Appendix D

Assessment of Chemical Attenuation

Appendices are located on attached disk.

This page intentionally left blank

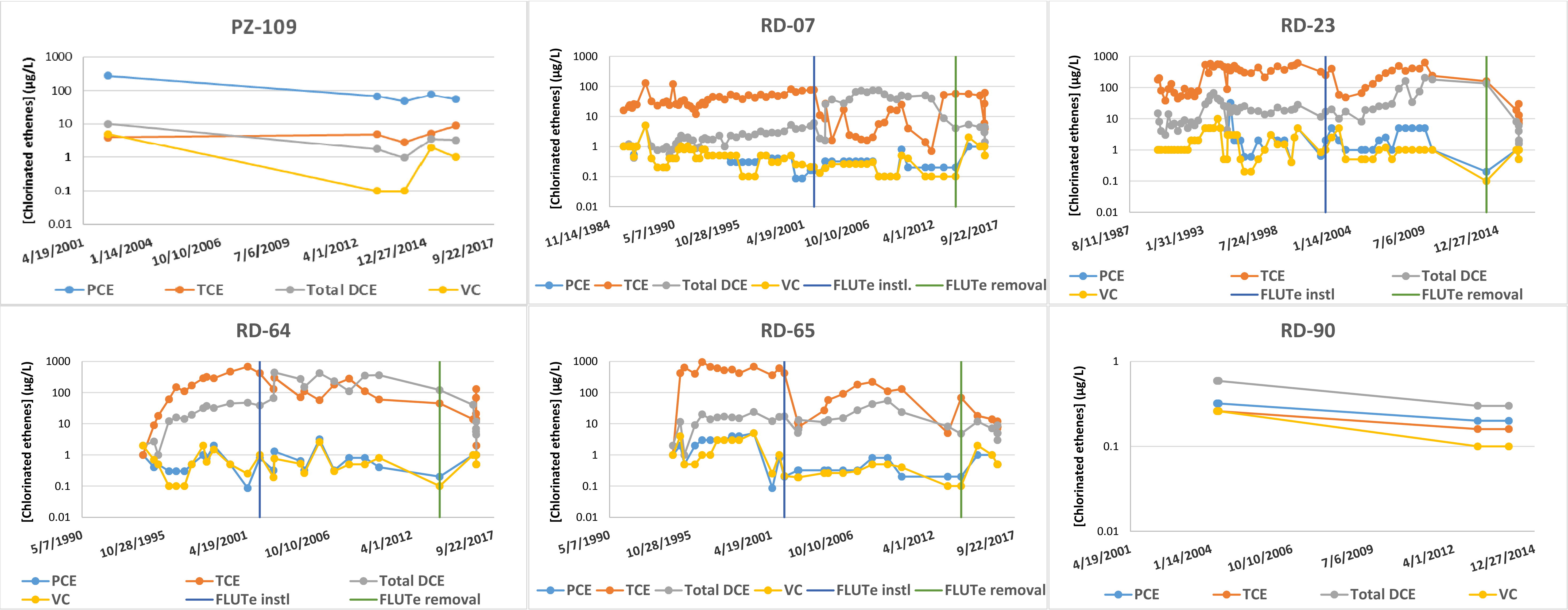

Figure D-1. Historical Chlorinated Ethene Concentration Trends
Santa Susana Field Laboratory
Ventura County, California

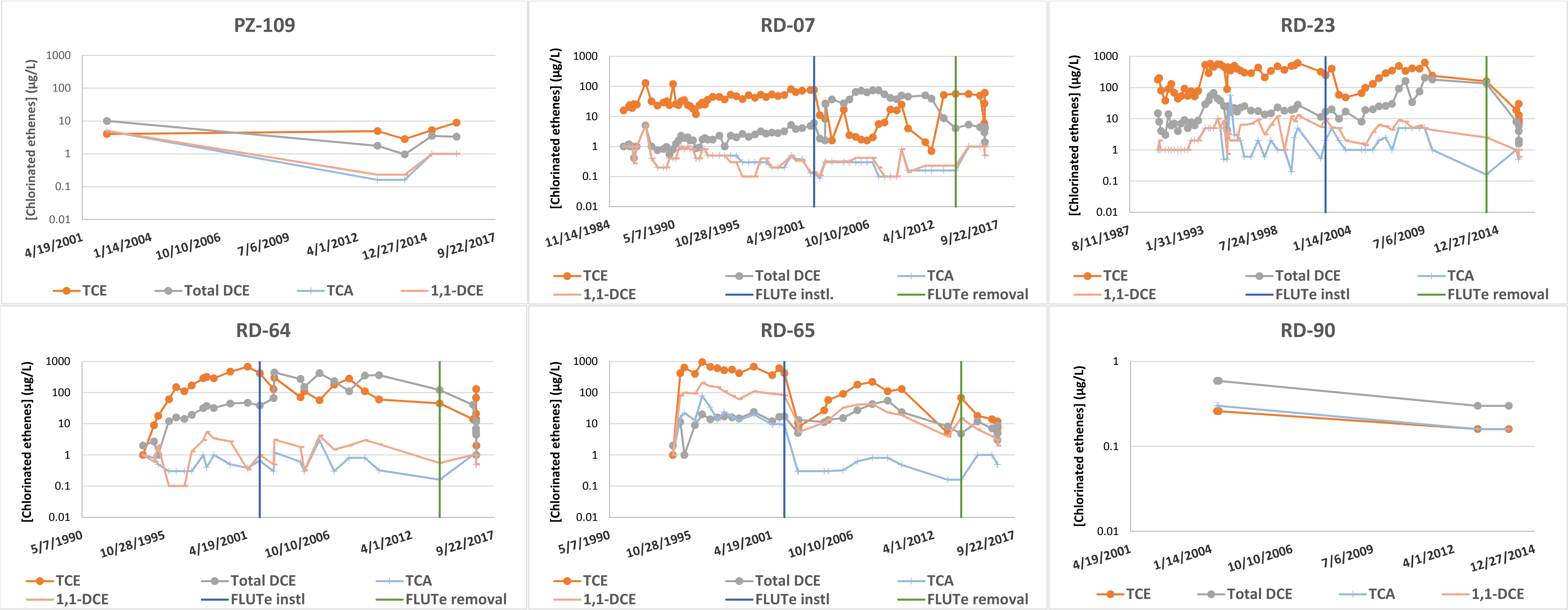

Figure D-2. Historical Chlorinated Ethene and Ethane Concentration Trends
Santa Susana Field Laboratory
Ventura County, California

Appendix D

Evaluation of Contaminant Attenuation Potential

This appendix provides background information pertinent to the various contaminant attenuation mechanisms in a groundwater system (D.1) and associated evaluation processes (D.2). Site-specific sampling methodology and comparison (D.3), analytical rationale (D.4), an evaluation and discussion of contaminant attenuation potential based on geochemical and microbiological analyses (D.5), and the overall assessment of contaminant attenuation potential observed at the SSFL Area IV (D.6) are also provided herein.

D.1 Contaminant Attenuation Mechanisms

The overall attenuation of contaminants in a groundwater system is based on the integration of several subsurface mechanisms that are classified as either destructive or non-destructive. Reductive dechlorination is typically the most significant and most commonly-documented destructive attenuation mechanism for chlorinated solvents, although destruction of some compounds may occur via biologically-mediated cometabolic pathways or abiotic pathways such as biogeochemical transformation (described further below). Additionally, common non-destructive attenuation mechanisms include dispersion, dilution, adsorption, absorption, and volatilization. In some cases, a combination of aforementioned attenuation processes will reduce dissolved contaminant concentrations to below regulatory standards before the contaminant plume reaches potential downgradient receptors. The efficacy of these attenuation mechanisms as a remedy component or as a stand-alone remedy is based on the site-specific assessment of these mechanisms in the context of transport to the receptors. This appendix presents a preliminary discussion of attenuation processes and mechanisms based on groundwater sampling conducted during the fall of 2016, and an assessment of observed attenuation of chlorinated solvents based on groundwater sampling results for the last 20 years.

Reductive Dechlorination

As previously mentioned, reductive dechlorination is typically the most important mechanism for natural attenuation of chlorinated solvents in most groundwater systems. Through biologically-mediated reactions, chlorinated solvents such as tetrachloroethene (PCE) or trichloroethene (TCE) are transformed via sequential removal of chlorine atoms to ultimately produce non-toxic end products. The discussion presented herein will focus primarily on TCE as it is the most prevalent volatile organic compound (VOC) detected at the Site (note that PCE also follows the same degradation pathways following its degradation to TCE, which occurs readily under most environmental conditions). The following reaction sequence depicts the primary reductive dechlorination pathway for TCE to non-toxic ethene, which is the terminal reductive dechlorination end-product:

TCE → cis-1,2-dichloroethene (cis-1,2-DCE) → vinyl chloride (VC) → ethene

Chlorinated ethanes such as 1,1,1- or 1,1,2-trichloroethane (1,1,1- or 1,1,2-TCA) and its associated degradation products have also been observed at the Site, although much less frequently and only at a few monitoring locations. Similar to chlorinated ethenes, parent chlorinated ethanes such as TCA are also subject to reductive dechlorination as depicted below:

TCA → 1,1-dichloroethane (1,1-DCA) → chloroethane → ethane

However, unlike PCE and TCE, TCA may also be subject to rapid hydrolysis to approximately 20% 1,1-dichloroethene (1,1-DCE) and 80% acetate. Therefore, presence of TCA and daughter products 1,1-DCA and 1,1-DCE at a monitoring location may indicate that the source could be nearby.

While most aerobic microorganisms utilize carbon and oxygen as the primary source of electron donor and electron acceptor, respectively, for microbial respiration, most anaerobic microorganisms utilize hydrogen as an electron donor and naturally-occurring electron acceptors such as oxygen, nitrate, and sulfate for electron transfer. When these electron acceptors are depleted, some microorganisms can also utilize chlorinated VOCs to complete the electron transfer. Specifically, the chlorinated VOCs serve as electron acceptors, whereas hydrogen generated during microbial consumption of naturally-occurring or artificially-introduced organic carbon serves as an electron donor. However, before these contaminants can be utilized for microbial respiration, the competing electron acceptors in groundwater must be depleted. The presence of naturally-occurring dissolved organic carbon can lead to removal of these electron acceptors, driving redox conditions from aerobic to nitrate-reducing, to iron-reducing, to sulfate-reducing, and finally to methanogenic. Reductive dechlorination of PCE and TCE to cis-1,2-DCE generally occurs under iron-reducing to sulfate-reducing conditions. However, complete dechlorination to ethene and ethane requires sulfate-reducing to methanogenic conditions, pH conditions conducive to microbial growth (6-8), and the presence of *Dehalococcoides* (DHC) at sufficient concentrations. Therefore, evaluation of groundwater geochemistry as well as microbiological and contaminant concentrations and historical/spatial trends can provide insights into whether active and destruction attenuation mechanisms are present and occurring at a site.

Cometabolism

Cometabolism of chlorinated compounds is an additional mechanism that should be evaluated when considering potential natural attenuation mechanisms. In aerobic cometabolism, bacterial enzymes that typically utilize compounds including methane, ethene, ethane, toluene, phenol, ammonia, propane, and propene as electron donors can also fortuitously transform chlorinated solvents under aerobic conditions. One difficulty in assessing the importance of cometabolism is that unlike reductive dechlorination, daughter products are not produced. The cometabolic oxidation essentially mineralizes the VOCs into chloride, carbon dioxide, and water. Because of this, other lines of evidence are needed to document active cometabolism at a site.

In Situ Biogeochemical Transformation

In situ biogeochemical transformation, i.e. abiotic degradation, involves biological formation of reactive minerals that can destroy chlorinated solvents such as TCE producing acetylene and carbon dioxide as end-products without accumulation of toxic intermediates such as vinyl chloride. Iron sulfides are one class of minerals that have been identified as being reactive with chlorinated solvents. These minerals are formed via anaerobic reduction of sulfate to sulfide followed by reaction of sulfide with solid-phase iron oxides or soluble ferrous ion. These minerals are formed under conditions that are favorable for biological reductive dechlorination because iron and sulfate reduction are required. While sulfate is elevated at SSFL, the lack of reducible iron likely renders biogeochemical transformation of TCE a minor attenuation mechanism and thus it is not investigated further herein.

D.2 Contaminant Attenuation Potential Evaluation Criteria

This section provides an evaluation of the suite of parameters applicable to the evaluation of intrinsic biodegradation of chlorinated solvents, including both reductive dechlorination and cometabolism. Included in this evaluation will be a discussion of electron donor [as total organic carbon (TOC)], electron acceptors that compete with VOCs for electron donor in reductive dechlorination and indicate overall redox conditions, and other geochemical conditions that indicate whether reductive dechlorination or cometabolism may occur as described in the *USEPA Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents* (USEPA 1998, USEPA 2004, USEPA 2008, USEPA 2011) and *Frequently Asked Questions about Monitored Natural Attenuation in Groundwater* (Adamson and Newell 2014). Based on guidance, the groundwater data parameters and “desired” concentrations for biogeochemical parameters in support of reductive dechlorination are shown below (note that results outside of these ranges do not absolutely preclude the potential for contaminant attenuation, but these values are used as an initial screening):

- TOC > 20 milligrams per liter (mg/L);
- Oxidation-reduction potential (ORP) < -50 millivolts (mV);
- Dissolved oxygen (DO) < 1 mg/L;
- Ferrous iron > 1 mg/L;
- Sulfate < 50 mg/L or decreasing trends;
- Methane > 1 mg/L; and
- pH between 6 and 8.

These biogeochemical parameters, combined with recent and historical VOC concentrations and VOC concentration trends, can be used to estimate the degree to which destructive contaminant attenuation is occurring. However, there is a high degree of variability associated with historical Site data at most of the wells of interest as shown in **Figure D-1** due to various operational changes over the years including installation and removal of the FLUTe liners. Additionally, the majority of the monitoring locations examined for this contaminant attenuation potential evaluation are open boreholes; while being collected at depth-discrete intervals, groundwater samples may be subject to dilution and mixing over hundreds of feet of the saturated zone. Also, many of the geochemical parameters listed above had not been consistently collected in many of the wells of interest. Other state-of-the art analyses such as quantitative polymerase chain reaction (qPCR) and compound-specific isotopic analysis (CSIA) were also performed but are not specifically addressed in the initial USEPA evaluation process. Because of these factors, this baseline sampling event was not intended to provide adequate information to make definitive conclusions about contaminant attenuation potential at SSFL. Rather, the collected data are meant to serve as baseline Site-specific conditions and subsequent monitoring events will be used to supplement the analysis provided herein.

D.3 Sampling Methodology and Comparison

In October 2016, six monitoring wells (PZ-109, RD-07, RD-23, RD-64, RD-65, and RD-90) were sampled for evidence of solvent chemical degradation assessing parameters introduced in the prior section. Five of the wells (PZ-109, RD-07, RD-23, RD-64, and RD-65) were selected because they exhibited elevated concentrations (>100 µg/L) of TCE and/or PCE historically and/or in 2016. RD-90 was sampled to serve as a study control well that was not impacted by TCE or PCE. Historically there are several other wells that once exhibited elevated TCE that were either dry or did not exhibit elevated contaminants in 2016 and thus were not included in this study.

Sampling Methodology Description

Monitoring well sampling included two methods: the low-stress, low-flow groundwater sampling technique per the SSFL Water Quality Sampling and Analysis Plan (Haley & Aldrich 2010) and ProHydro, Inc's Snap Sampler™ technology. Both methods were used to collect depth-discrete samples to be analyzed for contaminants, geochemical, and field data pertinent to evaluation of contaminant attenuation potential. Specifically, Snap Samplers™ were deployed to approximately the same depths that a bladder pumps are typically positioned during low-flow groundwater sampling at each of the wells of interest to aid collection of undisturbed VOC and dissolved gas samples. The Snap Samplers™ were deployed for at least a week prior to sample retrieval. Following proper retrieval of the Snap Samplers™, low-stress, low-flow groundwater sampling was performed at each of the wells. Upon stabilization of field parameters including pH, conductivity, DO, turbidity, and ORP, samples were collected for laboratory analyses including: sulfide; TOC; anions including chloride, nitrate, and sulfate; alkalinity; DNA; CSIA; mRNA; hydrogen; and field analyses of ferrous iron and DO. **Table D-1** proves the analytical parameters that were targeted for the groundwater samples.

Sampling Methodology Comparison

Comparisons of VOC results obtained using the Snap Samplers™ versus low-stress, low-flow sampling methodology (using a bladder pump) are presented in **Table D-2**. Specifically, the relative percent differences (RPDs) were calculated for the chlorinated ethenes of interest including PCE, TCE, cis- and trans-1,2-DCE, and VC that were detected during the baseline contaminant attenuation assessment sampling event. Except for DD-144 where significant differences in TCE and cis-1,2-DCE concentrations were observed between the snap sampling and the low-flow sampling methods (resulting in RPDs exceeding 100%), the average RPDs for all chlorinated ethenes in each monitoring location were near or below 40%. The average RPDs associated with each chlorinated ethenes across all sampled wells excluding DD-144 were near or below 30%. The significant discrepancy in VOC concentrations observed at DD-144 may be attributable to presence of productive, fractured bedrock zones where the sampling pump was placed during low-flow groundwater sampling. These results are generally promising considering that the concentrations of most constituents were very low (generally less than 50 µg/L and, in many cases, less than 10 µg/L), where a difference of a few µg/L can cause larger

RPD values. Collectively, these results indicate that Snap Samplers™ can be used to replicate VOC data collection obtained using low-flow sampling methodology at the Site.

D.4 Analytical Rationale

A brief description of the various analytes collected and their associated rationale are provided as follows:

- ***VOCs***: concentrations of parent chlorinated VOCs (TCE and PCE) and their degradation daughter products, including cis-1,2-DCE and VC, as well as compounds important for cometabolic evaluation, can provide insights into whether contaminant attenuation via reductive dechlorination or other degradation mechanisms is occurring.

- ***Dissolved gases***: complete reductive dechlorination of PCE and TCE results in generation of ethene and ethane and thus monitoring of dissolved gases can be used to assess contaminant attenuation and to elucidate the degradation mechanism. Additionally, degradation of PCE and TCE to innocuous end-products ethene and ethane occurs most optimally under methanogenic conditions and thus methane can be monitored to aid evaluation of redox conditions. Furthermore, acetylene is an end-product of abiotic degradation and can thus be used to assess that mechanism.

- ***TOC***: naturally-occurring or artificially-introduced organic carbon can be utilized by a variety of subsurface microorganisms for respiration and for development of reducing conditions required for complete reductive dechlorination.

- ***pH***: pH between 6 and 8 is most favorable for biologically-mediated degradation processes.

- ***DO***: the first electron acceptor that is depleted in development of reducing conditions

- ***ORP***: low ORP measurements and increasingly negative measurements are associated with DO deficiency and reducing conditions in groundwater

- ***Nitrate***: nitrate can also serve as an electron acceptor and its removal can be indicative of nitrate-reducing conditions.

- ***Ferrous iron***: ferrous iron is generated from the reduction of bioavailable ferric iron under reducing conditions. It should be noted that the reducible iron content in soil and groundwater may be low at the Site and therefore, ferrous iron concentrations may not be a reliable indicator of iron-reducing conditions. Because of this, the other electron acceptors will be key parameters to evaluate in order to understand redox conditions at the Site.

- ***Sulfate and sulfide***: under highly reducing conditions, sulfate can be used as an electron acceptor and sulfate reduction may result in elevated sulfide concentrations. Therefore, monitoring of sulfate and sulfide concentrations can be used to aid evaluation of redox conditions.

- ***Hydrogen***: hydrogen is the primary electron donor that is used by a variety of microorganisms to drive the sequential removal of chlorine atoms in reductive dechlorination reactions; its presence indicates reducing conditions.

- ***CSIA***: CSIA can be used to differentiate non-destructive attenuation mechanisms such as dilution and dispersion from destructive attenuation mechanisms such as reductive dechlorination.
- ***DNA and mRNA***:
    - Quantification of halorespiring bacteria such as *Dehalococcoides*, *Dehalobacter*, *Desulfuromonas*, and *Desulfitobacterium* spp and key functional genes such as TCE reductases and vinyl chloride reductases can provide insights into whether biologically-mediated reductive dechlorination is viable at a site.
    - In addition to reductive dechlorination, several types of bacteria including methanotrophs and bacteria utilizing toluene and phenol can fortuitously oxidize TCE, cis-1,2-DCE, and VC in a process known as aerobic cometabolism. Therefore, detections of functional genes such as soluble methane monooxygenase encoding enzymes in significant quantities can be indicative of cometabolism of chlorinated VOCs.
    - In some cases, etheneotrophs can utilize VC as a growth-supporting substrate to aid cometabolism and thus quantification of functional genes that are key in ethene metabolism can aid elucidation of this degradation pathway.

D.5 Evaluation and Discussion of Contaminant Attenuation Potential

Detailed contaminant attenuation potential evaluation was performed for each monitoring location in terms of redox conditions and evidences for destructive contaminant attenuation via biologically-mediated dechlorinating and/or cometabolic pathways. Assessments of the individual screening criteria and associated overall conclusions for monitoring locations examined for contaminant attenuation potential are provided in **Table D-3**. Microbiological results are presented in **Table D-4** and pertinent geochemistry and VOC data are presented in **Table D-5**. General assessment of potential for contaminant attenuation at the SSFL Area IV based on this baseline sampling event is provided below.

Geochemistry

Data obtained during the baseline sampling event at SSFL Area IV indicates that while natural attenuation of chlorinated VOCs may be occurring, the evidence to support this conclusion is limited. Based on the screening criteria from EPA guidance that was listed above, almost none of the parameters are in the ranges that would be considered strong evidence for contaminant attenuation potential. Overall, SSFL Area IV groundwater is carbon-limited; TOC values were low at all monitoring locations. This lack thereof does not allow for development of highly reducing redox conditions typical of sulfate reduction or methanogenesis, resulting in incomplete dechlorination of TCE. Overall, redox conditions in the aquifer are slightly aerobic to mildly reducing, which suggests that partial dechlorination could occur at some wells. However, based on the observation of methane and hydrogen at several wells where low levels of DO are detected, it is possible that there are intervals within the open boreholes with more strongly reducing conditions that are mixing with mildly reducing groundwater. For instance, methane and hydrogen were detected at some wells even though nitrate and sulfate were present. This suggests that while the data from the borehole indicates a mildly reducing condition overall, methane and hydrogen production in portions of the aquifer suggests strongly reducing conditions exist at select depth-discrete intervals.

CSIA

Regardless of redox conditions, the contaminant data further support that some complete dechlorination is occurring as evident by presence of ethene and ethane (albeit at low concentrations). CSIA data also supports this conclusion, with values associated with cis-1,2-DCE being more negative than those of TCE (e.g. being "lighter") in nearly all wells, indicating that the parent compound is being degraded through biologically-mediated dechlorination processes. This result is not surprising given that the presence of cis-1,2-DCE is most commonly associated with biological degradation.

Microbiology

The detection of DNA for dechlorinating bacteria throughout Area IV indicates that the bacterial communities necessary for partial or complete dechlorination are present. Furthermore, mRNA detections of reductive dechlorinating microbes indicate that in some cases, bacteria are actively creating the proteins necessary for reduction of contaminants. As would be expected based on redox conditions, the primary mRNA detections are observed in reductive dechlorinating microbes that are active in less-reduced conditions (nitrate or iron-reducing). The combination of appropriate redox conditions, presence of cis-1,2-DCE, the CSIA data that indicate that biologically-mediated reduction has occurred, and presence/activity of dechlorinating bacteria suggests that anaerobic reductive dechlorination is an active process, although it is likely very limited due to lack of available electron donor. Furthermore, substantial cis-1,2-DCE production and accumulation is not currently observed, indicating that while reductive dechlorination may be occurring, it is progressing at a slow rate. The inefficiency of reductive dechlorination observed at the Site may be attributable to the relatively low contaminant concentrations. Active treatment via enhanced bioremediation generally progresses very slowly when the total concentration of total chlorinated compounds is less than 200 micrograms per liter (µg/L).

Limited evidence for aerobic cometabolism and abiotic degradation exists at the Site. One of the primary requirements for cometabolism is presence of the primary growth substrate for the bacteria, which includes compounds such as methane, toluene, phenol, or ethene. In general, these compounds were not detected or were measured at very low levels, which would suggest that cometabolism is not occurring at rapid rates. However, the enzymes known to cometabolize VOCs can be induced by compounds other than their primary substrates; this can include naturally occurring organic matter in aquifers and even the contaminants themselves. While not likely a significant factor, it is possible that the apparent mixed redox condition of the groundwater allows for interaction of aerobic and anaerobic water types, which could facilitate cometabolism of contaminants at the interface.

The microbiological data for targets related to cometabolism further support the idea that intrinsic cometabolism could play a minor role in contaminant attenuation at the Site. While nearly all of the Area IV groundwater wells sampled showed low levels of DNA and mRNA enzyme targets, these low detections suggest that cometabolic degradation may be occurring at the site. The most direct method for assessing cometabolism is activity-dependent enzyme probes; this technique is not commercially available, but has been applied at other DOE sites to document active aerobic cometabolism at TCE sites and therefore could be considered at a future time. Regarding abiotic degradation, the lack of reduced iron and sulfide, as well as absence of acetylene, indicates that conditions are not conducive to contaminant removal via this mechanism.

The well that exhibited the most unique conditions was well PZ-109 located in the Buildings 4057/4059/4626 area. This well is the shallowest of those monitored during the baseline contaminant attenuation assessment sampling event, and is the only well exhibiting PCE contamination. Redox conditions appear to be less reducing when compared to other wells, but the microbiological and CSIA data are indicative of active degradation processes. The mildly reducing conditions may be attributable to the shallow depth of the well, as aerobic surface water likely recharges the aquifer at this depth interval more readily than the deeper bedrock wells.

In terms of the VOCs, TCE and cis-1,2-DCE are observed at the well, indicating reductive dechlorination has occurred, and the CSIA data from PZ-109 exhibit the least negative (e.g. “heaviest”) TCE and the most negative (e.g. “lightest”) cis-1,2-DCE isotopic signatures seen during this sampling event. These isotopic signatures suggest that this area had undergone reductive dechlorination from TCE to cis-1,2-DCE. However, the presence of PCE at this location complicates the CSIA data interpretation, as the TCE signature may represent a combination of TCE produced by reduction of PCE and TCE that was released as a parent compound. Despite the less reducing conditions, the microbial data at this well show the highest levels of reductive dechlorination targets and aerobic cometabolism targets. In addition, while the concentration was low at 4 mg/L, this was the highest detection of TOC of all the sampled wells. Again, being a shallow well, it is possible that organic carbon is more often replenished due to flushing of surface materials, which provides a carbon substrate for microbial growth of anaerobes.

Contaminant Data Trends

A brief description of the VOC concentration trends over time at the seven monitoring locations being examined is provided in this section. Discussion of notable historical VOC concentration trends at other onsite wells such as RS-54 and C-21 are also presented herein. The following discussions are organized based on the different types of VOCs including chlorinated ethenes such as TCE and its daughter products and chlorinated ethanes including TCA and its daughter products. Historical VOC trend charts for both chlorinated ethenes and chlorinated ethanes are provided in **Figure D-2**. It should be noted that VOC concentrations observed at PZ-109 and RD-90 are generally less than 10 and 1 µg/L, respectively, and thus these monitoring locations are excluded from the discussions below.

Chlorinated ethenes

Significant changes in concentrations of TCE and degradation daughter product cis-1,2-DCE were observed during the FLUTe era as well as following removal of the FLUTe liners at RD-07, RD-23, RD-64, and RD-65. At these monitoring locations, TCE concentrations were greater than those of cis-1,2-DCE by an order-of-magnitude or more prior to the FLUTe era. Following installation of the liners, cis-1,2-DCE concentrations generally increased significantly as TCE concentrations decreased. These changes in VOCs concentration trends, the most pronounced of which were observed at RD-07 and RD-64, are most likely attributable to changes in geochemistry induced by installation of the FLUTe liners. Specifically, prior to installation of the FLUTe liners, contaminants present within each monitoring location were likely subject to significant vertical mixing over hundreds of feet, resulting in aerobic geochemical conditions. Following installation of the liners, groundwater samples collected at the same set of monitoring wells were representative of much fewer water-bearing zones and some of which may have been under anaerobic conditions. Mildly reducing conditions typical of nitrate-reduction are known to be conductive to biological conversion of TCE to cis-1,2-DCE.

However, following the removal of the FLUTe liners, the pre-FLUTe TCE and cis-1,2-DCE concentrations were not re-established at the aforementioned monitoring locations except for RD-07. In fact, TCE and cis-1,2-DCE continued to decline following removal of the FLUTe liners at monitoring locations RD-23, RD-64, and RD-65. These reductions in contaminant concentrations are more likely attributable to the historic drought recently experienced in Southern California, resulting in significant decreases in groundwater levels. As the groundwater level dropped, some zones with residual contaminant mass in the bedrock matrix no longer contributed to the dissolved-phase contamination, resulting in decreases in contaminant concentrations. It should be noted that geochemical conditions observed at RD-23, RD-64, and RD-65 during the baseline contaminant attenuation potential sampling event were indicative of nitrate-reduction. Therefore, it is possible that geochemical conditions conductive to TCE's biologically-mediated degradation to cis-1,2-DCE have been sustained at these locations and/or decreases in groundwater levels resulted in reduced flux of aerobic water entering these boreholes. RD-07 was the exception to the aforementioned observations; TCE and cis-1,2-DCE concentrations observed during the pre-FLUTe era was re-established following removal of the liners.

In general, VC has not been frequently encountered in groundwater samples collected at the Site. Given the chemical's high volatility and the great depths associated with many of the onsite monitoring location, it is possible that a significant amount of VC is lost during groundwater sampling via volatilization and/or oxidation. Groundwater pumping and periodic groundwater sample collection were recently performed at several wells including RS-54 and C-21 (about 150 feet north of RS-54). Results from the groundwater samples collected during active pumping indicated that VC is present in bedrock fractures at the SSFL Area IV, albeit at low concentrations (generally less than 10 μg/L). It is likely that more formation-representative groundwater samples containing higher VC concentrations are captured during active pumping at high flow rates than during low-flow groundwater sampling. The presence of VC in these groundwater samples represents another line of evidence that complete dechlorination of parent chlorinated compounds PCE and TCE is occurring at the SSFL Area IV.

Chlorinated ethanes

Significant concentrations of chlorinated ethanes were only observed at monitoring location RD-65 and thus the discussion presented herein only revolves around RD-65. Unlike the chlorinated ethenes, no reversal in concentration trends attributable to FLUTe liner installation and removal were observed for chlorinated ethanes such as TCA and its breakdown product 1,1-DCE. This is likely because unlike TCE, TCA can be readily degraded to 1,1-DCE abiotically and under aerobic conditions. Therefore, the rate and extent of contaminant degradation of TCA were not as susceptible to changes in geochemical conditions compared to more recalcitrant chlorinated VOCs such as TCE. 1,1-DCE may be subject to further degradation to ethene and ethane via cometabolic and/or aerobic degradation pathways but the degradation rates associated with such processes are very slow. It should be noted that 1,1-DCE concentrations in all monitoring locations sampled during the baseline contaminant attenuation potential sampling event were below its California's Maximum Contaminant Level of 7 µg/L.

Unlike most other wells onsite, elevated TCA and TCE concentrations as high as approximately 15,000 and 5,000 µg/L, respectively, were observed historically at RS-54. The ratio of TCA to TCE remained relatively unchanged over time (around 3), indicating that a nearby source is attributable to the high VOC concentrations observed at RS-54. This relatively constant ratio of TCA to TCE observed at RS-54 with respect to time may likely be attributable to 1) the TCA contaminant source mass in the vicinity of RS-54 is much larger than that related to TCE and 2) TCA does not sorb to organic-rich materials such as silt and clay at as high of a propensity as TCE and thus TCA exists at much higher dissolved phase concentrations. On the other hand, the ratio of TCA to its degradation daughter product 1,1-DCE decreased significantly with respect to time at this location, confirming that TCA can be readily degraded to 1,1-DCE regardless of geochemical conditions that may be subject to change based on groundwater elevations. The lateral extent of TCA and TCE contamination in the downgradient area is also interesting. The TCA groundwater plume is very limited aerially, as shown in **Figure 5.1-4**, which confirms the rapid degradation of TCA away from the source area. On the other hand, the TCE plume is much more extensive, as shown in **Figure 5.1-2**, which confirms that TCE is much more recalcitrant than TCA and can only be degraded under select geochemical conditions.

D.6 Overall Assessment and Path Forward

Overall, results from this baseline attenuation assessment sampling event suggests that reductive dechlorination and cometabolism may be active attenuation mechanisms at the Site. Detections of VC in groundwater samples recently collected at RS-54 and C-21 during active pumping provide a strong evidence that complete dechlorination of the chlorinated ethenes is occurring at the SSFL Area IV. Note that the sampling performed in the fall of 2016 was intended to provide a snapshot of the baseline conditions at the Site; additional monitoring should be completed following the same protocol to determine trends in contaminants and supporting evidence. Advanced analytical techniques including the use of activity-dependent enzyme probes can also be employed in future sampling efforts to further assess the role of cometabolism in attenuating Site contaminants. In addition, considering that VC detections were observed in samples collected during active pumping and were generally absent in samples collected via low-flow sampling, additional sampling under the same hydraulic influence should be considered at other wells of interest at the SSFL Area IV to obtain a better understanding of the fate of groundwater contaminants in bedrock fractures, which may be not fully captured in samples collected using Snap Samplers or low-flow groundwater sampling.

Table D-1. Details Associated with the Baseline Contaminant Attenuation Potential Assessment Sampling Event
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sample ID	Sample type	Sampling date	RTI Laboratories					Pace Analytical Services				Microbial insights	
				VOCs	TOC	Sulfide	Alkalinity	Anions	MEE	Acetylene	CSIA	Hydrogen	DNA	mRNA
DD-144	DD-144_102616_01_L	Field sample	10/26/2016	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
DD-144	DD-144_102616_36_L	Duplicate sample	10/26/2016	✓	✓	✓	✓	✓	✓	✓	✓			
-	TB-102616	Trip blank	10/26/2016	✓										
RD-90	RD-90_102716_01_L	Field sample	10/27/2016	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
RD-07	RD-07_102716_01_L	Field sample	10/27/2016	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RD-07	RD-07_102716_06_L	MS/MSD	10/27/2016	✓					✓	✓				
-	TB-102716	Trip blank	10/27/2016	✓										
RD-65	RD-65_103116_01_L	Field sample	10/31/2016	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RD-65	RD-65_103116_06_L	MS/MSD	10/31/2016	✓					✓	✓				
RD-23	RD-23_103116_01_L	Field sample	10/31/2016	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
PZ-109	PZ-109_110116_01_L	Field sample	11/1/2016	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
RD-64	RD-64_110216_01_L	Field sample	11/2/2016	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
-	TB-110216	Trip blank	11/2/2016	✓										
-	EB-110216	Equipment blank	11/2/2016	✓										

***_Notes_** :

- ID: identification
- CSIA: compound-specific isotopic analysis
- DNA: deoxyribonucleic acid
- MEE: methane, ethane, ethene
- mRNA: messenger ribonucleic acid
- MS: matrix spike
- MSD: matrix spike duplicate
- TOC: total organic carbon
- VOC: volatile organic compound

Table D-2. Comparisons of VOC Results and RPDs Using Snap Samplers Vs. Low-Flow Sampling Methodology
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	**Contaminant concentration (µg/L)**					**RPD (%)**					**Average RPD (%)**
	PCE	**TCE**	**cis-1,2-DCE**	**trans-1,2-DCE**	**VC**	**PCE**	**TCE**	**cis-1,2-DCE**	**trans-1,2-DCE**	**VC**	
DD-144_102616_01_L	*5U*	190	16	*5U*	*5U*	*NA*	188%	191%	*NA*	*NA*	190%
DD-144_102616_01_L	*1U*	5.8	5.5	*2U*	*1U*						
PZ-109_110116_01_L	70	6.5	1.5J	*2U*	*2U*	18%	6%	14%	*NA*	*NA*	13%
PZ-109-110116_01_L	84	6.9	1.3	*1U*	*1U*						
RD-07_102716_01_L	*2U*	47	3.4	*2U*	*2U*	*NA*	4%	62%	*NA*	*NA*	33%
RD-07_102716_01_L	*1U*	45	2.1	*1U*	*1U*						
RD-23_103116_01_L	*1U*	22	2.1	2.3	*1U*	*NA*	29%	11%	26%	*NA*	22%
RD-23-103116_01_L	*1U*	31	1.9	3.1	*1U*						
RD-64_110216_01_L	*0.2U*	32	9	0.6J	*0.1U*	*NA*	3%	38%	12%	*NA*	18%
RD-64_110216_01_L	*1U*	31	6.1	0.53J	*1U*						
RD-65_103116_01_L	*1U*	4.1	3.9	4.8	*1U*	*NA*	46%	30%	50%	*NA*	42%
RD-65-103116_01_L	*1U*	7.6	3	3.2	*1U*						
RD-90_102716_01_L	*1U*	*1U*	*1U*	*1U*	*1U*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*
RD-90_102716_01_L	*1U*	*1U*	*1U*	*1U*	*1U*						
Average RPD (%) excluding DD_144						18%	18%	31%	29%	*NA*	

****Notes*** :

- %: percent
- cis-1,2-DCE: cis-1,2-dichloroethene
- J: estimated value
- NA: not applicable
- PCE: tetrachloroethene
- RPD: relative percent difference
- TCE: trichloroethene
- trans-1,2-DCE: trans-1,2-dichloroethene
- U: below detection limit
- VC: vinyl chloride
- Snap sampling results
- Low-flow sampling results
- Non-detect or non-applicable

Table D-3. Summary of Contaminant Attenuation Potential Assessment Results by Screening Criteria
Santa Susana Field Laboratory
Ventura County, California

Area	Monitoring location	Type	Adequate TOC to Promote Biologically-Mediated Attenuation Reactions	Evidence of Redox Conditions Conducive to Dechlorination	Evidence of Biologically-Mediated Dechlorination	Evidence of Destructive Contaminant Attenuation (CSIA)	Dechlorinating Bacteria Presence in Adequate Populations (DNA)	Adequate Enzyme Activity of Dechlorinating Bacteria (mRNA)	Cometabolic Bacteria Presence in Adequate Populations (DNA)	Adequate Enzyme Activity of Cometabolic Bacteria (mRNA)	Overall Conclusion
Building 56 Landfill	RD-07	Open borehole	**Limited** TOC was less than 10 mg/L over the entire saturated zone but elevated TOC may exist at discrete depth intervals.	**Limited** Likely in portions of the formation. Ferrous iron present, hydrogen detected, ORP and DO low, but no methane and sulfate is detected.	**Limited** Cis-DCE present but not VC or ethene. Elevated cis-DCE observed historically.	**Limited** Cis-DCE value more negative (“lighter”) than TCE value indicates it is a degradation product of TCE; further cis-DCE degradation likely not occurring.	**Limited** DSM (able to degrade TCE to cis-DCE only) highest population.	**Yes** DHBt elevated; DHC and DSM detected.	**Limited** Low detections of various enzymes.	**Limited** Low detections of PMMO, PHE.	Reducing conditions likely present in portions of borehole. Detections of DCE (current and historic) indicate dechlorination. Cometabolism likely limited.
FSDF	RD-23	Open borehole	**Limited** TOC was less than 10 mg/L over the entire saturated zone but elevated TOC may exist at discrete depth intervals.	**Yes** Likely in portions of the formation. Nitrate below detection, hydrogen elevated, low methane detection.	**Yes** Cis-, trans-, and 1,1-DCE detected, ethene detected (low).	**Limited** Cis-DCE value more negative (“lighter”) than TCE value indicates it is a degradation product of TCE; further cis-DCE degradation may not be occurring.	**Limited** DSM (able to degrade TCE to cis-DCE only) highest population; DHC and functional genes detected although at low populations.	**Yes** DHBt elevated; DHC and DSM detected.	**Limited** Low detections of various enzymes.	**No** Very low detection of PMMO only.	Lack of nitrate and high hydrogen indicates portions of formation are reducing. Presence of DCE isomers as well as DHC and functional genes indicate dechlorination has occurred. Poor evidence for cometabolism.
FSDF	RD-64	Open borehole	**Limited** TOC was less than 10 mg/L over the entire saturated zone but elevated TOC may exist at discrete depth intervals.	**Limited** Nitrate low, no hydrogen or methane detected, DO and sulfate are slightly elevated.	**Limited** Cis- and trans-DCE detected, but not VC or ethene. Higher cis-DCE and VC were observed during FLUTe.	**Limited** Cis-DCE value more negative (“lighter”) than TCE value indicates it is a degradation product of TCE; further cis-DCE degradation may not be occurring.	**Limited** DHBt and DSM (able to degrade TCE to cis-DCE only) highest populations; DHC detected at very low populations.	**Yes** DHBt and DSM elevated; DHC and DSB detected.	**Limited** Low detections of various enzymes.	**Limited** Low detections of PMMO, RDEG.	Low nitrate and high hydrogen indicates portions of formation are reducing. Presence of DCE isomers and elevated mRNA for dechlorinators indicate degradation. Cometabolism likely limited.
FSDF	RD-65	Open borehole	**Limited** TOC was less than 10 mg/L over the entire saturated zone but elevated TOC may exist at discrete depth intervals.	**Yes** Negative ORP, nitrate below detection, sulfate lower, methane concentration highest of wells sampled, and hydrogen detected at elevated concentration.	**Yes** Cis-, trans-, and 1,1-DCE detected, ethene detected (low).	**Yes** TCE value least negative (“heaviest”) at site indicates most degraded of the TCE still detected; cis-DCE value more negative (“lighter”) greater than TCE value indicates it is a degradation product of TCE.	**Moderate** DHBt and DSM (able to degrade TCE to cis-DCE only) highest observed of wells sampled; DHC and DSB also detected at lower populations	**Yes** DHBt and DSM elevated; DHC with functional genes present.	**Moderate** Low detections of various enzymes, but sMMO is an order of magnitude higher than other wells.	**Limited** Low detections of PMMO, SMMO.	Redox parameters indicate reducing conditions present in considerable portion of the borehole. High enzyme activity indicates dechlorinators are active. Presence of DHC with functional genes indicates complete dechlorination possible, but population is insufficient.
HMSF	DD-144	Open borehole	**Limited** TOC was less than 10 mg/L over the entire saturated zone but elevated TOC may exist at discrete depth intervals.	**Limited** ORP indicates strongly reducing conditions, although nitrate and sulfate still present. Minor methane detection but hydrogen was not detected	**Yes** Cis-DCE, ethane, and ethene detected.	**Limited** Cis-DCE value more negative (“lighter”) than TCE value indicates it is a degradation product of TCE; further cis-DCE degradation may not be occurring.	**Limited** DHBt and DSM (able to degrade TCE to cis-DCE only) highest populations; DHC and DSB detected at low populations.	**Yes** DHBt and DSM elevated; DHC detected.	**Limited** Low detections of various enzymes.	**No** No detections	Redox parameters indicate reducing conditions present in considerable portions of borehole. Degradation products indicate dechlorination is occurring. Presence of ethene and ethane suggests complete dechlorination is occurring although DHC and functional genes not present/not high populations.
Buildings 4057/ 4059/ 4626	PZ-109	Piezometer	**No** TOC was less than 10 mg/L.	**Limited** Elevated ORP; DO, nitrate, and sulfate are low but do not indicate reduction as much as other wells. Low detection of methane suggests some section of borehole may have reducing conditions.	**Limited** PCE is parent compound, and presence of TCE, cis-DCE, and low detections of ethane and ethene indicate dechlorination has occurred.	**Limited** TCE value is considerably more negative (lighter) than cis-DCE value, suggesting it may be a product of PCE reduction.	**Moderate** DHBt, DSB, and DSM (able to degrade TCE to cis-DCE only) all present at reasonable populations; highest observed of wells sampled; DHC also detected at lower populations.	**Yes** DHBt and DSM elevated; DHC and DSB also present.	**Yes** PHE and RDEG present at elevated levels; various other enzymes detected; overall highest detections for microbial DNA.	**Moderate** Detection of various enzymes including moderately high values for PHE and RDEG.	Reducing conditions do not appear as evident as at other wells, but dechlorination has occurred and appropriate bacteria/enzymes are present for either reductive dechlorination to DCE or cometabolism. Shallowness of well may be reason for more aerobic condition.
Tritium Plume	RD-90 (background well)	Open borehole	**Limited** TOC was less than 10 mg/L over the entire saturated zone but elevated TOC may exist at discrete depth intervals.	**Limited** ORP is elevated, suggesting aerobic conditions; DO, nitrate, and sulfate are low but do not indicate reduction as much as other wells. Low detection of methane suggests some section of borehole may have reducing conditions.	**No** 1,1-DCE is only compound detected; minor detections of ethane and ethene present.	**Not applicable**	**Limited** DSM present, low populations of DHC, DHBt, and DSB detected.	**No** Limited populations of DHC, DHBt, and DSM detected.	**Limited** Low detections of various enzymes.	**Limited** Low detections of PMMO, RDEG.	Background well. Redox conditions suggest that small portions of formation may be reducing. Bacteria/ enzyme data suggests that populations are widespread at the site regardless of contaminants.

*__Notes__ :
- CSIA: compound-specific isotopic analysis
- DCE: dichloroethene
- DO: dissolved oxygen
- mg/L: milligram per liter
- ORP: oxidation-reduction potential
- PCE: tetrachloroethene
- TCE: trichloroethene
- TOC: Total organic carbon
- VC: vinyl chloride

Reductive dechlorination:
- BVC: BAV1 vinyl chloride reductase
- CFR: Chloroform reductase
- DCA: 1,1 DCA Reductase
- DCAR: 1,2 DCA Reductase
- DCM: Dehalobacter DCM
- DECO: Dehalobium chlorocoercia
- DHBt: Dehalobacter spp.
- DHC: Dehalococcoides spp.
- DHG: Dehalogenimonas spp.
- DSB: Desulfitobacterium spp.
- DSM: Desulfuromonas spp.
- TCE: tceA Reductase
- VCR: vinyl chloride reductase

Aerobic (co)metabolism:
- DCMA: Dichloromethane dehalogenase
- EtnC: Ethene Monooxygenase
- EtnE: Epoxyalkane transferase
- PHE: Phenol Hydroxylase
- PMMP: Particulate Methane Monooxygenase
- RDEG: Toluene Monooxygenase 2
- RMO: Toluene Monooyxgenase
- SMMO: Soluble Methane Monooxygenase
- TCBO: Trichlorobenzene Dioxygenase
- TOD: Toluene Dioxygenase

Others:
- APS: Sulfate-reducing bacteria
- EBAC: Total Eubacteria
- MGN: methanogens

Table D-4. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Microbiological Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sampling date	QuantArray												
		Reductive Dechlorination												
		DHC	**TCE**	**BVC**	**VCR**	**DHBt**	**DCM**	**DHG**	**DSB**	**DECO**	**DSM**	**CFR**	**DCA**	**DCAR**
		cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL
DD-144	10/26/2016	*7.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*2.03E+03*	*< 5.00E+00*	*< 5.00E+00*	*1.57E+02*	*4.24E+02*	*5.36E+03*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*
PZ-109	11/1/2016	*3.32E+01*	*< 5.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*1.01E+03*	*< 5.00E+00*	*2.16E+03*	*3.80E+03*	*1.53E+03*	*1.64E+04*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*
RD-07	10/27/2016	*5.00E-01 J*	*< 5.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*9.90E+00*	*1.00E-01 J*	*< 5.00E+00*	*1.07E+01*	*2.83E+01*	*1.53E+03*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*
RD-23	10/31/2016	*9.00E-01*	*2.00E-01 J*	*4.00E-01 J*	*< 5.00E-01*	*1.43E+02*	*< 5.00E+00*	*< 5.00E+00*	*1.07E+01*	*9.32E+01*	*2.43E+03*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*
RD-64	11/2/2016	*2.00E-01 J*	*< 5.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*1.80E+03*	*< 5.00E+00*	*< 5.00E+00*	*5.10E+02*	*2.15E+02*	*1.30E+03*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*
RD-65	10/31/2016	*6.60E+00*	*< 5.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*4.03E+04*	*< 5.00E+00*	*2.66E+04*	*3.05E+03*	*3.50E+02*	*1.78E+04*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*
RD-90	10/27/2016	*3.00E-01 J*	*< 5.00E-01*	*< 5.00E-01*	*< 5.00E-01*	*7.00E+00*	*< 5.00E+00*	*< 5.00E+00*	*1.07E+01*	*< 5.00E+00*	*4.37E+03*	*< 5.00E+00*	*< 5.00E+00*	*< 5.00E+00*

****Notes***:
- cells/mL: cells per milliliter
- J: estimated value

Reductive dechlorination:
- BVC: BAV1 vinyl chloride reductase
- CFR: Chloroform reductase
- DCA: 1,1 DCA Reductase
- DCAR: 1,2 DCA Reductase
- DCM: Dehalobacter DCM
- DECO: Dehalobium chlorocoercia
- DHBt: Dehalobacter spp.
- DHC: Dehalococcoides spp.
- DHG: Dehalogenimonas spp.
- DSB: Desulfitobacterium spp.
- DSM: Desulfuromonas spp.
- TCE: tceA Reductase
- VCR: vinyl chloride reductase

Aerobic (co)metabolism:
- DCMA: Dichloromethane dehalogenase
- EtnC: Ethene Monooxygenase
- EtnE: Epoxyalkane transferase
- PHE: Phenol Hydroxylase
- PMMP: Particulate Methane Monooxygenase
- RDEG: Toluene Monooxygenase 2
- RMO: Toluene Monooyxgenase
- SMMO: Soluble Methane Monooxygenase
- TCBO: Trichlorobenzene Dioxygenase
- TOD: Toluene Dioxygenase

Others:
- APS: Sulfate-reducing bacteria
- EBAC: Total Eubacteria
- MGN: methanogens

Table D-4. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Microbiological Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sampling date	QuantArray												
		Aerobic (Co)Metabolic										Other		
		SMMO	PMMO	TOD	PHE	TCBO	RDEG	RMO	EtnC	EtnE	DCMA	EBAC	APS	MGN
		cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL
DD-144	10/26/2016	2.78E+02	2.74E+01	2.69E+01	8.61E+01	< 5.00E+00	1.69E+01	3.98E+01	< 5.00E+00	< 5.00E+00	< 5.00E+00	2.75E+05	1.52E+05	2.26E+01
PZ-109	11/1/2016	1.05E+02	2.31E+01	2.74E+01	1.20E+04	1.56E+02	1.16E+04	4.70E+00 J	3.02E+01	3.65E+02	< 5.00E+00	1.07E+06	2.57E+05	2.02E+01
RD-07	10/27/2016	6.61E+01	1.92E+02	6.80E+00	1.43E+02	< 5.00E+00	3.89E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	8.25E+04	2.04E+04	5.20E+00
RD-23	10/31/2016	1.56E+02	3.77E+01	2.03E+01	8.76E+02	< 5.00E+00	1.06E+03	3.95E+01	6.80E+00	< 5.00E+00	< 5.00E+00	1.00E+05	7.55E+04	2.19E+01
RD-64	11/2/2016	4.59E+02	3.22E+01	4.08E+01	1.23E+03	< 5.00E+00	7.87E+02	5.00E-01 J	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.76E+06	7.36E+05	4.50E+00 J
RD-65	10/31/2016	5.03E+03	3.87E+01	4.06E+01	3.71E+03	< 5.00E+00	1.72E+02	8.32E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.61E+06	6.82E+05	1.33E+01
RD-90	10/27/2016	8.20E+00	7.20E+00	7.00E-01 J	1.19E+02	< 5.00E+00	1.10E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	7.21E+04	1.84E+04	6.00E-01 J

****Notes***:
- cells/mL: cells per milliliter
- J: estimated value

Reductive dechlorination:
- BVC: BAV1 vinyl chloride reductase
- CFR: Chloroform reductase
- DCA: 1,1 DCA Reductase
- DCAR: 1,2 DCA Reductase
- DCM: Dehalobacter DCM
- DECO: Dehalobium chlorocoercia
- DHBt: Dehalobacter spp.
- DHC: Dehalococcoides spp.
- DHG: Dehalogenimonas spp.
- DSB: Desulfitobacterium spp.
- DSM: Desulfuromonas spp.
- TCE: tceA Reductase
- VCR: vinyl chloride reductase

Aerobic (co)metabolism:
- DCMA: Dichloromethane dehalogenase
- EtnC: Ethene Monooxygenase
- EtnE: Epoxyalkane transferase
- PHE: Phenol Hydroxylase
- PMMP: Particulate Methane Monooxygenase
- RDEG: Toluene Monooxygenase 2
- RMO: Toluene Monooyxgenase
- SMMO: Soluble Methane Monooxygenase
- TCBO: Trichlorobenzene Dioxygenase
- TOD: Toluene Dioxygenase

Others:
- APS: Sulfate-reducing bacteria
- EBAC: Total Eubacteria
- MGN: methanogens

Table D-4. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Microbiological Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sampling date	mRNA												
		Reductive Dechlorination												
		DHC	TCE	BVC	VCR	DHBt	DCM	DHG	DSB	DECO	DSM	CFR	DCA	DCAR
		gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL
DD-144	10/26/2016	1.24E+02	< 5.00E-01	< 5.00E-01	< 5.00E-01	9.38E+05	< 5.00E+00	< 5.00E+00	< 5.00E+00	9.94E+01	1.66E+04	< 5.00E+00	< 5.00E+00	< 5.00E+00
PZ-109	11/1/2016	3.08E+03	< 5.00E-01	< 5.00E-01	< 5.00E-01	1.29E+05	< 5.00E+00	6.28E+02	2.39E+04	6.49E+03	1.45E+05	< 5.00E+00	< 5.00E+00	< 5.00E+00
RD-07	10/27/2016	1.15E+02	< 5.00E-01	< 5.00E-01	< 5.00E-01	1.36E+04	1.04E+01	< 5.00E+00	< 5.00E+00	2.52E+02	8.96E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00
RD-23	10/31/2016	1.22E+01	< 5.00E-01	< 5.00E-01	< 5.00E-01	1.76E+05	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.34E+02	1.04E+03	< 5.00E+00	< 5.00E+00	< 5.00E+00
RD-64	11/2/2016	2.22E+01	< 5.00E-01	< 5.00E-01	< 5.00E-01	2.83E+06	< 5.00E+00	< 5.00E+00	4.49E+03	3.34E+03	5.60E+04	< 5.00E+00	< 5.00E+00	< 5.00E+00
RD-65	10/31/2016	7.58E+03	1.13E+01	8.00E-01	< 5.00E-01	1.42E+06	< 5.00E+00	< 5.00E+00	< 5.00E+00	6.67E+01	1.58E+05	< 5.00E+00	< 5.00E+00	< 5.00E+00
RD-90	10/27/2016	1.44E+02	< 5.00E-01	< 5.00E-01	< 5.00E-01	7.49E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.19E+03	< 5.00E+00	< 5.00E+00	< 5.00E+00

****Notes*** :
- cells/mL: cells per milliliter
- J: estimated value

Reductive dechlorination:
- BVC: BAV1 vinyl chloride reductase
- CFR: Chloroform reductase
- DCA: 1,1 DCA Reductase
- DCAR: 1,2 DCA Reductase
- DCM: Dehalobacter DCM
- DECO: Dehalobium chlorocoercia
- DHBt: Dehalobacter spp.
- DHC: Dehalococcoides spp.
- DHG: Dehalogenimonas spp.
- DSB: Desulfitobacterium spp.
- DSM: Desulfuromonas spp.
- TCE: tceA Reductase
- VCR: vinyl chloride reductase

Aerobic (co)metabolism:
- DCMA: Dichloromethane dehalogenase
- EtnC: Ethene Monooxygenase
- EtnE: Epoxyalkane transferase
- PHE: Phenol Hydroxylase
- PMMP: Particulate Methane Monooxygenase
- RDEG: Toluene Monooxygenase 2
- RMO: Toluene Monooyxgenase
- SMMO: Soluble Methane Monooxygenase
- TCBO: Trichlorobenzene Dioxygenase
- TOD: Toluene Dioxygenase

Others:
- APS: Sulfate-reducing bacteria
- EBAC: Total Eubacteria
- MGN: methanogens

Table D-4. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Microbiological Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sampling date	mRNA												
		Aerobic (Co)Metabolic										Other		
		SMMO	PMMO	TOD	PHE	TCBO	RDEG	RMO	EtnC	EtnE	DCMA	EBAC	APS	MGN
		gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL	gene copies/mL
DD-144	10/26/2016	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	6.15E+07	2.00E+00 J	< 5.00E+00
PZ-109	11/1/2016	8.90E+00	2.90E+01	1.00E+00 J	2.96E+02	< 5.00E+00	4.19E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	3.73E+08	1.80E+00 J	1.44E+02
RD-07	10/27/2016	< 5.00E+00	1.33E+02	< 5.00E+00	2.43E+01	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	9.07E+06	< 5.00E+00	< 5.00E+00
RD-23	10/31/2016	< 5.00E+00	8.10E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	6.79E+07	< 5.00E+00	< 5.00E+00
RD-64	11/2/2016	< 5.00E+00	3.22E+01	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.11E+02	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	2.35E+08	3.60E+00 J	7.90E+00
RD-65	10/31/2016	9.65E+01	3.86E+01	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.18E+09	< 5.00E+00	2.92E+01
RD-90	10/27/2016	< 5.00E+00	5.60E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.69E+01	< 5.00E+00	< 5.00E+00	< 5.00E+00	< 5.00E+00	1.21E+07	< 5.00E+00	< 5.00E+00

*<u>**Notes**</u> :
- cells/mL: cells per milliliter
- J: estimated value

Reductive dechlorination:
- BVC: BAV1 vinyl chloride reductase
- CFR: Chloroform reductase
- DCA: 1,1 DCA Reductase
- DCAR: 1,2 DCA Reductase
- DCM: Dehalobacter DCM
- DECO: Dehalobium chlorocoercia
- DHBt: Dehalobacter spp.
- DHC: Dehalococcoides spp.
- DHG: Dehalogenimonas spp.
- DSB: Desulfitobacterium spp.
- DSM: Desulfuromonas spp.
- TCE: tceA Reductase
- VCR: vinyl chloride reductase

Aerobic (co)metabolism:
- DCMA: Dichloromethane dehalogenase
- EtnC: Ethene Monooxygenase
- EtnE: Epoxyalkane transferase
- PHE: Phenol Hydroxylase
- PMMP: Particulate Methane Monooxygenase
- RDEG: Toluene Monooxygenase 2
- RMO: Toluene Monooyxgenase
- SMMO: Soluble Methane Monooxygenase
- TCBO: Trichlorobenzene Dioxygenase
- TOD: Toluene Dioxygenase

Others:
- APS: Sulfate-reducing bacteria
- EBAC: Total Eubacteria
- MGN: methanogens

Table D-5. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Pertinent Geochemical and Contaminant Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sampling date	Geochemical parameters											
		pH	**Total Alk**	**Conductivity**	**TOC**	**ORP**	**DO**	**Nitrate as N**	**Ferrous iron**	**Sulfate**	**Sulfide**	**Methane**	**Hydrogen**
		SU	mg/L CaCO3	µS/cm	mg/L	mV	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	nM
DD-144	10/26/2016	7.09	330	1013	1.4 J	-174.5	0.92	2.60	0.10	110	< 0.1	1.3	2.6
PZ-109	11/1/2016	7.17	530	1242	4	166.9	1.33	3.90	0.05	110	< 0.1	0.99	#N/A
RD-07	10/27/2016	7.14	250	713	0.68 J	43.8	1.93	1.50	0.16	72 J	< 0.1	0.059 J	2.1
RD-23	10/31/2016	7.52	210	665	0.74 J	61.7	2.38	< 0.25	0.01	78	< 0.1	0.19 J	16
RD-64	11/2/2016	6.77	250	959	1.2 J	98.7	2.74	0.12	0.01	120	< 0.1	0.23 J	12
RD-65	10/31/2016	6.84	210	518	1.7 J	-57.2	1.86	< 0.25	0.01	42	< 0.1	26	4.2
RD-90	10/27/2016	6.96	330	1154	1.2 J	135.7	1.64	0.86	0.04	130	< 0.1	0.096 J	#N/A

Table D-5. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Pertinent Geochemical and Contaminant Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	Sampling date	Chlorinated ethene/ethane and daughter products							
		PCE	TCE	cis-1,2-DCE	trans-1,2-DCE	VC	1,1,2,2-PCA	1,1,2-TCA	1,1-DCE
		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
DD-144	10/26/2016	< 1	5.8	5.5	< 1	< 1	< 1	< 1	< 1
PZ-109	11/1/2016	84	6.9	1.3	< 1	< 1	< 1	< 1	< 1
RD-07	10/27/2016	< 1	45	2.6	< 1	< 1	< 1	< 1	< 1
RD-23	10/31/2016	< 1	31	1.9	3	< 1	< 1	< 1	0.71 J
RD-64	11/2/2016	< 1	31	6.1	0.53 J	< 1	< 1	< 1	< 1
RD-65	10/31/2016	< 1	7.6	3	3.2	< 1	< 1	< 1	3.5
RD-90	10/27/2016	< 1	< 1	< 1	< 1	< 1	< 1	< 1	7.8

Table D-5. Contaminant Attenuation Potential Assessment Baseline Sampling Event - Pertinent Geochemical and Contaminant Results
Santa Susana Field Laboratory
Ventura County, California

Monitoring location	**Sampling date**				CSIA		
		Chloroethane	**Ethane**	**Ethene**	**Delle - TCE**	**Delle - DCE**	**Delle - VC**
		µg/L	µg/L	µg/L	‰	‰	‰
DD-144	10/26/2016	*< 2*	*3.4*	*4.2*	*-26.23*	*-31.65*	*U*
PZ-109	11/1/2016	*< 2*	*0.015 J*	*0.068 J*	*-37.92*	*-18.25*	*U*
RD-07	10/27/2016	*< 2*	*< 0.1*	*< 0.1*	*-22.37*	*-27.30*	*U*
RD-23	10/31/2016	*< 2*	*< 0.1*	*0.029 J*	*-17.64*	*-26.78*	*U*
RD-64	11/2/2016	*< 2*	*0.0072 J*	*0.0094 J*	*-19.12*	*-25.73*	*U*
RD-65	10/31/2016	*< 2*	*< 0.1*	*0.018 J*	*-15.46*	*-23.95*	*U*
RD-90	10/27/2016	*< 2*	*0.011 J*	*0.024 J*	*U*	*U*	*U*

****Notes*** :

- #N/A: not available
- µg/L: microgram per liter
- µS/cm: microSiemen per centimeter
- ‰: part per thousand
- 1,1,2,2-PCA: 1,1,2,2-tetrachloroethane
- 1,1,2-TCA: 1,1,2-trichloethane
- 1,1-DCE: 1,1-2dichloroethene
- Alk: alkalinity
- cis-1,2-DCE: cis-1,2-dichloroethene
- CSIA: compound-specific isotopic analysis
- DO: dissolved oxygen
- ID: identification
- J: estimated value
- mg/L: milligram per liter
- N: nitrogen
- nM: nanoMolar
- ORP: oxidation-reduction potential
- PCE: tetrachloroethene
- SU: standard unit
- TCE: trichloroethene
- TOC: total organic carbon
- trans-1,2-DCE: trans-1,2-dichloroethene
- U: below detection limit
- VC: vinyl chloride