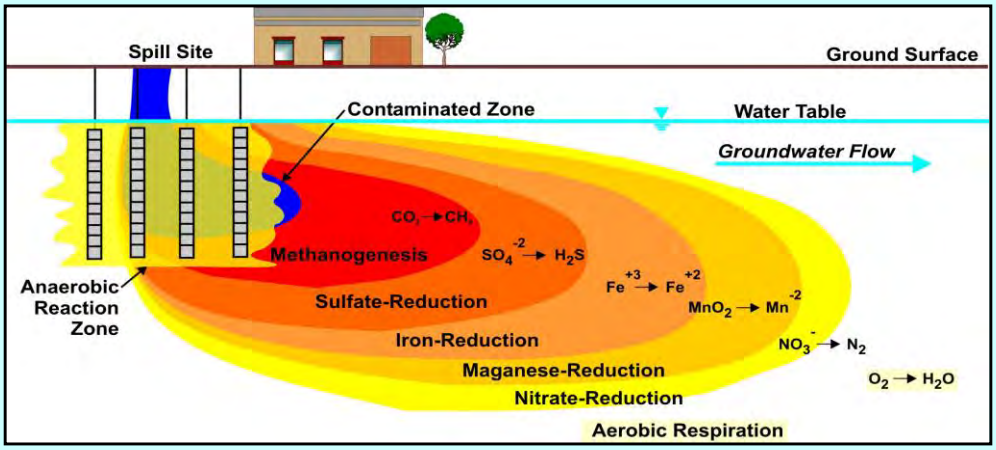


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Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row D

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	300	1-10,000	feet	for ISB/ISCR barriers - summation of all 4 barrier widths
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	for ISB/ISCR barriers
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	3000	--	ft^2	
Treatment Zone Volume	120,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	269,352	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	269,352	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC - CHANGE AS NEE
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	760,946	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.00	0.1 to- 20	mg/L	ranged from ND to 3.8 mg/L
Sulfate	12	10 to 5,000	mg/L	max 35.2
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.022	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	--	mg/L	
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	°C	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	47	10 to 1,000	mg/L	from MW09
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	380	10 to 10,000	mg/L	site max
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

aiming to have 4 barriers

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row D

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	300	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	10	1-100	feet
Treatment Zone Cross Sectional Area	3000	--	ft^2
Treatment Zone Volume	120,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	269,352	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	760,946	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	3.15	7.94	0.40	4
Nitrate (denitrification)	1.0	2.25	12.30	0.18	5
Sulfate	12	26.97	11.91	2.26	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	22.48	1.99	11.29	8
Soluble Competing Electron Acceptor Demand (lb.)				**14.14**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	11.89	27.25	0.44	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	27.37	55.41	0.49	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.93**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.05	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.00**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.00	20.57	0.00	8
Trichloroethene (TCE)	107	0.00	0.01	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.00	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	63	0.00	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.00**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	8.89	7.94	1.12	4
Nitrate (denitrification)	1.0	6.35	10.25	0.62	5
Sulfate	12	76.20	11.91	6.40	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	63.50	1.99	31.91	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**40.0**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.14	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.01**	

Initial Hydrogen Requirement First Year (lb)	**55.1**
Total Life-Cycle Hydrogen Requirement (lb)	**175.3**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**2,050.7**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	45,816	45,816	2.08E+10	1,657
Sodium Lactate Product (60 percent solution)	11.7	45,816	95,055	2.08E+10	1,657
Molasses (assuming 6 0	11.7	43,525	72,542	1.97E+10	1,574
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	45,826	57,283	2.08E+10	1,657
Ethanol Product (assuming 80% ethanol by weight)	11.7	23,432	29,290	1.06E+10	848
Whey (assuming 100% lactose)	11.7	31,627	45,181	1.43E+10	1,144
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	34,731	34,731	1.58E+10	1,005
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	17,833	17,833	8.09E+09	645
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	17,833	29,722	8.09E+09	645

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row D

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	300	feet	91	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	4	years	4	years

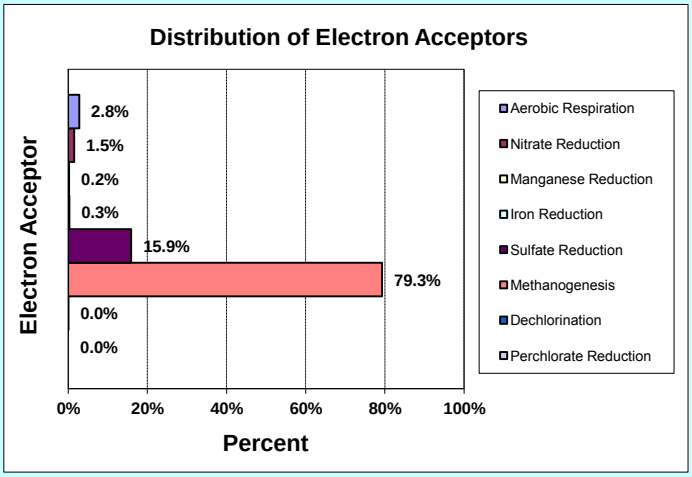
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	30.96	ft/day	1.1E-02	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.31	ft/day	9.4E+00	cm/day
Average Groundwater Seepage Velocity	113	ft/yr	34.4	m/yr
Total Treatment Zone Pore Volume	269,352	gallons	1,019,580	liters
Groundwater Flux (per year)	760,946	gallons/year	2,880,415	liters/year
Total Groundwater Volume Treated (over entire design period)	3,313,137	gallons total	12,541,239	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.8%	4.875
Nitrate Reduction	1.5%	2.661
Sulfate Reduction	15.9%	27.856
Manganese Reduction	0.2%	0.436
Iron Reduction	0.3%	0.494
Methanogenesis	79.3%	138.928
Dechlorination	0.0%	0.029
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**175.28**

Hydrogen demand in pounds/gallon:	5.29E-05
Hydrogen demand in grams per liter:	6.34E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	95,055	8,641	1,657	as lactic acid
2. Molasses Product	72,542	6,045	1,574	as sucrose
3. Fructose Product	57,283	5,115	1,657	as fructose
4. Ethanol Product	29,290	4,245	848	as ethanol
5. Sweet Dry Whey (lactose)	45,181	sold by pound	1,144	as lactose
6. HRC®	34,731	sold by pound	1,005	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	17,833	2,286	645	as soybean oil
8. Emulsified Vegetable Oil	29,722	3,811	645	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

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Calculation Tables

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Table S.3 - Hydrogen Produced by Common Substrates

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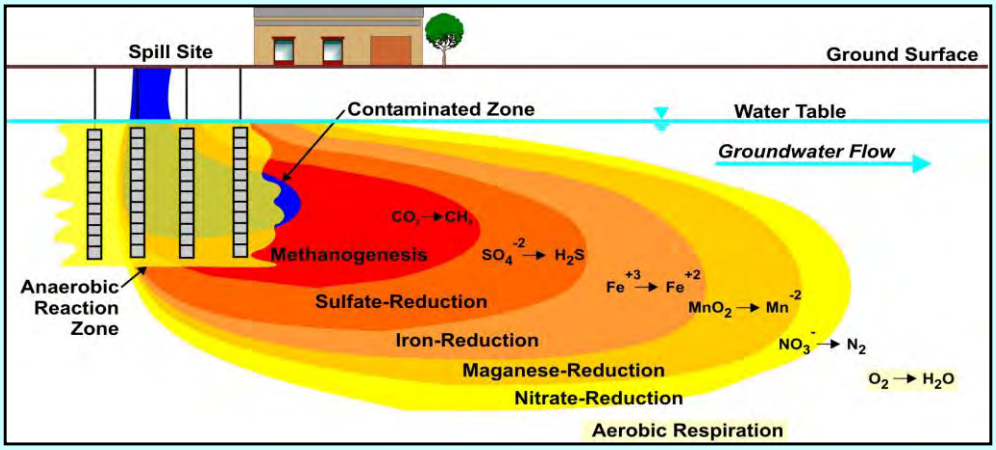

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Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row C

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NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	325	1-10,000	feet	for ISB/ISCR barriers - summation of all 4 barrier widths
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	for ISB/ISCR barriers
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	3250	--	ft^2	
Treatment Zone Volume	130,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	291,798	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	291,798	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC - CHANGE AS NEE
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	824,359	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.00	0.1 to- 20	mg/L	ranged from ND to 3.8 mg/L
Sulfate	12	10 to 5,000	mg/L	max 35.2
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.022	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	--	mg/L	
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	°C	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	47	10 to 1,000	mg/L	from MW09
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	380	10 to 10,000	mg/L	site max
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

aiming to have 4 barriers

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row C

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	325	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	10	1-100	feet
Treatment Zone Cross Sectional Area	3250	--	ft^2
Treatment Zone Volume	130,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	291,798	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	824,359	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	3.41	7.94	0.43	4
Nitrate (denitrification)	1.0	2.43	12.30	0.20	5
Sulfate	12	29.22	11.91	2.45	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	24.35	1.99	12.24	8
Soluble Competing Electron Acceptor Demand (lb.)				**15.32**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	12.88	27.25	0.47	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	29.65	55.41	0.54	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**1.01**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.05	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.00**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.00	20.57	0.00	8
Trichloroethene (TCE)	107	0.00	0.02	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.00	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	63	0.00	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.00**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	9.63	7.94	1.21	4
Nitrate (denitrification)	1.0	6.88	10.25	0.67	5
Sulfate	12	82.55	11.91	6.93	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	68.79	1.99	34.57	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**43.4**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.15	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.01**	

Initial Hydrogen Requirement First Year (lb)	**59.7**
Total Life-Cycle Hydrogen Requirement (lb)	**189.9**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**2,221.6**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	49,634	49,634	2.25E+10	1,657
Sodium Lactate Product (60 percent solution)	11.7	49,634	102,976	2.25E+10	1,657
Molasses (assuming 6 0	11.7	47,152	78,587	2.14E+10	1,574
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	49,645	62,057	2.25E+10	1,657
Ethanol Product (assuming 80% ethanol by weight)	11.7	25,385	31,731	1.15E+10	848
Whey (assuming 100% lactose)	11.7	34,262	48,946	1.55E+10	1,144
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	37,626	37,626	1.71E+10	1,005
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	19,320	19,320	8.76E+09	645
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	19,320	32,199	8.76E+09	645

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row C

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	325	feet	99	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	4	years	4	years

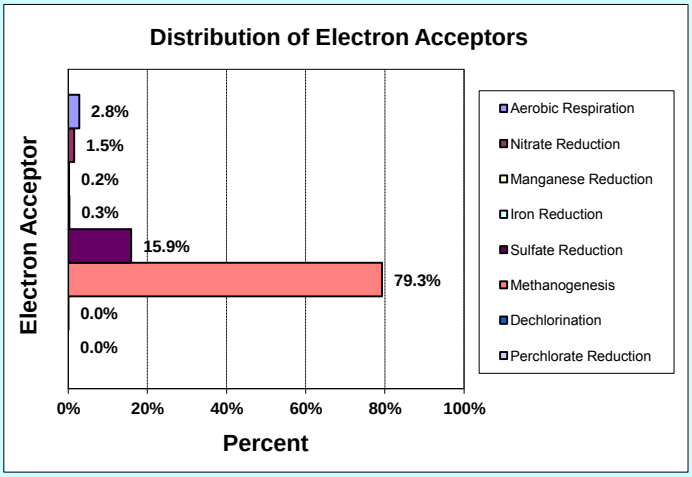
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	30.96	ft/day	1.1E-02	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.31	ft/day	9.4E+00	cm/day
Average Groundwater Seepage Velocity	113	ft/yr	34.4	m/yr
Total Treatment Zone Pore Volume	291,798	gallons	1,104,545	liters
Groundwater Flux (per year)	824,359	gallons/year	3,120,449	liters/year
Total Groundwater Volume Treated (over entire design period)	3,589,232	gallons total	13,586,342	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.8%	5.281
Nitrate Reduction	1.5%	2.882
Sulfate Reduction	15.9%	30.177
Manganese Reduction	0.2%	0.473
Iron Reduction	0.3%	0.535
Methanogenesis	79.3%	150.505
Dechlorination	0.0%	0.031
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**189.88**

Hydrogen demand in pounds/gallon:	5.29E-05
Hydrogen demand in grams per liter:	6.34E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	102,976	9,361	1,657	as lactic acid
2. Molasses Product	78,587	6,549	1,574	as sucrose
3. Fructose Product	62,057	5,541	1,657	as fructose
4. Ethanol Product	31,731	4,599	848	as ethanol
5. Sweet Dry Whey (lactose)	48,946	sold by pound	1,144	as lactose
6. HRC®	37,626	sold by pound	1,005	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	19,320	2,477	645	as soybean oil
8. Emulsified Vegetable Oil	32,199	4,128	645	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

Table S.3 - Hydrogen Produced by Common Substrates

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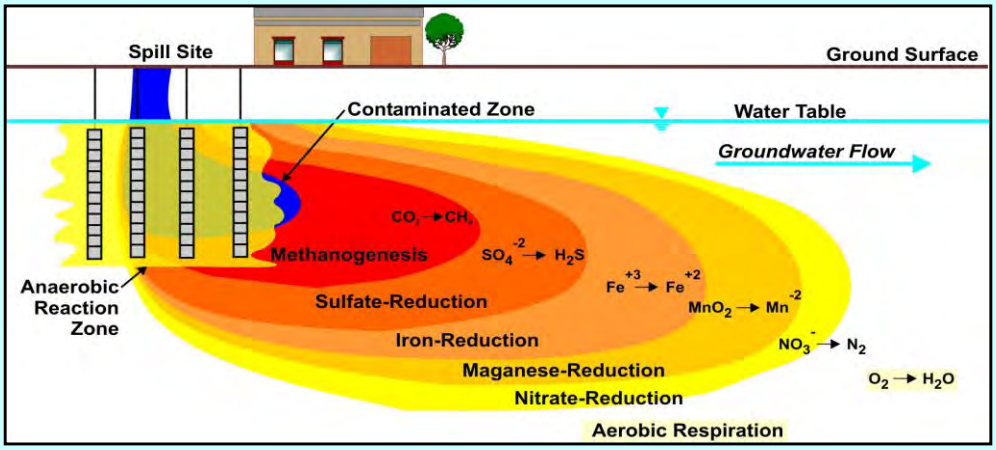
Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row B

RETURN TO COVER PAGE

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	250	1-10,000	feet	for ISB/ISCR barriers - summation of all 4 barrier widths
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	for ISB/ISCR barriers
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	2500	--	ft^2	
Treatment Zone Volume	100,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	224,460	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	224,460	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC - CHANGE AS NEE
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	634,122	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.00	0.1 to- 20	mg/L	ranged from ND to 3.8 mg/L
Sulfate	12	10 to 5,000	mg/L	max 35.2
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.022	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	--	mg/L	
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	°C	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	47	10 to 1,000	mg/L	from MW09
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	380	10 to 10,000	mg/L	site max
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

aiming to have 4 barriers

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row B

RETURN TO COVER PAGE

NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	250	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	10	1-100	feet
Treatment Zone Cross Sectional Area	2500	--	ft^2
Treatment Zone Volume	100,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	224,460	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	634,122	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	2.62	7.94	0.33	4
Nitrate (denitrification)	1.0	1.87	12.30	0.15	5
Sulfate	12	22.48	11.91	1.89	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	18.73	1.99	9.41	8
Soluble Competing Electron Acceptor Demand (lb.)				**11.78**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	9.91	27.25	0.36	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	22.81	55.41	0.41	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.78**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.04	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.00**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.00	20.57	0.00	8
Trichloroethene (TCE)	107	0.00	0.01	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.00	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	63	0.00	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.00**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	7.41	7.94	0.93	4
Nitrate (denitrification)	1.0	5.29	10.25	0.52	5
Sulfate	12	63.50	11.91	5.33	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	52.91	1.99	26.59	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**33.4**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.12	21.73	0.01	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.01**	

Initial Hydrogen Requirement First Year (lb)	**45.9**
Total Life-Cycle Hydrogen Requirement (lb)	**146.1**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**1,709.0**

6. Acronyns and Abbreviations

°C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	38,180	38,180	1.73E+10	1,657
Sodium Lactate Product (60 percent solution)	11.7	38,180	79,212	1.73E+10	1,657
Molasses (assuming 6 0	11.7	36,271	60,451	1.65E+10	1,574
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	38,189	47,736	1.73E+10	1,657
Ethanol Product (assuming 80% ethanol by weight)	11.7	19,527	24,408	8.86E+09	848
Whey (assuming 100% lactose)	11.7	26,356	37,651	1.20E+10	1,144
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	28,943	28,943	1.31E+10	1,005
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	14,861	14,861	6.74E+09	645
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	14,861	24,769	6.74E+09	645

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row B

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	250	feet	76	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	4	years	4	years

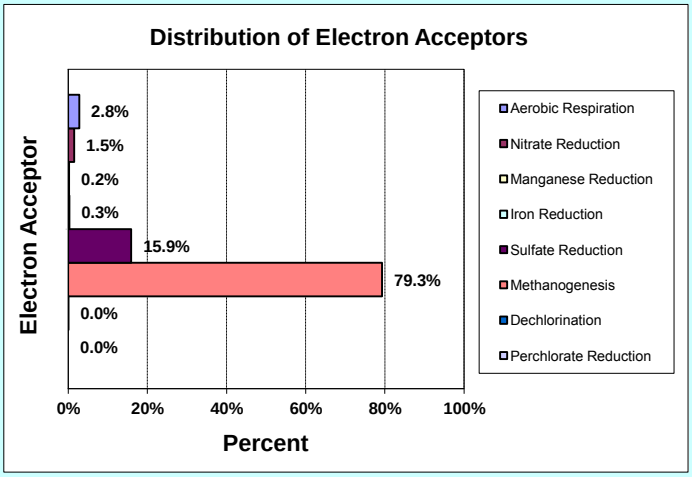
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	30.96	ft/day	1.1E-02	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.31	ft/day	9.4E+00	cm/day
Average Groundwater Seepage Velocity	113	ft/yr	34.4	m/yr
Total Treatment Zone Pore Volume	224,460	gallons	849,650	liters
Groundwater Flux (per year)	634,122	gallons/year	2,400,346	liters/year
Total Groundwater Volume Treated (over entire design period)	2,760,948	gallons total	10,451,032	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.8%	4.062
Nitrate Reduction	1.5%	2.217
Sulfate Reduction	15.9%	23.213
Manganese Reduction	0.2%	0.364
Iron Reduction	0.3%	0.412
Methanogenesis	79.3%	115.773
Dechlorination	0.0%	0.024
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**146.06**

Hydrogen demand in pounds/gallon:	5.29E-05
Hydrogen demand in grams per liter:	6.34E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	79,212	7,201	1,657	as lactic acid
2. Molasses Product	60,451	5,038	1,574	as sucrose
3. Fructose Product	47,736	4,262	1,657	as fructose
4. Ethanol Product	24,408	3,537	848	as ethanol
5. Sweet Dry Whey (lactose)	37,651	sold by pound	1,144	as lactose
6. HRC®	28,943	sold by pound	1,005	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	14,861	1,905	645	as soybean oil
8. Emulsified Vegetable Oil	24,769	3,175	645	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

SUBSTRATE ESTIMATING TOOL FOR ENHANCED ANAEROBIC BIOREMEDIATION OF CHLORINATED SOLVENTS

Version 1.1
February 2010

Site Data Input Table

TABLE S.1 - INPUT TABLE

Calculation Tables

Table S.2 - Substrate Calculations in Hydrogen Equivalents

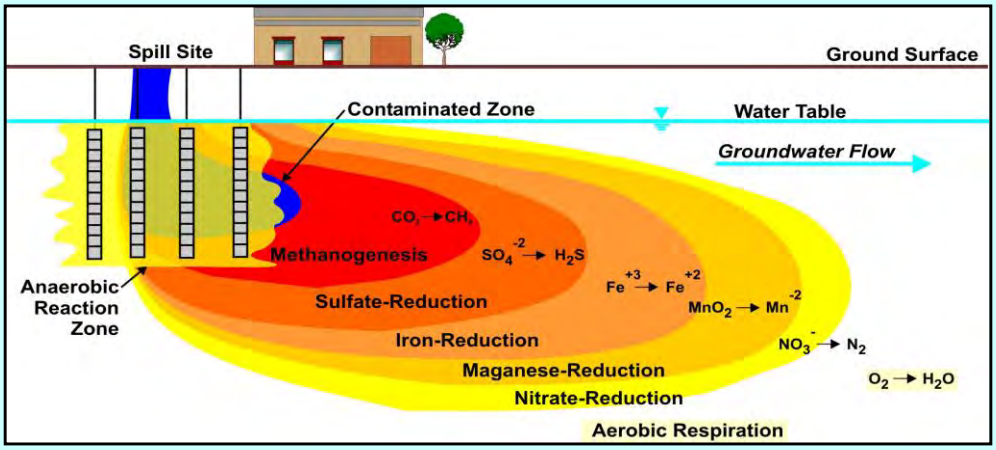
Table S.3 - Hydrogen Produced by Common Substrates

Table S.4 - Estimated Substrate Requirements for Hydrogen Demand

Output Summary Table

TABLE S.5 - OUTPUT TABLE

PRINT SUMMARY TABLE



This Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents has been developed by Parsons Infrastructure & Technology Group, Inc. (Parsons) for the Environmental Security Technology Certification Program (ESTCP). This substrate estimating tool is made available on an as-is basis without guarantee or warranty of any kind, express or implied. The United States Government, Parsons, the authors, and the reviewers accept no liability resulting from the use of this substrate estimating tool or its documentation; nor does the above warrant or otherwise represent in any way the accuracy, adequacy, efficacy, or applicability of the contents hereof. This substrate estimating tool is intended soley for educational and site screening purposes. Implementation of the substrate estimating tool and interpretation or use of the results provided in the model are the sole responsibility of the user. The substrate estimating tool is provided free of charge for everyone to use, but is not supported in any way by the United States Government or Parsons. Mention of trade names in this report is for information purposes only; no endorsement is implied.

Table S.1 Input for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row A

RETURN TO COVER PAGE

NOTE: Unshaded boxes are user input.

1. Treatment Zone Physical Dimensions	Values	Range	Units	User Notes
Width (Perpendicular to predominant groundwater flow direction)	125	1-10,000	feet	for ISB/ISCR barriers - summation of all 4 barrier widths
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet	for ISB/ISCR barriers
Saturated Thickness	10	1-100	feet	
Treatment Zone Cross Sectional Area	1250	--	ft^2	
Treatment Zone Volume	50,000	--	ft^3	
Treatment Zone Total Pore Volume (total volume x total porosity)	112,230	--	gallons	
Treatment Zone Effective Pore Volume (total volume x effective porosity)	112,230	--	gallons	
Design Period of Performance	4.0	.5 to 5	year	
Design Factor (times the electron acceptor hydrogen demand)	11.7	2 to 20	unitless	arbitrary to get to a 500 mg/L dosage of TOC - CHANGE AS NEE
2. Treatment Zone Hydrogeologic Properties				
Total Porosity	30%	.05-50	percent	
Effective Porosity	30%	.05-50	percent	sand, gravel, and clay mixture
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day	1.38 to 30.96 ft/day, avg 14.45
Average Hydraulic Gradient	0.003	0.0001-0.1	ft/ft	
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day	
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr	
Average Groundwater Discharge through the Treatment Zone	317,061	--	gallons/year	
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3	no data
Soil Fraction Organic Carbon (foc)	0.05%	0.01-10	percent	no data
3. Native Electron Acceptors				
A. Aqueous-Phase Native Electron Acceptors				
Oxygen	1.4	0.01 to 10	mg/L	
Nitrate	1.00	0.1 to- 20	mg/L	ranged from ND to 3.8 mg/L
Sulfate	12	10 to 5,000	mg/L	max 35.2
Carbon Dioxide (estimated as the amount of Methane produced)	10.0	0.1 to 20	mg/L	
B. Solid-Phase Native Electron Acceptors				
Manganese (IV) (estimated as the amount of Mn (II) produced)	0	0.1 to 20	mg/L	site average
Iron (III) (estimated as the amount of Fe (II) produced)	1	0.1 to 20	mg/L	site average
4. Contaminant Electron Acceptors				
Tetrachloroethene (PCE)	0.000	--	mg/L	
Trichloroethene (TCE)	0.022	--	mg/L	
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	--	mg/L	
Vinyl Chloride (VC)	0.000	--	mg/L	
Carbon Tetrachloride (CT)	0.000	--	mg/L	
Trichloromethane (or chloroform) (CF)	0.000	--	mg/L	
Dichloromethane (or methylene chloride) (MC)	0.000	--	mg/L	
Chloromethane	0.000	--	mg/L	
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	--	mg/L	
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	--	mg/L	
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	--	mg/L	
Chloroethane	0.000	--	mg/L	
Perchlorate	0.000	--	mg/L	
5. Aquifer Geochemistry (Optional Screening Parameters)				
A. Aqueous Geochemistry				
Oxidation-Reduction Potential (ORP)	249	-400 to +500	mV	average
Temperature	14	5.0 to 30	°C	average
pH	4.9	4.0 to 10.0	su	average
Alkalinity	47	10 to 1,000	mg/L	from MW09
Total Dissolved Solids (TDS, or salinity)	100	10 to 1,000	mg/L	no data
Specific Conductivity	270	100 to 10,000	µs/cm	average
Chloride	380	10 to 10,000	mg/L	site max
Sulfide - Pre injection	0.0	0.1 to 100	mg/L	
Sulfide - Post injection	0.0	0.1 to 100	mg/L	
B. Aquifer Matrix				
Total Iron	10000	200 to 20,000	mg/kg	no data
Cation Exchange Capacity	NA	1.0 to 10	meq/100 g	no data
Neutralization Potential	10.0%	1.0 to 100	Percent as $CaCO_3$	no data

NOTES:

aiming to have 4 barriers

Table S.2 Substrate Calculations in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row A

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NOTE: Open cells are user input.

1. Treatment Zone Physical Dimensions

	Values	Range	Units
Width (Perpendicular to predominant groundwater flow direction)	125	1-10,000	feet
Length (Parallel to predominant groundwater flow)	40	1-1,000	feet
Saturated Thickness	10	1-100	feet
Treatment Zone Cross Sectional Area	1250	--	ft^2
Treatment Zone Volume	50,000	--	ft^3
Treatment Zone Total Pore Volume (total volume x total porosity)	112,230	--	gallons
Design Period of Performance	4.0	.5 to 5	year

2. Treatment Zone Hydrogeologic Properties

Total Porosity	0.3	.05-50	
Effective Porosity	0.3	.05-50	
Average Aquifer Hydraulic Conductivity	30.96	.01-1000	ft/day
Average Hydraulic Gradient	0.003	0.1-0.0001	ft/ft
Average Groundwater Seepage Velocity through the Treatment Zone	0.31	--	ft/day
Average Groundwater Seepage Velocity through the Treatment Zone	113.0	--	ft/yr
Average Groundwater Flux through the Treatment Zo 0	317,061	--	gallons/year
Soil Bulk Density	1.7	1.4-2.0	gm/cm^3
Soil Fraction Organic Carbon (foc)	0.0005	0.0001-0.1	

3. Initial Treatment Cell Electron-Acceptor Demand (one total pore volume)

A. Aqueous-Phase Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	1.31	7.94	0.17	4
Nitrate (denitrification)	1.0	0.94	12.30	0.08	5
Sulfate	12	11.24	11.91	0.94	8
Carbon Dioxide (estimated as the amount of methane produced)	10.0	9.37	1.99	4.71	8
Soluble Competing Electron Acceptor Demand (lb.)				**5.89**	

B. Solid-Phase Native Electron Acceptors (Based on manganese and iron produced)	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Manganese (IV) (estimated as the amount of Mn (II) produced)	0.4	4.95	27.25	0.18	2
Iron (III) (estimated as the amount of Fe (II) produced)	1.0	11.40	55.41	0.21	1
Solid-Phase Competing Electron Acceptor Demand (lb.)				**0.39**	

C. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.02	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand (lb.)				**0.00**	

D. Sorbed Contaminant Electron Acceptors (Soil Concentration = Koc x foc x Cgw)	Koc (mL/g)	Soil Conc. (mg/kg)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	263	0.00	0.00	20.57	0.00	8
Trichloroethene (TCE)	107	0.00	0.01	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	45	0.00	0.00	24.05	0.00	4
Vinyl Chloride (VC)	3.0	0.00	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	224	0.00	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	63	0.00	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	28	0.00	0.00	21.06	0.00	4
Chloromethane	25	0.00	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	117	0.00	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	105	0.00	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	30	0.00	0.00	24.55	0.00	4
Chloroethane	3	0.00	0.00	32.00	0.00	2
Perchlorate	0.0	0.00	0.00	12.33	0.00	6
Total Sorbed Contaminant Electron Acceptor Demand (lb.)					**0.00**	

(continued)

Table S.2 Substrate Calculations in Hydrogen Equivalents

4. Treatment Cell Electron-Acceptor Flux (per year)

A. Soluble Native Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Oxygen	1.4	3.70	7.94	0.47	4
Nitrate (denitrification)	1.0	2.65	10.25	0.26	5
Sulfate	12	31.75	11.91	2.67	8
Carbon Dioxide (estimated as the amount of Methane produced)	10	26.46	1.99	13.30	8
Total Competing Electron Acceptor Demand Flux (lb/yr)				**16.7**	

B. Soluble Contaminant Electron Acceptors	Concentration (mg/L)	Mass (lb)	Stoichiometric demand (wt/wt h_2)	Hydrogen Demand (lb)	Electron Equivalents per Mole
Tetrachloroethene (PCE)	0.000	0.00	20.57	0.00	8
Trichloroethene (TCE)	0.022	0.06	21.73	0.00	6
Dichloroethene (cis-DCE, trans-DCE, and 1,1-DCE)	0.000	0.00	24.05	0.00	4
Vinyl Chloride (VC)	0.000	0.00	31.00	0.00	2
Carbon Tetrachloride (CT)	0.000	0.00	19.08	0.00	8
Trichloromethane (or chloroform) (CF)	0.000	0.00	19.74	0.00	6
Dichloromethane (or methylene chloride) (MC)	0.000	0.00	21.06	0.00	4
Chloromethane	0.000	0.00	25.04	0.00	2
Tetrachloroethane (1,1,1,2-PCA and 1,1,2,2-PCA)	0.000	0.00	20.82	0.00	8
Trichloroethane (1,1,1-TCA and 1,1,2-TCA)	0.000	0.00	22.06	0.00	6
Dichloroethane (1,1-DCA and 1,2-DCA)	0.000	0.00	24.55	0.00	4
Chloroethane	0.000	0.00	32.00	0.00	2
Perchlorate	0.000	0.00	12.33	0.00	6
Total Soluble Contaminant Electron Acceptor Demand Flux (lb/yr)				**0.00**	

Initial Hydrogen Requirement First Year (lb)	**23.0**
Total Life-Cycle Hydrogen Requirement (lb)	**73.0**

5. Design Factors

Microbial Efficiency Uncertainty Factor	2X - 4X
Methane and Solid-Phase Electron Acceptor Uncertainty	2X - 4X
Remedial Design Factor (e.g., Substrate Leaving Reaction Zone)	1X - 3X
Design Factor	**11.7**
Total Life-Cycle Hydrogen Requirement with Design Factor (lb)	**854.5**

6. Acronyns and Abbreviations

^{o}C =degrees celsius
µs/cm = microsiemens per centimeter
cm/day = centimeters per day
cm/sec = centimeters per second
ft^2 = square feet
ft/day = feet per day
ft/ft = foot per foot
ft/yr = feet per year
gm/cm^3 = grams per cubic centimeter
kg of CaCO3 per mg = kilograms of calcium carbonate per milligram
lb = pounds
meq/100 g = milliequivalents per 100 grams
mg/kg = milligrams per kilogram
mg/L = milligrams per liter
m/m = meters per meters
mV = millivolts
m/yr = meters per year
su = standard pH units
wt/wt H2 = concetration molecular hydrogen, weight per weight

Table S.3

Hydrogen Produced by Fermentation Reactions of Common Substrates

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Substrate	Molecular Formula	Substrate Molecular Weight (gm/mole)	Moles of Hydrogen Produced per Mole of Substrate	Ratio of Hydrogen Produced to Substrate (gm/gm)	Range of Moles H_2/Mole Substrate
Lactic Acid	$C_3H_6O_3$	90.1	2	0.0448	**2 to 3**
Molasses (assuming 100% sucrose)	$C_{12}H_{22}O_{11}$	342	8	0.0471	**8 to 11**
High Fructose Corn Syrup (assuming 50% fructose and 50% glucose)	$C_6H_{12}O_6$	180	4	0.0448	**4 to 6**
Ethanol	C_2H_6O	46.1	2	0.0875	**2 to 6**
Whey (assuming 100% lactose)	$C_{12}H_{22}O_{11}$	342	11	0.0648	**11**
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	$C_{39}H_{56}O_{39}$	956	28	0.0590	**28**
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	$C_{18}H_{32}O_2$	281	16	0.1150	**16**

Table S.4
Estimated Substrate Requirements for Hydrogen Demand in Table S.3

Design Life (years): 4

Substrate	Design Factor	Pure Substrate Mass Required to Fulfill Hydrogen Demand (pounds)	Substrate Product Required to Fulfill Hydrogen Demand (pounds)	Substrate Mass Required to Fulfill Hydrogen Demand (milligrams)	Effective Substrate Concentration (mg/L)
Lactic Acid	11.7	19,090	19,090	8.66E+09	1,657
Sodium Lactate Product (60 percent solution)	11.7	19,090	39,606	8.66E+09	1,657
Molasses (assuming 6 0	11.7	18,135	30,226	8.23E+09	1,574
HFCS (assuming 40% fructose and 40% glucose by weight)	11.7	19,094	23,868	8.66E+09	1,657
Ethanol Product (assuming 80% ethanol by weight)	11.7	9,763	12,204	4.43E+09	848
Whey (assuming 100% lactose)	11.7	13,178	18,825	5.98E+09	1,144
HRC® (assumes 40% lactic acid and 40% glycerol by weight)	11.7	14,471	14,471	6.56E+09	1,005
Linoleic Acid (Soybean Oil, Corn Oil, Cotton Oil)	11.7	7,431	7,431	3.37E+09	645
Commercial Vegetable Oil Emulsion Product (60% oil by weight)	11.7	7,431	12,384	3.37E+09	645

NOTES: Sodium Lactate Product

1. Assumes sodium lactate product is 60 percent sodium lactate by weight.
2. Molecular weight of sodium lactate (CH_3-CHOH-COONa) = 112.06.
3. Molecular weight of lactic Acid ($C_6H_6O_3$) = 90.08 .
4. Therefore, sodium lactate product yields 48.4 (0.60 x (90.08/112.06)) percent by weight lactic acid.
5. Weight of sodium lactate product = 11.0 pounds per gallon.
6. Pounds per gallon of lactic acid in product = 1.323 x 8.33 lb/gal H2O x 0.60 x (90.08/112.06) = 5.31 lb/gal.

NOTES: Standard HRC Product

1. Assumes HRC product is 40 percent lactic acid and 40 percent glycerol by weight.
2. HRC® weighs approximately 9.18 pounds per gallon.

NOTES: Vegetable Oil Emulsion Product

1. Assumes emulsion product is 60 percent soybean oil by weight.
2. Soybean oil is 7.8 pounds per gallon.
3. Assumes specific gravity of emulsion product is 0.96.

Table S.5 Output for Substrate Requirements in Hydrogen Equivalents

Site Name: Weston Solutions JBA SS-28 Row A

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1. Treatment Zone Physical Dimensions

	Values	Units	Values	Units
Width (perpendicular to groundwater flow)	125	feet	38	meters
Length (parallel to groundwater flow)	40	feet	12.2	meters
Saturated Thickness	10	feet	3.0	meters
Design Period of Performance	4	years	4	years

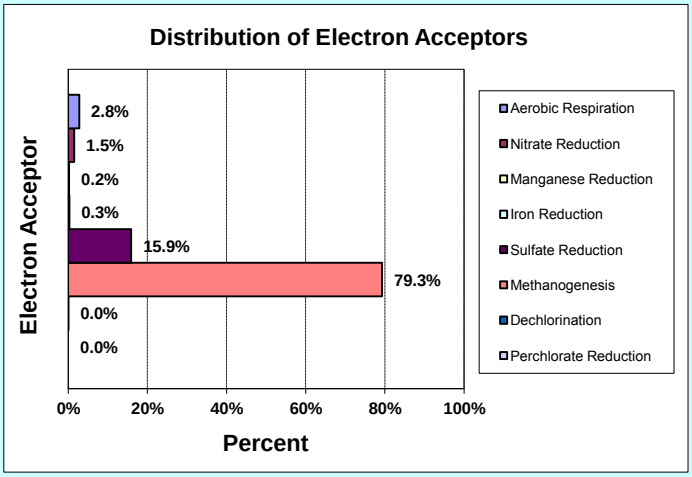
2. Treatment Zone Hydrogeologic Properties

	Values	Units	Values	Units
Total Porosity	0.3	percent	0.3	percent
Effective Porosity	0.3	percent	0.3	percent
Average Aquifer Hydraulic Conductivity	30.96	ft/day	1.1E-02	cm/sec
Average Hydraulic Gradient	0.003	ft/ft	0.003	m/m
Average Groundwater Seepage Velocity	0.31	ft/day	9.4E+00	cm/day
Average Groundwater Seepage Velocity	113	ft/yr	34.4	m/yr
Total Treatment Zone Pore Volume	112,230	gallons	424,825	liters
Groundwater Flux (per year)	317,061	gallons/year	1,200,173	liters/year
Total Groundwater Volume Treated (over entire design period)	1,380,474	gallons total	5,225,516	liters total

3. Distribution of Electron Acceptor Demand

	Percent of Total	Hydrogen Demand (lb)
Aerobic Respiration	2.8%	2.031
Nitrate Reduction	1.5%	1.109
Sulfate Reduction	15.9%	11.606
Manganese Reduction	0.2%	0.182
Iron Reduction	0.3%	0.206
Methanogenesis	79.3%	57.887
Dechlorination	0.0%	0.012
Perchlorate Reduction	0.0%	0.000
Totals:	**100.00%**	**73.03**

Hydrogen demand in pounds/gallon:	5.29E-05
Hydrogen demand in grams per liter:	6.34E-03



4. Substrate Equivalents: Design Factor = 11.7

Product	Quantity (lb)	Quantity (gallons)	Effective Concentration (mg/L)	Effective concentration is for total volume of groundwater treated.
1. Sodium Lactate Product	39,606	3,601	1,657	as lactic acid
2. Molasses Product	30,226	2,519	1,574	as sucrose
3. Fructose Product	23,868	2,131	1,657	as fructose
4. Ethanol Product	12,204	1,769	848	as ethanol
5. Sweet Dry Whey (lactose)	18,825	sold by pound	1,144	as lactose
6. HRC®	14,471	sold by pound	1,005	as 40% lactic acid/40% glycerol
7. Linoleic Acid (Soybean Oil)	7,431	953	645	as soybean oil
8. Emulsified Vegetable Oil	12,384	1,588	645	as soybean oil

Notes:
1. Quantity assumes product is 60% sodium lactate by weight.
2. Quantity assumes product is 60% sucrose by weight and weighs 12 pounds per gallon.
3. Quantity assumes product is 80% fructose by weight and weighs 11.2 pounds per gallon.
4. Quantity assumes product is 80% ethanol by weight and weighs 6.9 pounds per gallon.
5. Quantity assumes product is 70% lactose by weight.
6. Quantity assumes HRC® is 40% lactic acid and 40% glycerol by weight.
7. Quantity of neat soybean oil, corn oil, or canola oil.
8. Quantity assumes commercial product is 60% soybean oil by weight.

PERSULFATE AMENDMENT
IN SITU CHEMICAL OXIDATION

Klozur® Activated Persulfate Demand Calculations

15-Jan-2015

Customer:	**Weston**	**Prepared by:**	
Contact:	**Mary Boggs**	**Brant Smith, PhD, PE**	
Site Location:	**SS-28 CT/Benzene Area;**	**1-603-793-1291**	
Proposal Number:	**PeroxyChem-0**	**Brant.Smith@peroxychem.com**	

PRODUCT OVERVIEW

Because of its ability to treat a wide range of contaminants, Klozur® Activated Persulfate is the oxidant of choice for in situ chemical oxidation (ISCO). When properly activated, Klozur® Persulfate provides an unmatched combination of oxidative power and control that can be delivered both safely and cost effectively. Klozur activated persulfate generates the sulfate radical (SO4•-), one of the strongest oxidizing species available, giving Klozur® Persulfate the power to destroy the most recalcitrant of contaminants.

SITE INFORMATION

	Value	Unit	Note
Area of Treatment	38,000	ft x ft	customer supplied
Treatment Zone Thickness	15	ft	customer supplied
Treatment Volume	570,000	ft3	calculated value
Porosity	30	%	default value
Ground Water Volume	171,000	ft3	calculated value
Soil Density	90	lbs/ft3	default value
Soil Mass	25,650.0	ton	calculated value
Soil Oxidant Demand	1	g Klozur / kg soil	estimated value, it is recommend that this be analytically determined

CONTAMINANTS OF CONCERN (COCs)

Constituent	GW (mg/L)	Soil (mg/kg)	Total COI Mass (lb)
benzene	0.2	0.083	6.4

*Unless provided, sorbed concentrations were roughly estimated based on expected groundwater concentrations, foc and Koc values. For a more refined estimate, it is recommended that actual values be verified via direct sampling of the targeted treatment interval.

KLOZUR® PERSULFATE DEMAND

Demand from COCs	293	lb
Demand from SOD	0	lb
Total Klozur® Persulfate Demand	293	lb

KLOZUR® PERSULFATE PACKAGING OPTIONS AND PRICING

Available Packaging Types	# of packages / pallet	lb Klozur® / pallet	# of packages needed [1]
55.1 # bags	42	2314.2	6
1102 # super sacks	2	2204	1
2204 # super sacks	1	2204	1

Available Packaging Types	Unit Rate [2] ($ / lb)	Total Mass (lbs)	Cost in USD [3, 4] (FOB Tonawanda, NY)
55.1 # bags	1.59	330.6	$525.65
1102 # super sacks	1.48	1,102	$1,630.96
2204 # super sacks	1.46	2,204	$3,217.84

1) Number of packages needed is rounded up to nearest whole unit.

2) Price valid for 90 days from date at top of document. Terms: net 30 days.

3) Any applicable taxes not included. Please provide a copy of your tax exempt certificate or resale tax number when placing your order. In accordance with the law, applicable state and local taxes will be applied at the time of invoicing if PeroxyChem has not been presented with your fully executed tax exemption documentation.

4) Shipping not included. Freight rates from Tonawanda NY available upon request. Standard delivery time can vary from 1-3 weeks from time of order, depending upon volume. Expedited transport can be arranged at extra cost.

5) All sales are per PeroxyChem's Terms and Conditions.

Disclaimer:

The estimated dosage and recommended application methodology described in this document are based on the site information provided to us, but are not meant to constitute a guaranty of performance or a predictor of the speed at which a given site is remediated. Klozur® persulfate and activator demand calculations are based on stoichiometry, and do not take into account the kinetics, or speed of the reaction, and represent the minimum anticipated amount needed to mineralize the constituents of concern (COCs). As a result, these calculations should be used as a general approximation for purposes of an initial economic assessment. PeroxyChem recommends that oxidant demand and treatability testing be performed to verify the quantities of oxidant needed.

KLOZUR® ACTIVATION CHEMISTRIES

Klozur® Persulfate activation chemistries are used to convert Klozur® Persulfate into the highly reactive persulfate radical, a very strong oxidant capable of destroying a wide range of contaminants. Choosing the right activator chemistry for your contaminants of concern is important in obtaining a successful site remediation. The choice of activator will be dependent upon the target contaminants, site lithology and hydrogeology, and site conditions. While activator demand quantities for all methods are given, not all method are recommended for your given contaminant or site conditions. Please consult with an PeroxyChem Environmental Solutions technologist for proper selection of activation chemistry.

Recommended methods to activated Klozur® Persulfate:	**FeEDTA**	**high pH**	**hydrogen peroxide**

***PeroxyChem Corporation is the owner or licensee under various patent applications relating to the use of activation chemistries**

Calculation for FeEDTA demand:

Note, it is not recommended mixing Fe and Klozur Persulfate Prior to Injection

Recommended concentration of Fe available in the groundwater	150	ppm
Calculated FeEDTA demand based on gw volume	12,223.3	lb
# of bags of FeEDTA needed (55.1 lb / 25 kg bags)	222	bags
Pricing	$4.00	$ / lb
Cost in USD (FOB Tonawanda, NY)	$48,928.80	

Calculation for NaOH (high pH) demand:

NaOH demand = NaOH to neutralize generate HSO4 from persulfate decomposition + amount needed to raise ground water / soil to a pH of 11-12

Soil buffering amount = NaOH for ground water / soil pH adjustment, which can be determined in the laboratory via titration.

NaOH demand for HSO4 neutralization	98.3	lb @ 100% basis
Soil buffering amount	Not available	lb @ 100% basis
Total NaOH demand	98.3	lb @ 100% basis

PeroxyChem recommends using a 25 wt% or less NaOH concentration **

Amount of	25	wt% solution needed	37.1 393.3	gal lb	+ soil buffering amount + soil buffering amount
Klozur Caustic Pricing (25% NaOH solution)			0.39	$/lb	in 560 # drums
FOB, Tonawanda, NY. Freight quote upon request			0.52	$/lb	in 2800 # totes

** note: the addition of concentrated NaOH to water is very exothermic. Add NaOH slowly to water, and allow for excess heat to dissipate.

KLOZUR® ACTIVATION CHEMISTRIES (continued)

Calculation for Hydrogen Peroxide demand:

demand based on the recommended peroxide to Klozur® persulfate mole ratio of:		5 : 1	
Hydrogen Peroxide demand		208.9	lb @ 100% basis

PeroxyChem recommends using a 17.5 wt% or less H2O2 concentration

Amount of	17.5	wt% solution needed	135.1	gal

	Drum	Bulk
# of containers	3	not available
total gallons	151	135
total lb	1,335	
Pricing in $/lb*	0.28	
Cost in USD $*	373.80	

* for drums, pricing is FOB Tonawanda, NY, bulk pricing is FOB Bayport, TX, and does not include delivery charge or fuel surcharge.

APPENDIX B
GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODEL SIMULATION SUMMARY

B. GROUNDWATER FLOW AND TRANSPORT MODELING

A preliminary steady state groundwater flow and contaminant transport model was constructed for the SS-28 site to compare the predicted time to cleanup of comingled Trichloroethene (TCE), Carbon Tetrachloride (CTC), and Benzene contaminant plumes among the remedies proposed in this feasibility study. The model was assembled using Environmental Simulation, Inc.'s (ESI) Groundwater Vistas 6 (GWV6) visual interface for several industry standard finite difference simulators by the United States Geological Survey (USGS). The USGS components used for the SS-28 site model were MODFLOW (McDonald and Harbaugh, 1988), MODPATH (Pollack, 1994), and MT3DMS (Zheng and Wang, 1999). These tools simulate groundwater flow, particle tracking, and contaminant transport, respectively.

B.1 MODEL DESIGN

The model was designed to simulate localized unconfined groundwater flow in the unconsolidated surficial Upland Deposits beneath the site (Mack, 1966). The 2.9-square mile (mi^2) (9,000-ft by 9,000-ft) model domain depicted in **Figure B-1** was centered on the site TCE plume and was made large enough to prevent the model boundaries from impacting contaminant transport predictions. The model uses a variable resolution ranging from 25 feet in the vicinity of the contaminant plume to 100 feet elsewhere. The model was constructed by modifying an existing digital conceptual site model (CSM) for the entire installation (Bay West, 2013) using a geologic modeling package called EarthVision (Dynamic Graphics, 2014). **Figure B-2** depicts the primary stages of model construction: (a) potentiometric surface interpolation, (b) hydrostratigraphic modeling, (c) MODFLOW layer design, and (d) initial contaminant distribution modeling.

The potentiometric surface (Panel A of **Figure B-2**) was interpolated from all available Joint Base Andrews monitoring well static water levels and was informed by the 2013 sitewide potentiometric surface model provided in the Bay West CSM. The FT-02 and SS-28 data used in the interpolation represent averages of 3 to 13 rounds of water levels (varies by well) collected by Bay West, URS, and WESTON. The data from surrounding areas represent averages of 2 to 3 water level rounds provided in the Bay West CSM. The surface also accounts for National

Hydrography Dataset (NHD) stream elevations derived from a USGS 10-meter resolution digital elevation model (DEM) of the topography. Both the stream network and the DEM for the Joint Base Andrews vicinity were obtained using The National Map Viewer (TNM) (Dollison, 2010).

The hydrostratigraphy (Panel B of **Figure B-2**) also represents an update to the Bay West CSM. The updated model honors both the Calvert formation contours provided in the URS 2013 Remedial Investigation (RI) report and the lithologic data provided in the Bay West 2013 CSM. The structural contours provided in the Bay West CSM were used to inform the shapes of surfaces in the absence of other data. The DEM was used as the surface of the model and the potentiometric surface was used to identify the saturated portions of each layer. Both the lithologic and potentiometric surfaces from the stratigraphic model were then imported to GWV via Surfer grids to produce the MODFLOW layering structure depicted in Panel C of **Figure B-2**.

The Calvert Confining Unit and the overlying Deep Upland Deposits make up the two deepest layers in the MODFLOW model and the Intermediate Upland Deposits (IUD) make up the two shallowest. A 3-foot buffer was added to the potentiometric surface to form the upper boundary of the model. The few slivers of saturated Shallow Upland Deposits were incorporated into the IUD for simplicity. The IUD was divided into two equal thickness layers to accommodate coupled wells in the SS-28 area and to discretize contaminant mass within the aquifer. This allowed small vertical gradients between layers to be better honored and a more accurate representation of the contaminant plumes in the model.

Panel D of **Figure B-2** depicts the contaminant distribution modeling performed to generate initial conditions for contaminant transport simulations. Concentrations for TCE, CTC, and Benzene from both monitoring wells and direct push borings provided in the URS 2013 RI were interpolated in three dimensions. The resulting plumes were intersected with the MODFLOW layers to derive maximum contaminant concentrations of each plume within each IUD layer. These distributions are depicted in **Figure B-3** and were imported to GWV via Surfer grids.

The MODFLOW model boundary conditions are shown in **Figure B-4**. The Joint Base Andrews drain system and the NHD streams depicted in Panel B of **Figure B-2** were imported to the appropriate model layers (shown in the legend of **Figure B-4**) based on the boundary elevations

within each grid cell. Both boundary types consist of a series of line segments to accommodate changes in boundary elevations in different areas. The stream boundary elevations were derived from the USGS DEM, whereas the drain boundary elevations were set manually for consistency with the average groundwater elevations from nearby monitoring wells on the assumption that the water table is influenced by the drain elevation. The potentiometric surface was used as the initial head distribution for the model as well as to assign general head boundaries, which allow water to move across the model edges. The recharge distribution applied to the top of the model was prepared by multiplying a maximum assumed recharge of 10-in/yr (approximately 20% of annual precipitation) by estimates of pervious cover percentage from the National Land Cover Database (NLCD) (Jin, 2013), obtained using the TNM viewer.

B.2 FLOW CALIBRATION

The static steady-state groundwater flow model was calibrated to the available site-specific data using a powerful inverse modeling code called PEST (Doherty, 2010). In essence, the PEST procedure entails hundreds of individual model runs through which the sensitivity to numerous model parameters is determined and the collection of values that, subject to user-specified constraints, yield the lowest model residuals is ultimately achieved. For this model, average water level data were used as calibration targets and slug test results were used as constraints. All targets and constraints were imported to GWV6 using text files that provided well identification, target values, and locational data (including layer assignments).

PEST was allowed to vary both the horizontal (Kh) and vertical (Kz) hydraulic conductivity distributions in each model layer in order to optimize fit to the head targets. This was accomplished through the use of Kh and Kz "pilot points," which are synthetic locations to which PEST assigns discrete values that are interpolated over the model domain, along with the slug test constraints, to obtain a continuous distribution for each of the numerous model runs performed during the course of the PEST simulation. The Kh and Kz pilot points were placed strategically in each aquifer layer (**Figure B-5**) to enable a sufficient amount of K variation between the various head targets and constraints without inflating the number of model runs unnecessarily. All pilot points were assigned minimum and maximum values to keep PEST from using values that deviate too much from observed values. The Kh and Kz ranges allowed

in the aquifer were 0.5 to 60-ft/day and 0.15 to 15-ft/day, respectively. The Kh/Kz ranges allowed in the two deeper layers were 0.1 to 10-ft/day and 0.001 to 1-ft/day, respectively.

The PEST calibration results for the aquifer are depicted in **Figure B-5**. The PEST-derived Kh distributions for each layer are provided as a semi-transparent color flood and the simulated head distributions are provided for comparison with the initial potentiometric head distribution inferred from the head targets. The Kz distributions are not shown because the variation in the aquifer (1 to 5-ft/day) is much smaller than Kh. The resulting K anisotropy (Kh divided by Kz) ranges from 0.5 to 20 and exhibits a pattern similar to Kh. The head target residuals are posted on both figures as circles that reveal both the magnitude and bias of the residual. The residuals tend to be smaller within the vicinity of the plume because of the higher pilot point density in this area and a doubling of the target weights compared to those outside the area of primary interest. **Figure B-6** shows that overall model bias and residuals are low. The absolute mean residual in the aquifer is 0.69 feet with a 1.15-foot standard deviation. The scaled absolute mean residual (absolute mean residual divided by the observed data range) is approximately 1% overall and 2% in the aquifer, which is below the 5% generally accepted for model calibration.

Despite the good calibration, forward particle tracking results depicted in **Figure B-5** do not appear to corroborate the flow direction inferred from the TCE plume outline. This is because current head target data suggest that groundwater flow directions within SS-28 may be different now than for prior conditions that resulted in the current plume configuration. The storm sewers in the SS-28 vicinity under the flightline are suspected to leak and a higher variance of water levels in close proximity to them corroborates this theory. They may be acting as drains and causing localized depression of the water table. Historical water level data reflecting conditions prior to the potential failure of the sewers were not available to use as model calibration targets.

B.3 BASELINE TRANSPORT MODEL

The calibrated flow model was augmented with the initial plume conditions depicted in **Figure B-3** and estimates for parameters governing retardation and decay of the three contaminants to produce a baseline fate and transport model. There are currently no site-specific data for key contaminant transport parameters such as porosity, bulk density, foc, dispersivity, and site-specific degradation rates. **Table B-1** provides the values used for several parameters, which

were adjusted slightly from those used for modeling of nearby SS-26 (WESTON, 2013a) to account for the lack of degradation products at SS-28 and to approximate the current plume configurations based on an assumed age of 45 years.

Table B-1. Transport Parameter Assumptions

Parameter	Value	Units
Bulk density	1.76	g/cm^3
Porosity	0.25	ft^3/ft^3
Aquifer foc	0.001	kg/kg
Longitudinal dispersivity	100	feet
Transverse dispersivity	1	feet
Half-life of TCE and CTC	20	yrs
Half-life of Benzene	2	yrs
Aquifer foc	0.001	kg/kg
TCE sorption coefficient	0.1	L/kg
CTC sorption coefficient	0.06	L/kg
Benzene sorption coefficient	0.04	L/kg

Notes:
g/cm^3= grams per cubic centimeter
ft^3/ft^3 = cubic foot per cubic foot
kg/kg = kilogram per kilogram
L/kg = liter per kilogram

The refined model was used to simulate the fate of the three contaminant plumes attenuating naturally starting from current conditions. **Figure B-7** depicts the time it takes for concentrations of each contaminant to attenuate to less than 5 micrograms per liter (µg/L) under monitored natural attenuation (MNA) as they migrate eastward from the source areas according to the calibrated steady-state flow field and attenuate according to the properties defined in **Table B-1**. The time-to-cleanup contours are presented in separate panels for each contaminant and for all three combined in the lower right panel. A comparison of these panels reveals that the time-to-cleanup is higher for TCE than for the other contaminants; consequently, TCE is the primary driver for the composite time-to-cleanup for MNA (40 years). The hashed areas in the combined panel show areas where the cleanup of the other contaminants is slower than that of TCE, but the time-to-cleanup magnitudes in these areas are still lower than that of TCE along the centerline of the predicted plume.

B.4 REMEDIAL SCENARIO IMPLEMENTATION

The steady-state flow and transport model developed for SS-28 was used to evaluate the efficacy, using time-to-cleanup as the metric, of the following remedial strategies relative to that of MNA:

- In Situ Biodegradation with carbon coated zero-valent iron (In Situ Biodegradation/In Situ Chemical Reduction [ISB/ISCR]).
- In Situ Chemical Oxidation source treatment with ISB (ISCO/ISB).
- Groundwater extraction and ex situ treatment (P&T) with downgradient ISB.

The design of the ISB/ISCR scenario calls for amendments to be injected into groundwater via direct push borings spaced sufficiently throughout the target area to modify the redox chemistry and microbial communities for accelerated plume degradation for a 5-year duration. This modification was emulated in the model by lowering the half-life within the discrete representations of the target areas depicted in **Figure B-8**. Small buffer zones of longer half-life were added slightly downgradient of the source areas to account for advection and depletion of the amendment over the 5-year time period. In the absence of site-specific pilot studies, the accelerated half-lives of TCE and CTC were assumed to be the same as those used for TCE in previous SS-11 (WESTON, 2013b) and SS-26 modeling studies (WESTON, 2013a). The simulated half-lives for ISB/ISCR (used in source areas) and ISB alone (used at plume margins) were 6 and 9 months, respectively. A half-life of 3 years was used in the downgradient buffer regions for both contaminants as well as in the target areas themselves following the initial 5-year treatment phase. The half-life of benzene was not changed in the ISB/ISCR application areas because benzene degradation occurs aerobically. The aerobic degradation of benzene with ISB in this scenario was accomplished through an instantaneous 90% reduction of the initial plume concentrations within the application area shown in the lower left panel of **Figure B-8**.

The ISB/ISCO scenario is similar to that of ISB/ISCR except that target area overlapping the CTC plume, depicted in **Figure B-9**, received an instantaneous 90% reduction of all contaminant plumes instead of an accelerated half-life. The half-lives for TCE and CTC were set to 20 years during the 5-year ISCO treatment phase to simulate the deleterious effect of the oxidant on

microbes and were set to 3 years afterward to simulate the attempt to establish anaerobic conditions with ISB following the ISCO treatment.

The P&T scenario employed the four extraction wells depicted in **Figure B-10** to expedite source mass removal and ISB at the plume margins to provide some treatment of the lower concentration areas not captured by the extraction system. Extraction wells were not used further downgradient due to the marginal returns for the high cost and difficulty associated with installing larger system that extends under the flightline. Based on the model calibration, the aquifer could likely only sustain pumping rates of less than 5 gallons per minute (gpm) within and around the source area. A rate of 3 gpm was assigned to each of the four wells for a total system rate of 12 gpm. This design was selected because it yielded a composite 10-year capture zone wide enough to cover the entire source area without extending too far upgradient.

B.5 TIME-TO-CLEANUP COMPARISON

The predicted time-to-cleanup was calculated for each of the three proactive remedial scenarios for comparison with the baseline MNA scenario time-to-cleanup of 40 years. **Table B-2** provides a summary of the results, which are depicted in **Figures B-8** through **B-10**.

Table B-2. Time-to-Cleanup Comparison in Years

Scenario	TCE	CTC	Benzene	Max TCC	% Reduction over MNA
ISB/ISCR	20	18	10	20	50
ISCO/ISB	20	16	5	20	50
P&T	29	19	8	29	27

Note: TCC – Time-to-Cleanup

The ISB/ISCR and ISCO/ISB scenarios yield the same maximum time-to-cleanup, which is half of the MNA time-to-cleanup. The distributions of times-to-cleanup differ subtly in the source areas between these scenarios but are identical downgradient, which is the area that dictates the maximum time-to-cleanup. The P&T scenario yields only a 27% reduction of time-to-cleanup from that of MNA due to the slightly elevated concentrations that are allowed to persist slightly downgradient of the capture zone but upgradient of the treatment areas at the plume margins.

B.6 CONCLUSIONS

Based on the current design and assumptions of the SS-28 flow and transport model, the ISB/ISCR and ISCO/ISB scenarios are equally effective at significantly reducing the simulated time-to-cleanup compared with MNA and more effective than P&T. However, the transport model is highly sensitive to several unknown parameters such as the aquifer foc, ISB and ISCR decay rates, ISCO mass reduction potential, and the likelihood of establishing reducing conditions following the ISCO injection. Although foc data would be relatively inexpensive to obtain, the results of pilot scale ISB/ISCR and ISCO injections would not.

B.7 REFERENCES

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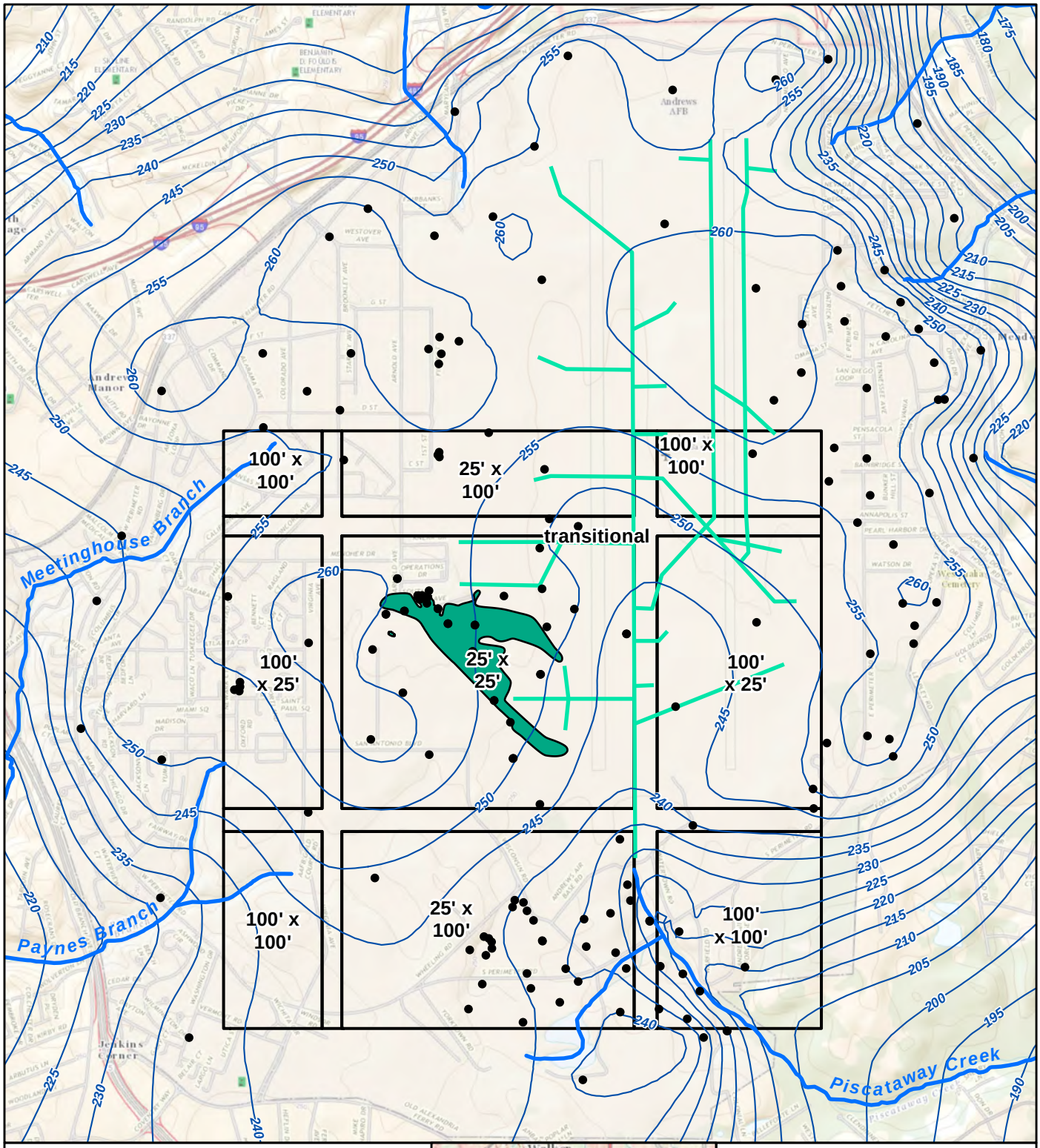
FIGURES



Legend

Basemap: USGS Topo webservice

- SS28 Contaminant Plume Outline
- AAFB Monitoring Well
- Average Potentiometric Head Surface (ft MSL)
- AAFB Drain System
- Surface Water Boundaries
- Model Grid Boundary and Resolution (feet)

MDSP NAD83

N

1:26,000

0 1,000 2,000 ft

SS-28 Site
Andrews Air Force Base, Maryland

Figure B-1
Model Design

Drafted: 3/12/2015
Modified: 3/17/2015
User: STROBRID

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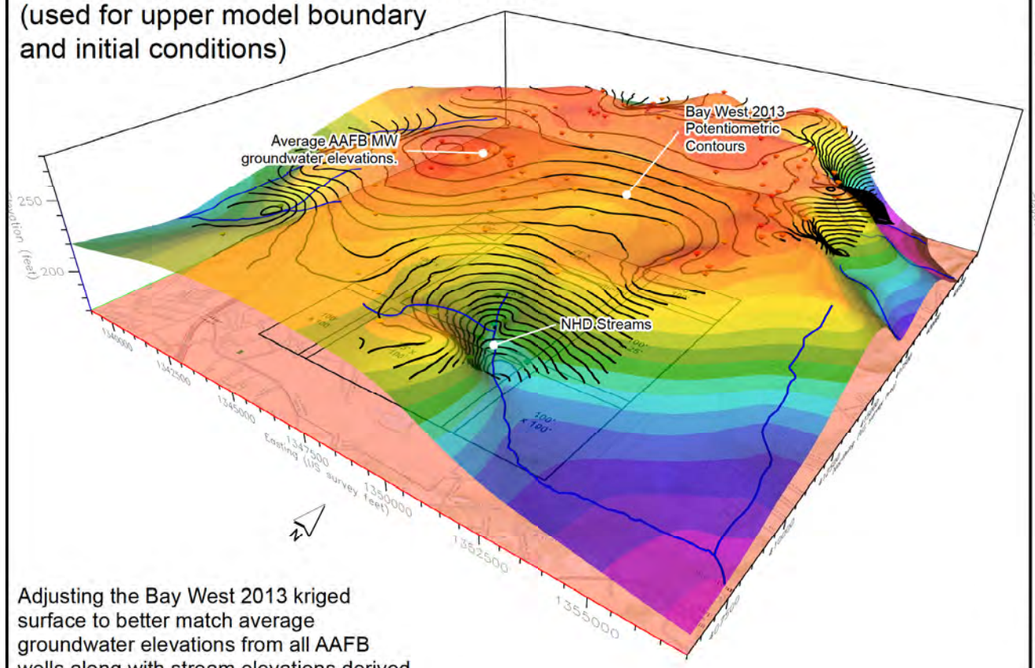
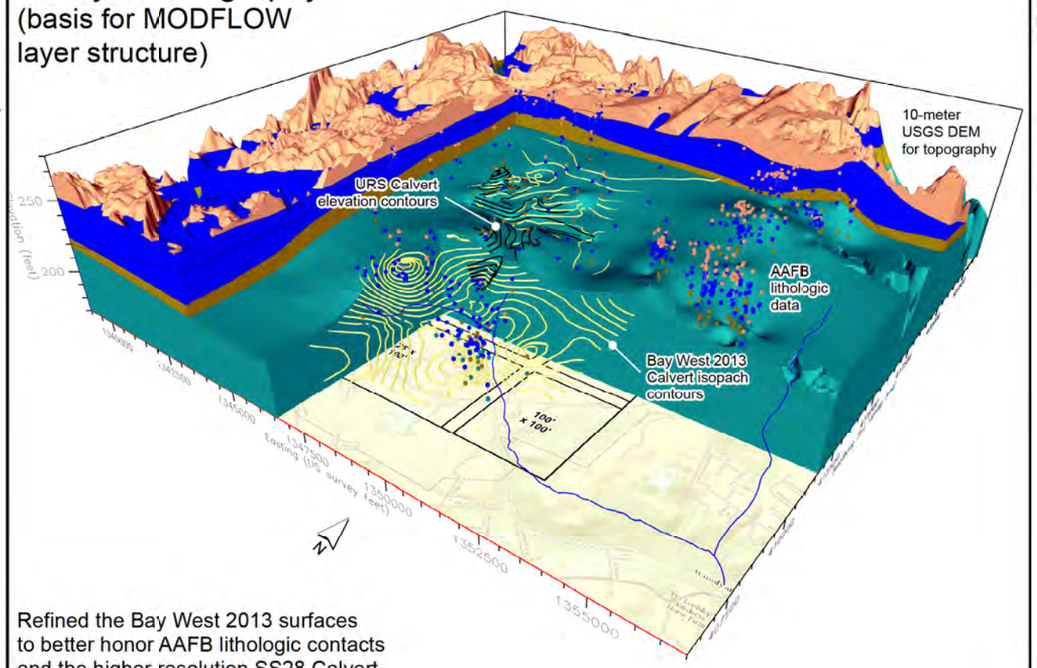
A. Average Potentiometric Surface
(used for upper model boundary and initial conditions)



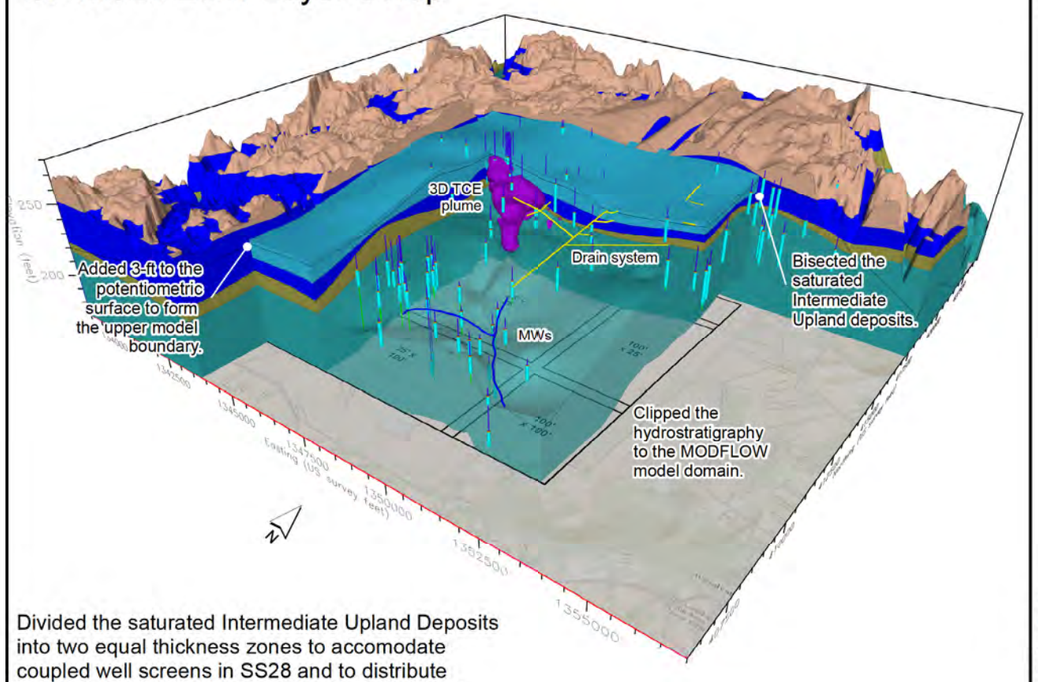
Adjusting the Bay West 2013 kriged surface to better match average groundwater elevations from all AAFB wells along with stream elevations derived from the 10-meter resolution DEM.

B. Hydostratigraphy
(basis for MODFLOW layer structure)



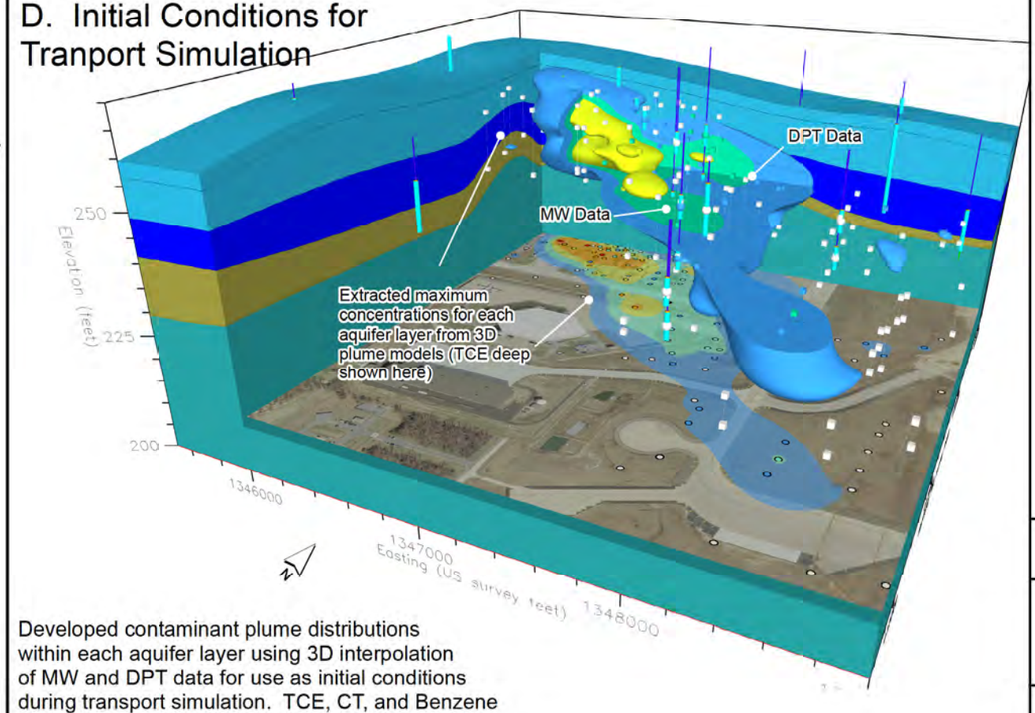
Refined the Bay West 2013 surfaces to better honor AAFB lithologic contacts and the higher resolution SS28 Calvert contours developed by URS.

C. MODFLOW Layer Setup



Divided the saturated Intermediate Upland Deposits into two equal thickness zones to accomodate coupled well screens in SS28 and to distribute contaminant mass more accurately in the model.

D. Initial Conditions for Tranport Simulation



Developed contaminant plume distributions within each aquifer layer using 3D interpolation of MW and DPT data for use as initial conditions during transport simulation. TCE, CT, and Benzene were all modeled but only TCE is shown here.

Legend

Modflow Layer / Lithologic Unit

Modflow Layer	Lithologic Unit	
N/A	Shallow	Upland Deposits
1	Upper Intermediate	Upland Deposits
2	Lower Intermediate	Upland Deposits
3	Deep	Upland Deposits
4	Calvert Formation	

Potentiometric Surface (ft MSL)

280	220
270	210
260	200
250	190
240	180
230	170

Contaminant Concentration (ug/L)

- <5 (not shown)
- 5 - 20
- 20 - 50
- 50 - 100
- 100 - 500
- >500

USGS Topo webservice used as the basemap for panels A-C. USGS EROS 1-ft Imagery Webservice used in panel D.

SS-28 Site
Andrews Air Force Base, Maryland

Figure B-2
Model Construction

Drafted: 3/12/2015
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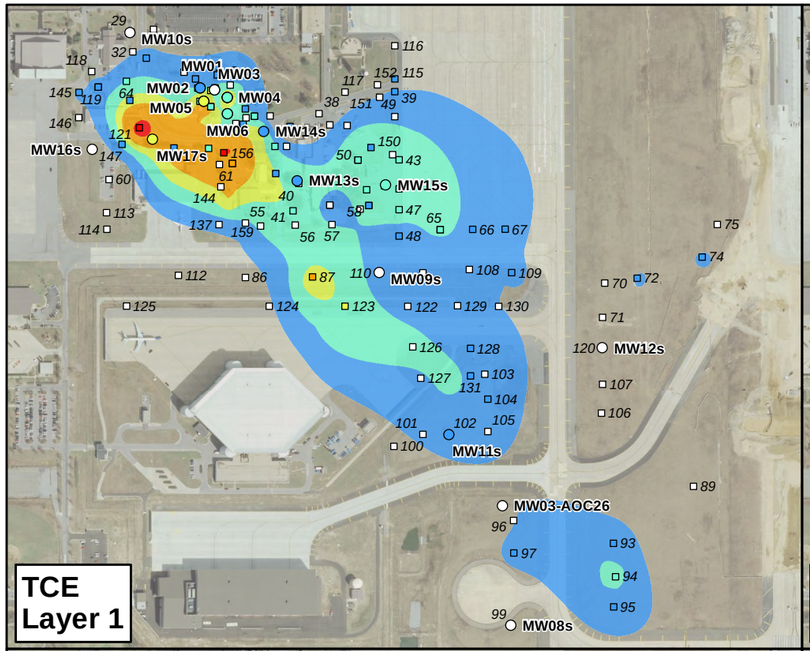

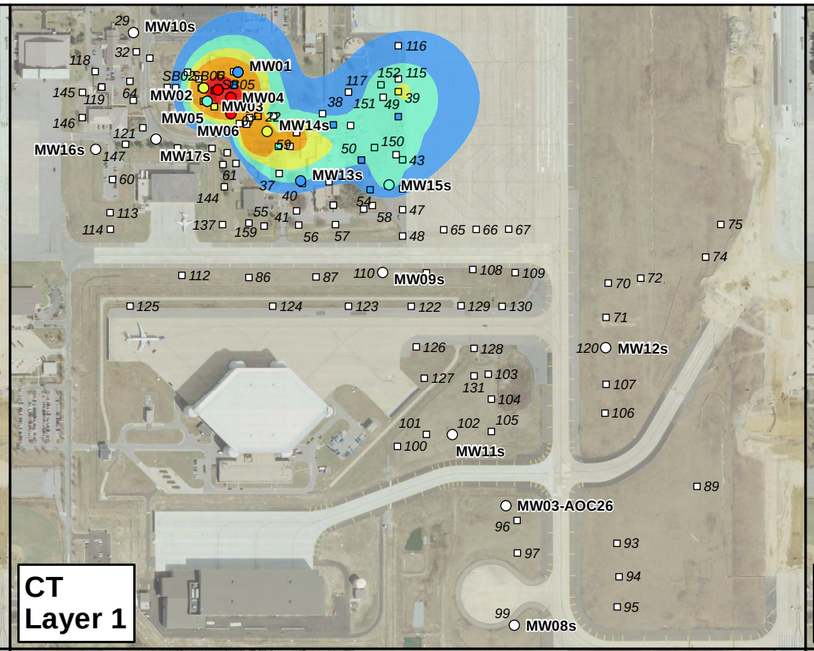

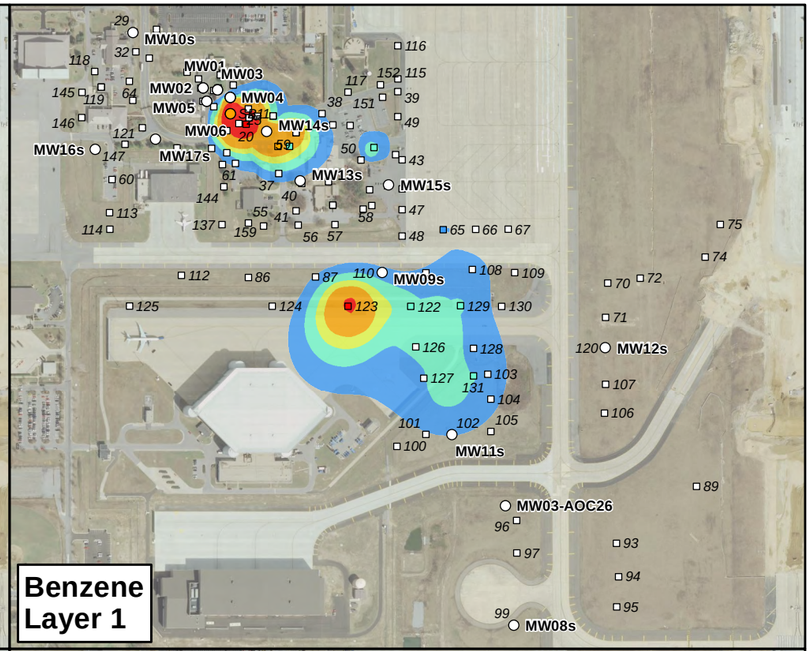

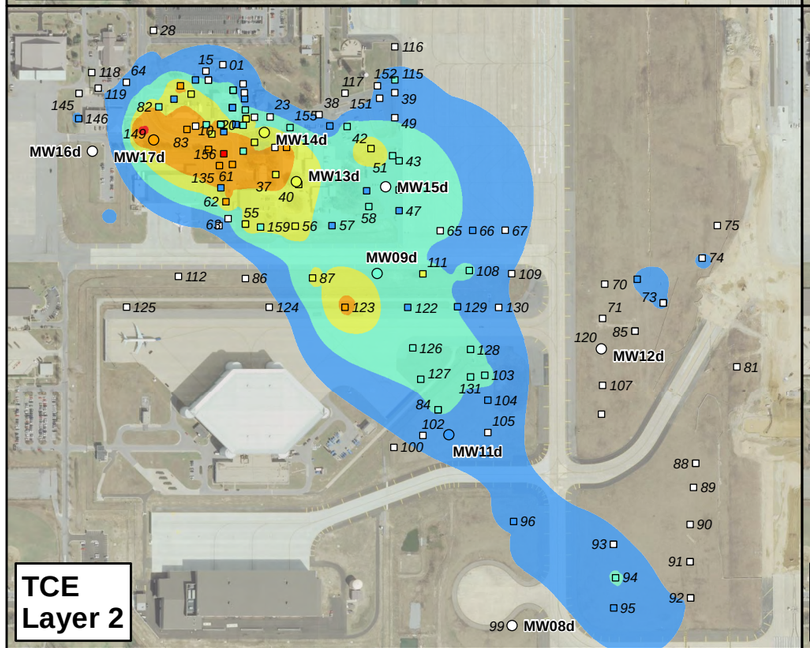

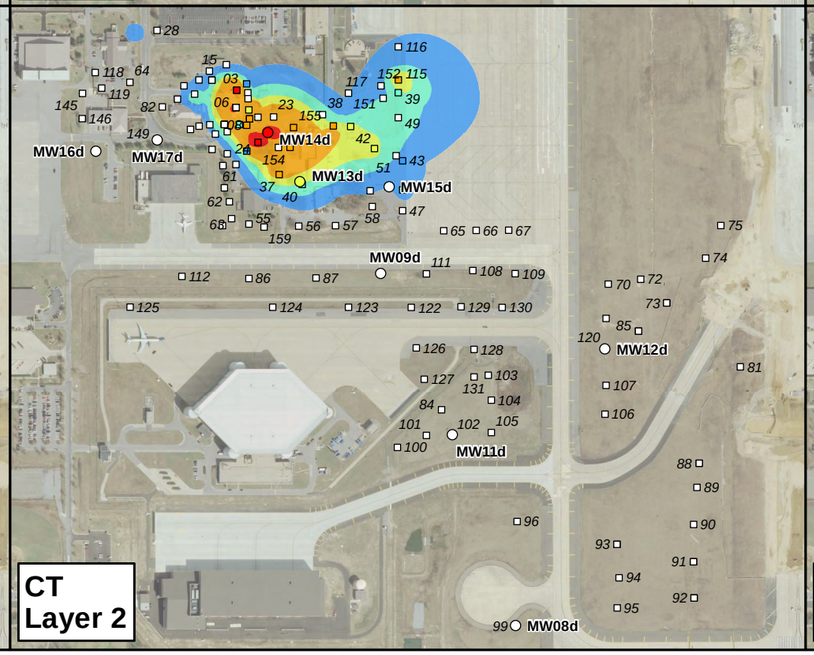

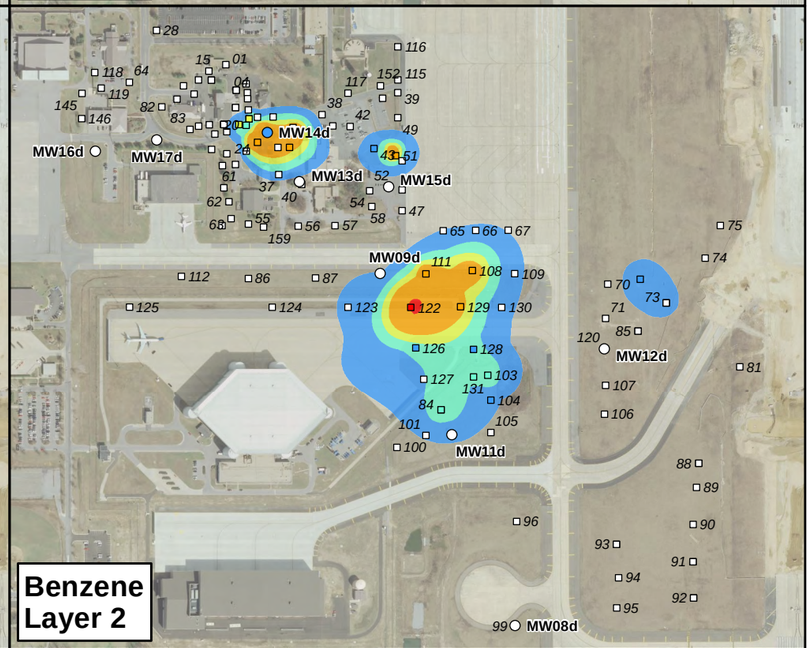

Legend

Data (ug/L)	Model (ug/L)
<5	<5 (not shown)
5 - 20	5 - 20
20 - 50	20 - 50
50 - 100	50 - 100
100 - 500	100 - 500
>500	>500

Notes:

1. *Not all boring IDs are shown due to high sample density.*
2. *DP- prefixes have been removed for clarity.*
3. *The modeled plumes may not appear to honor some data in plan view because some samples were collected above or below the region of highest predicted plume concentrations with depth.*
4. *Only the maximum concentration is shown when more than one sample was collected within the applicable aquifer layer.*

Basemap: USGS EROS 1-ft Imagery webservice

MDSP NAD83

N

1:8,400

0 200 400 600 ft

SS-28 Site
Andrews Air Force Base, Maryland

Figure B-3
Initial Conditions for Contaminant Transport Simulation

Drafted: 3/16/2015
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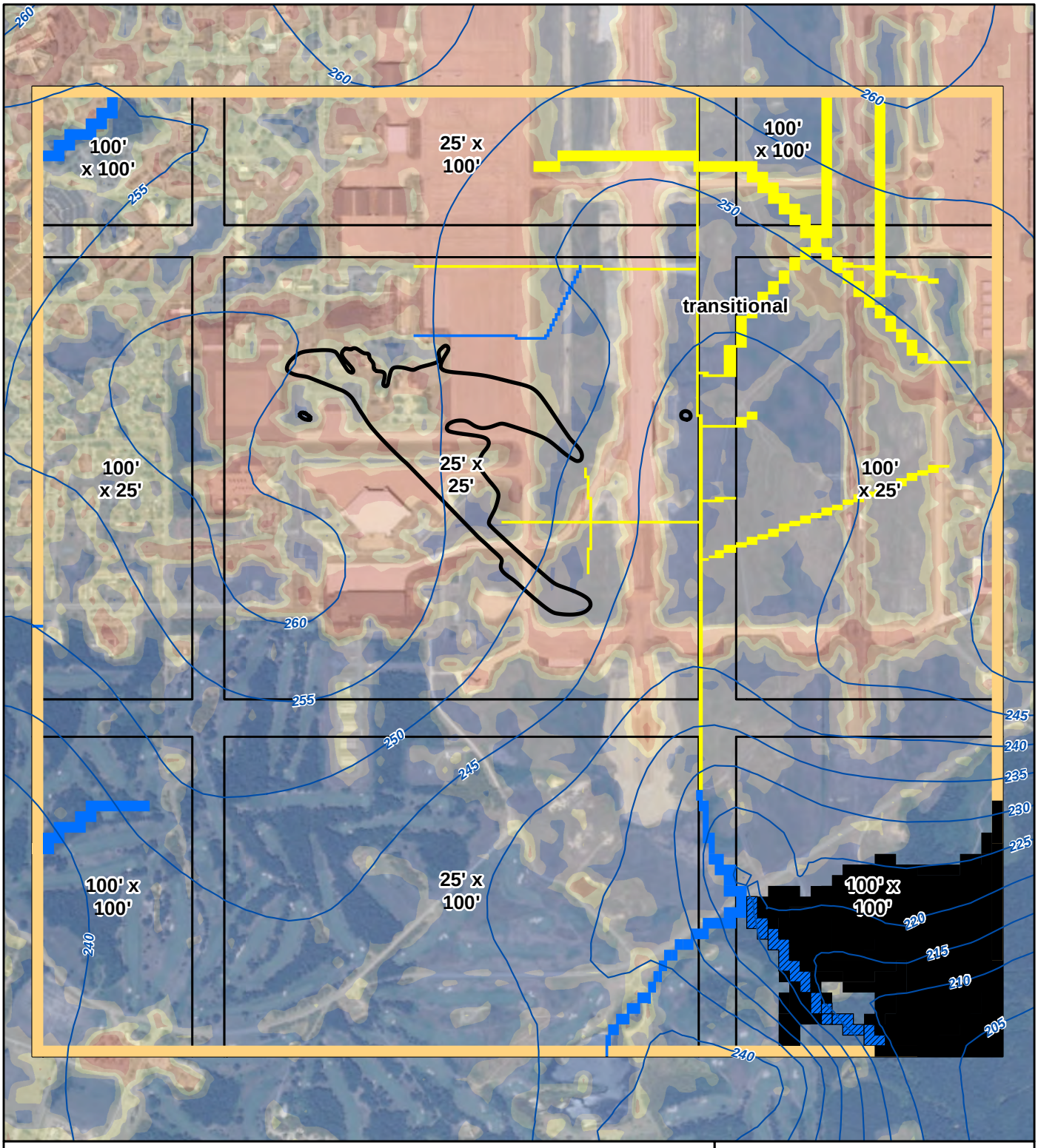

Basemap: USGS imagery webservice

Legend

- SS28 Contaminant Plume Outline
- Average Potentiometric Head Surface (ft MSL)
- Model Grid Boundary and Resolution (feet)

Boundary Conditions

- River (Lyr1 Dry)
- River (Lyrs 1-3)
- Drain (Lyr 1)
- General Head (Lyrs 1-2)
- No Flow (Dry)

Recharge (in/yr)

- < 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10

MDSP NAD83

N

1:16,000

0 500 1,000 1,500 ft

SS-28 Site
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Figure B-4
Model Boundary Conditions

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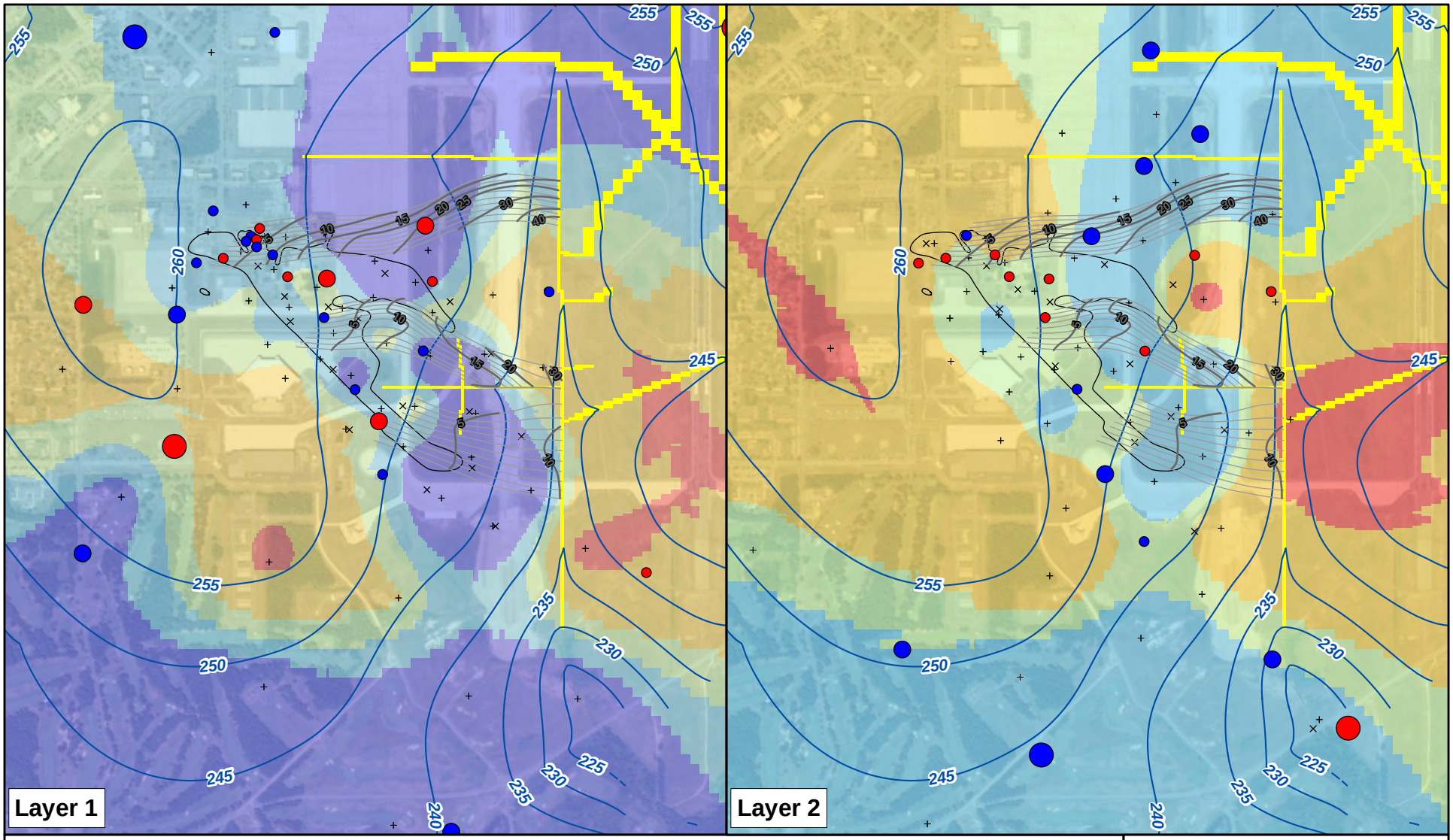

Legend

- Drains
- Plume
- Kx Pilot Point
- Kz Pilot Point
- Potentiometric Head (ft MSL)
- Particle Track
- Travel Time (years)

Calibration Target Absolute Residuals (feet)

K_h (ft/day)	Over-Predicted	Under-Predicted
< 1	< 0.5	< 0.5
1 - 5	0.5 - 2	0.5 - 2
5 - 10	> 2	> 2
10 - 50		
> 50		

MDSP
NAD83

N

1:18,000

0 500 1,000 1,500 ft

Notes:

1. *USGS imagery webservice used as basemap*
2. *Model layers 3 and 4 had uniform K distributions:*
   Layer 3: Kxy=9, Kz=2, Kanis=4.5
   Layer 4: Kxy=0.8, Kz=0.2, Kanis=4

SS-28 Site
Andrews Air Force Base, Maryland

Figure B-5
Model Calibration Results

Drafted: 3/13/2015
Modified: 3/17/2015
User: STROBRID

WESTON SOLUTIONS

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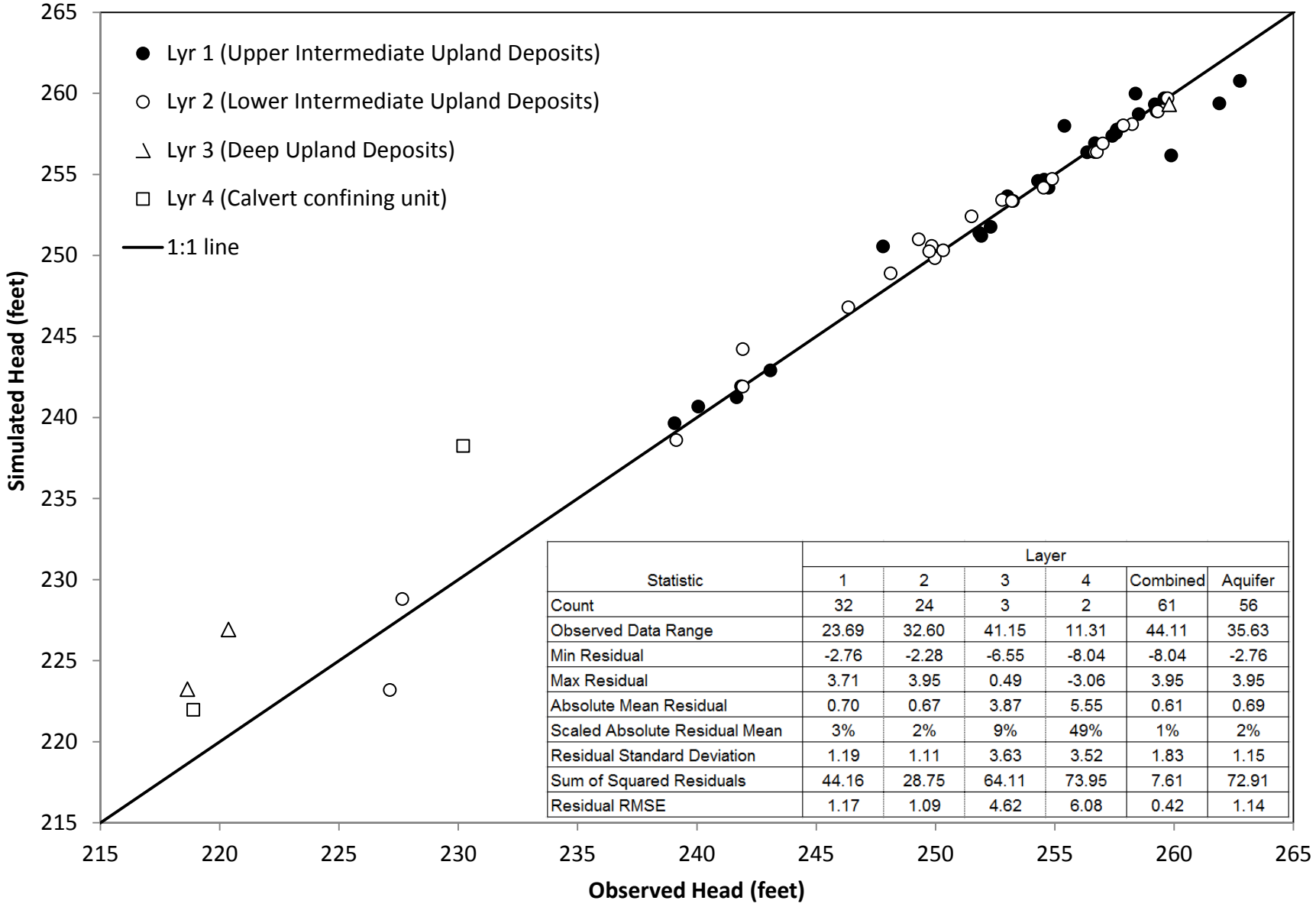
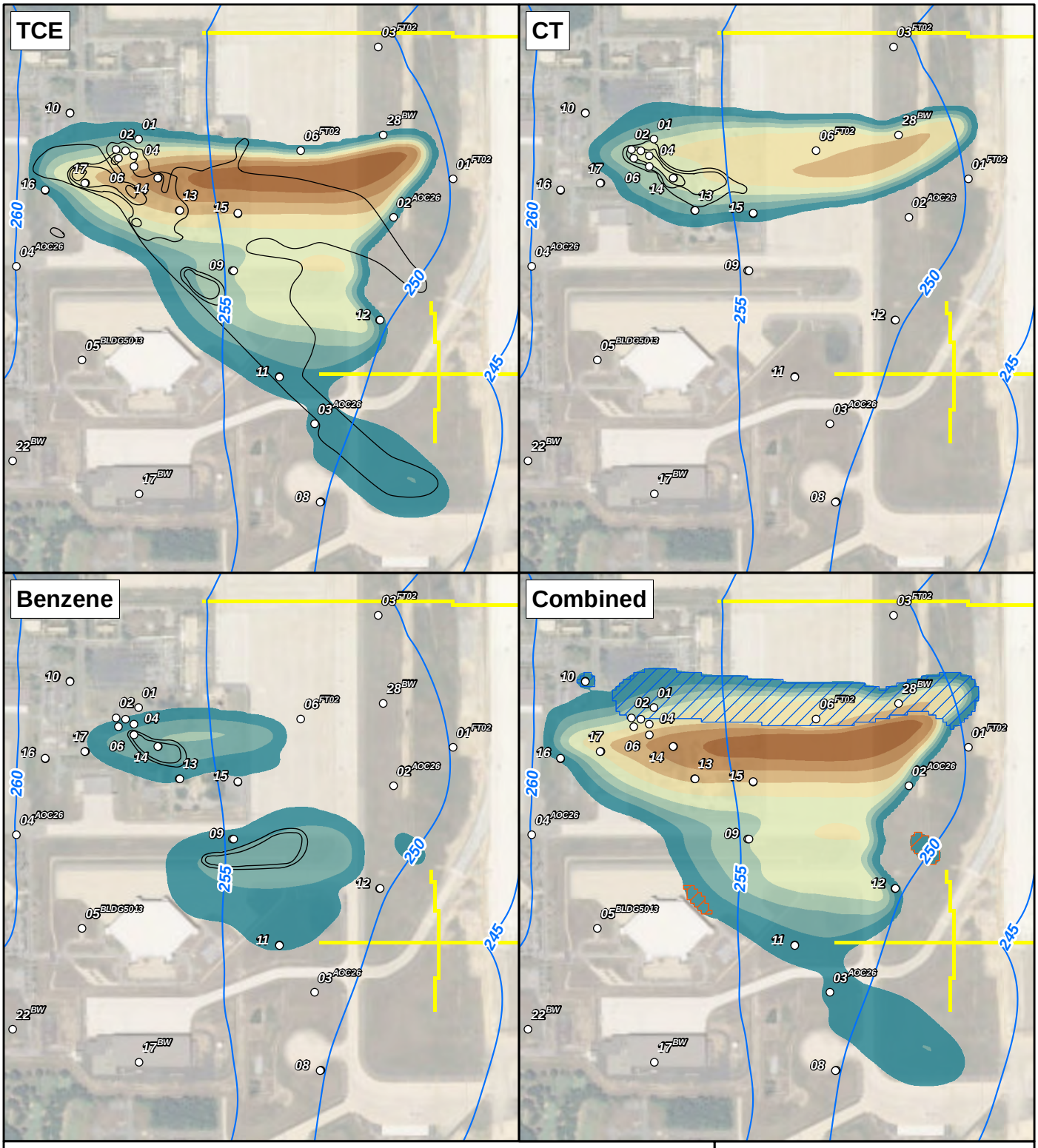
Figure B-6
Calibrated Flow Model Residuals



Statistic	Layer					
	1	2	3	4	Combined	Aquifer
Count	32	24	3	2	61	56
Observed Data Range	23.69	32.60	41.15	11.31	44.11	35.63
Min Residual	-2.76	-2.28	-6.55	-8.04	-8.04	-2.76
Max Residual	3.71	3.95	0.49	-3.06	3.95	3.95
Absolute Mean Residual	0.70	0.67	3.87	5.55	0.61	0.69
Scaled Absolute Residual Mean	3%	2%	9%	49%	1%	2%
Residual Standard Deviation	1.19	1.11	3.63	3.52	1.83	1.15
Sum of Squared Residuals	44.16	28.75	64.11	73.95	7.61	72.91
Residual RMSE	1.17	1.09	4.62	6.08	0.42	1.14



Legend

- Monitoring Well
- Potentiometric Head (ft MSL)
- Drains
- Original Plume

TTC (yrs)

- < 5
- 5
- 10
- 15
- 20
- 25
- 30
- 35

TTC Driver

- TCE
- CT
- Benzene

Notes:

1. *USGS imagery webservice used as basemap*
2. *Monitoring well prefixes and suffixes removed for clarity and are in SS28 unless otherwise noted by superscript.*
3. *The half-lives ($t_{0.5}$) for benzene and TCE/CT are 2- and 20-yrs, respectively.*

MDSP
NAD83

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SS-28 Site
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Figure B-7
Predicted Time To Cleanup (TTC)
for Alternative 2 (MNA)

Drafted: 3/12/2015
Modified: 3/19/2015
User: STROBRID

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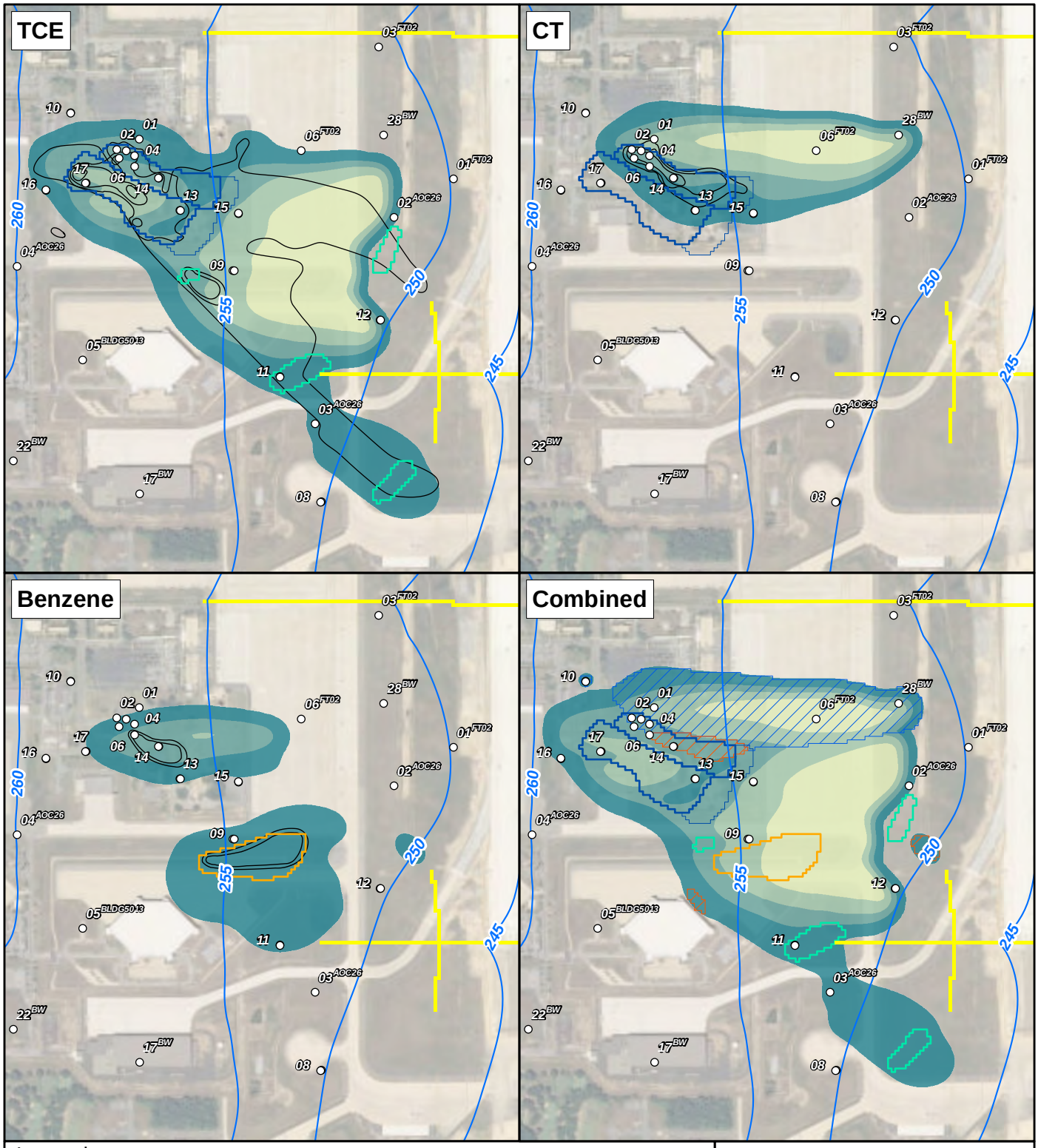
File: C:\Projects\AndrewsAFB\GIS\MXD\SS28\TTC_MNA.mxd, 3/19/2015 10:03:08 AM, STROBRID



Legend

- Monitoring Well
- Potentiometric Head (ft MSL)
- Drains
- Original Plume

Treatment Zones

- ISB/ISCR[a]
- ISB/ISCR[b]
- ISB[c]
- ISB[d]

TTC (yrs)

- < 5
- 5
- 10
- 15
- 20
- 25
- 30
- 35

TTC Driver

- TCE
- CT
- Benzene

Notes:

1. *USGS imagery webservice used as basemap*
2. *Monitoring well prefixes and suffixes removed for clarity and are in SS28 unless otherwise noted by superscript.*
3. *The half-life ($t_{0.5}$) for benzene and TCE/CT are 2- and 20-yrs, respectively except within treatment zones:*
   - *a: 6-mo for TCE/CT for first 5 years and 3-yr afterward*
   - *b: 3-yr for TCE/CT throughout the simulation representing advection and depletion of amendment downgradient.*
   - *c: 9-mo for TCE/CT for first 5 years and 3-yr afterward*
   - *d: Instantaneous benzene reduction of 50%*

MDSP
NAD83

N

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0 500 1,000 ft

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Andrews Air Force Base, Maryland

Figure B-8
Predicted Time To Cleanup (TTC)
for Alternative 3 (ISB/ISCR)

Drafted: 3/12/2015
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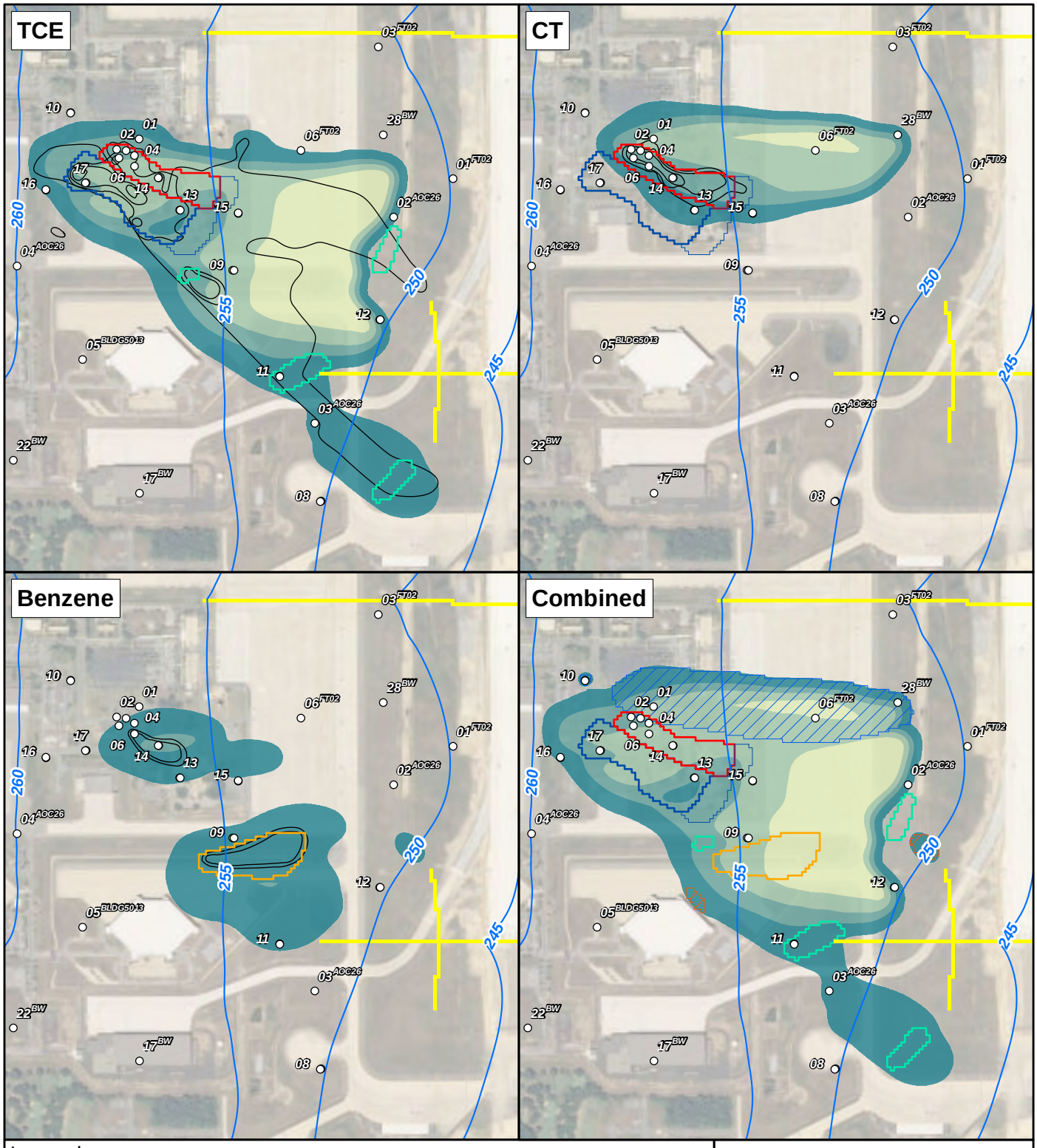

Legend

- Monitoring Well
- Potentiometric Head (ft MSL)
- Drains
- Original Plume

Treatment Zones

- ISB/ISCR[a]
- ISCO[a2]
- ISB/ISCR[b]
- ISB[c]
- ISB[d]

TTC (yrs)

- < 5
- 5
- 10
- 15
- 20
- 25
- 30
- 35

TTC Driver

- TCE
- CT
- Benzene

Notes:

1. *USGS imagery webservice used as basemap*
2. *Monitoring well prefixes and suffixes removed for clarity and are in SS28 unless otherwise noted by superscript.*
3. *The half-life ($t_{0.5}$) for benzene and TCE/CT are 2- and 20-yrs, respectively except within treatment zones:*
   - *a: 6-mo for TCE/CT for first 5 years and 3-yr afterward*
   - *a2: 20-yrs for TCE/CT for first 5 years and 3-yr afterward*
   - *b: 3-yr for TCE/CT throughout the simulation representing advection and depletion of amendment downgradient.*
   - *c: 9-mo for TCE/CT for first 5 years and 3-yr afterward*
   - *d: Instantaneous benzene reduction of 50%*

MDSP
NAD83
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0 500 1,000 ft

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Figure B-9
Predicted Time To Cleanup (TTC) for Alternative 4 (ISCO, ISB/ISCR)

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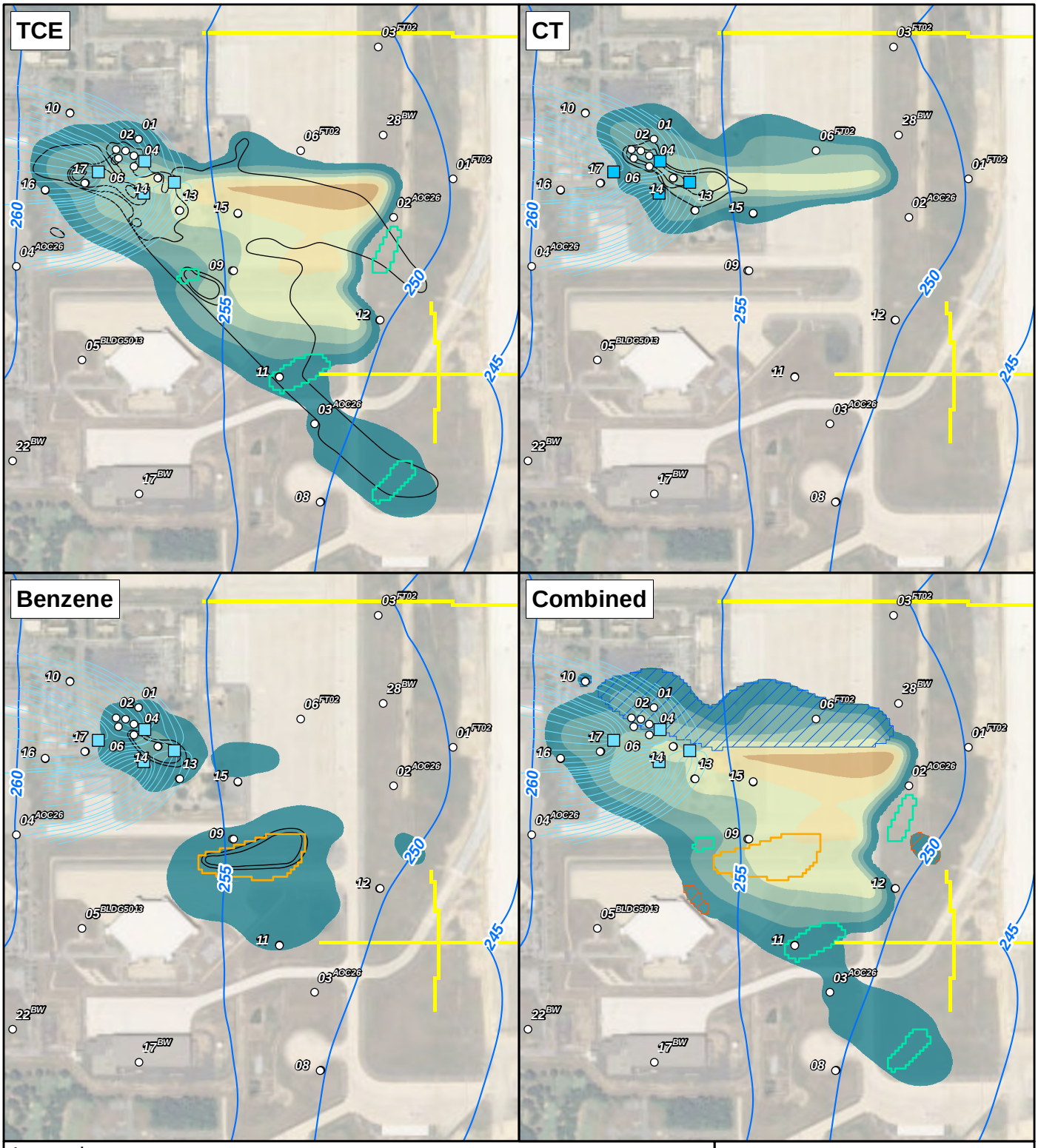
File: C:\Projects\AndrewsAFB\GIS\MXD\SS28\TTC_Alt4b.mxd, 3/19/2015 10:06:41 AM, STROBRID



Legend

- Monitoring Well
- Potentiometric Head (ft MSL)
- Drains
- Original Plume
- Extraction System
- 10-yr Capture Zone

Treatment Zones

- ISB[c]
- ISB[d]

TTC (yrs)

- < 5
- 5
- 10
- 15
- 20
- 25
- 30
- 35

TTC Driver

- TCE
- CT
- Benzene

Notes:

1. *USGS imagery webservice used as basemap*
2. *Monitoring well prefixes and suffixes removed for clarity and are in SS28 unless otherwise noted by superscript.*
3. *The half-life ($t_{0.5}$) for benzene and TCE/CT are 2- and 20-yrs, respectively except within treatment zones:*
   - *c: 9-mo for TCE/CT for first 5 years and 3-yr afterward*
   - *d: Instantaneous benzene reduction of 50%*

MDSP
NAD83

N

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0 500 1,000 ft

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Figure B-10
Predicted Time To Cleanup (TTC)
for Alternative 5 (Pump & Treat)

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