Technical Memorandum:
ISB Phase I and ISCO Phase II Results and Downgradient Area Pilot Study Work Plan

GEORGETOWN FACILITY

SEATTLE, WASHINGTON

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Prepared by:

DALTON, OLMSTED, & FUGLEVAND
10827 NE 68th St., Suite B
Kirkland, Washington 98033

Prepared for:

STERICYCLE ENVIRONMENTAL SOLUTIONS
CORRECTIVE ACTION GROUP
18000 72nd Avenue South, Suite 217
Kent, WA 98032
(425) 227-6149

DALTON
OLMSTED
FUGLEVAND

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1.0 INTRODUCTION

Dalton, Olmsted, and Fuglevand, Inc. (DOF), has prepared this In-Situ Bioremediation (ISB) Phase I and In-Situ Chemical Oxidation (ISCO) Phase II Results Summary and Downgradient Area Pilot Study Work Plan on behalf of Stericycle Environmental Solutions, Inc. (Stericycle). This memorandum is for the closed Stericycle facility (the site) located in the Georgetown area of Seattle, Washington (Figure 1), with corrective actions regulated under the Washington State Department of Ecology (Ecology) Agreed Order DE 7347. This memorandum addresses the next steps in Stericycle's obligations to implement a contingent remedy for 1,4-dioxane in groundwater for the area downgradient of the site (Figure 2), as outlined in the Agreed Order (AO) DE7347, the 1,4-Dioxane Remediation Approach Focused Feasibility Study (FFS) (AMEC, 2015b), the 1,4-Dioxane Remedial Design/Remedial Action Work Plan [RD/RA Work Plan] (AMEC, 2015a), and the Revised ISCO Pilot Study Work Plan (DOF and AMEC, 2016).

The RD/RA Work Plan originally proposed four phases of work: Phase I included bench scale studies for both ISCO and ISB, Phase II included in-situ pilot scale work for both (if necessary), Phase III was full scale implementation for both (if necessary), and Phase IV was implementation reporting. ISB was recognized as an emerging technology for 1,4-dioxane remediation, with the potential that bench or pilot results would show ISB was not favorable to use onsite. Further ISB implementation would cease if that became clear.

Phase I for ISB is complete, this memorandum summarizes results from the ISB Phase I bench scale study. The results from ISB Phase I showed bioremediation of 1,4-dioxane is possible; therefore, ISB will proceed to Phase II. This memorandum includes the work plan for in-situ pilot study of ISB.

Phase I for ISCO was previously completed and reported in the Revised ISCO Pilot Study Work Plan. This memorandum provides the results of the Phase II in-situ pilot study, and ideally this should have completed ISCO Phase II. However, the results of the ISCO pilot study were different than anticipated in the RD/RA Work Plan. Stericycle representatives met with Ecology on September 21, 2016 to discuss next steps. During this meeting Ecology agreed to further pilot study for both ISB and ISCO, and to delay the full scale work plan for ISCO (Phase III) until pilot studies for both technologies could be completed.

During this meeting Ecology also agreed that Stericycle could combine reports for ISB and ISCO into this single memorandum, which includes final validated data collected as part of the ISCO pilot study, including additional monitoring results collected after the meeting with Ecology.

In summary, the following information is covered in this document:

- A summary of the Phase I ISB bench scale results from the Sentinel Group and their effect on implementation of ISB for the downgradient area.
- Results and findings from the Phase II ISCO pilot scale study and their effect on implementation of ISCO for the downgradient area.
- A Work Plan for further pilot testing of both ISB and ISCO technologies in the downgradient area.

The project description, regulatory background, site history, site characterization, and site conditions are described in the Revised Engineering Design Report (EDR) (AMEC Geomatrix, 2011) and are not repeated here. An overview of the cleanup measure and the AO requirements were presented in the RD/RA Work Plan, and are not repeated here. The definitions of terminology and the abbreviations and acronyms used in this Work Plan are those described in the EDR and the RD/RA Work Plan.

2.0 PHASE I ISB BENCH SCALE STUDY RESULTS

Several studies were published in the last five years highlighting that 1,4-dioxane degrades in-situ at industrial sites in North America, counter to the common belief that concentration declines are solely due to dilution and dispersion. The goal of the bench scale study was to determine whether 1,4-dioxane is actively degraded in site groundwater. If verified, the study sought to determine at what rate degradation occurs and what remedial strategies might improve biodegradation of 1,4-dioxane in-situ (including evaluation of biostimulation and bioaugmenation).

The Sentinel Environmental Group (Sentinel), a subsidiary of Rice University, performed the bench scale study and provided their final Bioremediation Treatability Study Report to Stericycle on August 10, 2016. The report was provided to Ecology on August 11, 2016 as part of the 2nd Quarter 2016 Progress Report.

Groundwater and sediment samples from monitoring wells CG-122-60, CG-127-40, CG-134-40, and CG-137-40 were sent to Sentinel for a bench scale microcosm study in April 2015. After 30 weeks of microcosm studies with catabolic gene biomarker analysis, there was no conclusive, statistically significant evidence of sustained 1,4-dioxane biodegradation. There was reduction in 1,4-dioxane concentrations in the CG-122-60 microcosm for several weeks, but degradation stopped before becoming statistically significant. This limited degradation could have been spurred by a an unidentified 1,4-dioxane degrading organism that ran out of a specific nutrient or was limited due to other laboratory conditions incompatible with site specific 1,4-dioxane degraders. As a result, no degradation rate was calculable and biostimulation studies were not performed for the microcosms.

After reviewing the initial results with Sentinel, Stericycle agreed to pursue bioaugmentation studies using the existing microcosms. Once the initial microcosm study was complete, the site soils and groundwater based microcosms were bioaugmented with known 1,4-dioxane degrading bacteria (including strains of bacteria referred to as CB1190 and PH-06). Bioaugmented microcosms showed statistically significant declines in 1,4-dioxane concentrations to well below the proposed cleanup level of 78 part per billion (ppb).

Further testing was performed with oxygen releasing compounds because the field conditions are microaerophilic (dissolved oxygen of typically less than 1 part per million [ppm] Table 1) and the bacteria needs at least some oxygen to degrade 1,4-dioxane. Sentinel evaluated whether oxygen was limiting the ability of the bacteria to break down 1,4-dioxane. Sentinel found that CB1190 survived prolonged periods under anaerobic conditions and the fastest biodegradation occurred under microaerophilic conditions without the addition of oxygen releasing chemicals.

The Stericycle team discussed implementability of bioaugmentation onsite after the release of their August 2016 report. Sentinel provided the following additional details:

- They expect that the bacteria should survive pressures of 10 to 40 pounds per square inch (PSI) during an injection event (this is within the majority of the injection pressures from pilot scale tests for ISCO already completed as noted in Table 2).
- The different strains of 1,4-dioxane degraders have different degradation rates and have varying limits of effectiveness; i.e. typically CB1190 will degrade 1,4-dioxane more quickly, but PH-06 can degrade 1,4-dioxane down to lower overall concentrations.
- Results indicate that a mixture of different 1,4-dioxane degrading cultures may be best for testing in-situ.

Given the promising results Stericycle asked Sentinel to scale up production of 1,4-dioxane degrading bacteria cultures for in-situ pilot scale testing in the downgradient area.

3.0 PHASE II ISCO PILOT STUDY RESULTS

The objective of the ISCO Pilot Study was to provide data to optimize the design of full-scale ISCO implementation adjacent to the CG-127 well cluster, while effectively and safely treating the affected area and depths near the intersection of S. Lucile St. and Maynard Ave. S. adjacent to monitoring well CG-122-60. This section documents how the pilot study was performed, results of the study, and implications for full scale ISCO implementation.

3.1 Field Implementation and Monitoring

The following tasks were conducted prior to performing the pilot study injections of chemical oxidant.

- Stericycle and Ecology performed community outreach via preparation of a public notice that was posted on Ecology’s website and distributed door to door within a one block radius of the pilot study location.
- Semi-permanent groundwater monitoring wells IMW-1 and IMW-2 were installed (Figure 3). Construction and boring logs are included in Attachment A. The wells were installed consistent with the Revised ISCO Pilot Study Work Plan (DOF and AMEC, 2016) except for the screen depth at IMW-1 was set slightly higher, from 47.5 to 57.5 feet below ground surface (bgs) instead of 50-60 feet bgs, due to extreme heaving sand conditions encountered during drilling. Two attempts were required to install the well due to the field conditions.
- On June 21, 2016, baseline groundwater samples were collected consistent with the Work Plan at wells CG-122-60, CG-122-75, IMW-1, and IMW-2 (results are presented in Table 1.)

Injection of persulfate at injection points IP-1 through IP-4 (Figure 3) was conducted on June 23 and 24, 2016. The full design volume of persulfate was injected (1,000 gallons at 8.5% concentration) however drilling conditions at location IP4 were more challenging than the other locations, requiring higher pressures to inject and several drill rods broke during injection. The breakage led to this point receiving a lower volume of persulfate than the other points, though in total, the design volume was attained for the target area. A summary of injection volumes, pressures, and concentrations is included in Table 2, with more detailed information provided on Table 3 (including pressures and flow rates), and the field logging forms are included in Attachment B.

The following monitoring and data collection was conducted as part of the pilot study after injection.

- Grab groundwater from IMW-1 and IMW-2 was tested on June 24, 2016 for persulfate, using the Chemetrics field test kit.
- Groundwater samples were collected from wells CG-122-60, CG-122-75, IMW-1, and IMW-2 during four separate events on June 30, July 7 and 14, and August 4, 2016. After discussions with Ecology, the groundwater samples collected on August 4 were sampled after purging the wells at a higher purge rate to attempt to pull in groundwater from a larger radius around the monitoring well. An additional monitoring event was added based on preliminary results and discussions with Ecology in September 2016. Wells CG-122-60, IMW-1, IMW-2, and downgradient well CG-161-60 were sampled on September 29, 2016. Field forms with specific flow rate information are included in Attachment B.
- Direct push borings DP-1 through DP-8 were drilled and sampled during four separate events conducted on July 1, 8, 15, and August 5, 2016 consistent with the Work Plan. During each event the soil was logged between the depths of 40 to 60 feet, and groundwater samples were collected via temporary screens set from 53 to 57 feet. The boring logs are included in Attachment A. The soil observed at each boring was relatively similar consisting of predominantly fine sand with intermittent small silt lens or intervals of slightly higher silt content. No visual indicators of persulfate (change in color or texture) were observed at any of the direct push borings. A soil sample was collected at DP-3 and submitted to Analytical Resources Inc. for grain size distribution testing which confirmed the material consisted of primarily fine sand (91.4% sand, 4.1% silt, 2.7% gravel, and 1.7% clay).
- All sampling and injection points were surveyed by Hugh Goldsmith on August 22, 2016. The survey report is included in Attachment A.

3.2 Analytical Results

All analytical data were validated consistent with the Revised ISCO Pilot Study Work Plan. Summary results were provided in tabulated form along with several figures, provided as Attachment C to this memorandum. Table 1 includes a summary of results; the laboratory reports are included in Attachment D.

Overall, 1,4-dioxane concentrations declined at all four monitoring wells screened across the target treatment depth:

- IMW-1 (210 to 160 ppb, 24% reduction),
- IMW-2 (370 to 220 ppb, 41% reduction),
- CG-122-60 (310 to 240 ppb, 23% reduction), and
- CG-122-75 (160 to 110 ppb, 31% reduction).

Given that the injections were successful with the target oxidant amount injected into the treatment area, the amount of reduction was less than predicted by the bench scale study (52% destruction over 21 days). In addition, field readings and sulfate concentrations were inconsistent with design expectations.

Results of samples collected by direct push were similarly inconsistent, with high variability in results for 1,4-dioxane, specific conductivity, and sulfate (Table 1 and Attachment C). Redox generally increased over time, as expected. Although the last round of direct push samples had the lowest concentration of 1,4-dioxane, concentrations were highest during the third monitoring event (3 weeks post injection) and lower during the 2nd monitoring event (2 weeks post injection.) In some cases, direct push locations were less than 2 feet apart and only 2 weeks apart in sample time and still varied by several orders of magnitude in 1,4-dioxane and/or persulfate concentration (for example see Figure 3, DP-4 at 8.7 ppb and DP-2 at 250 ppb).

CG-122-75 is the one deeper well monitored during the pilot study. It is screened more than ten feet deeper than target injection area, so a more muted response to the oxidant was expected. Persulfate was not detected at CG-122-75 and sulfate concentrations did not significantly change over time. However, redox values did in general increase with a significant decline in 1,4-dioxane observed over time (Table 1).

Results for heavy metals are also provided in Table 1. No significant differences in metal concentrations were detected at any of the monitoring wells or direct push borings. Metals mobilization did not occur and groundwater geochemical parameters and pH effects were also minimal.

3.3 Review of Design Assumptions

Several findings during the pilot study contrasted with design assumptions and complicated analysis of the pilot study results:

- Soil samples from direct push borings did not show any observable effects of the oxidant. It was hoped that physical effects would be visually evident, such as changes in coloring or consistency in treated soils, and aid in understanding the injection distribution. No such changes were observed.
- Injection pressures were typically much lower than expected, often around 10 to 15 pounds per square inch (psi) much less than 21 psi or 50 feet of water column (the minimum pressure expected from the head from the water column in the intermediate aquifer).
- Soils in the intermediate aquifer were generally expected to be silty sands or sandy silts with interbedded silt or clay lenses. Borings around CG-122-60 showed silty lens but were predominantly sandy, as verified by the laboratory analyzed sample from DP-3 showing greater than 91% sand.
- Chemical trends for 1,4-dioxane concentrations, field readings, and other analytical results (sulfate, etc.) did not rise and fall as expected during treatment.

Given the lack of soil observations, the differences in pressure, and the differences in soil type, the assumed radius of influence (ROI) of five feet was not verified. While chemical analysis in monitoring wells did confirm persulfate reached at least five feet away, the combined data indicate that the distribution is likely through micro channels of higher permeability that provide sporadic cover over the target five foot ROI at best.

The EDR provided a hydraulic conductivity of 5.1 x 10-3 centimeters per second and a hydraulic gradient of 0.0016 for the intermediate aquifer unit. Assuming an effective porosity of 20%, the groundwater seepage velocity was estimated at 0.8 feet per week or 42 feet per year. Selection of monitoring locations was based on these assumed porosities and conductivities, but the high variability in injection pressures indicates that the soil properties vary considerably due to the heterogeneity of the soils.

If the persulfate had contacted 1,4-dioxane consistently over the desired ROI the following pattern of trends in concentration were anticipated during the pilot study monitoring:

- A sharp decrease in 1,4-dioxane concentration where high persulfate concentrations are detected.
- Sulfate concentrations increasing as persulfate concentrations decrease.
- Rebound in 1,4-dioxane concentrations (several weeks later as untreated water flowed into the target area).
- Redox conditions changing significantly upon addition of the oxidant and then rebounding to pre-injection conditions as aquifer groundwater flowed into the treatment area.
- Specific conductivity increasing with addition of the oxidant and then decreasing as groundwater flushes the treatment area.

Actual monitoring results showed different patterns. High concentrations of persulfate (greater than 70 ppm) were detected on June 24, 2016 in the monitoring wells IMW-1 and IMW-2, immediately following completion of oxidant injections. However, one week later persulfate concentrations declined several orders of magnitude without a corresponding increase in sulfate concentrations. Sulfate concentrations did not show any significant increase until one week later in IMW-1 and more than 6 weeks later in CG-122-60 and IMW-2. A large spike in sulfate was measured in IMW-2 more than 3 months later, even though IMW-2 is on the very edge of the injection area and upgradient of most of the injection points (see Table 1 and Attachment C).

Similarly, 1,4-dioxane concentrations varied until six weeks post-injection, when 1,4-dioxane concentrations started to show significant decreases in CG-122-60, IMW-1, and IMW-2. Specific conductivity and redox also did not show significant changes until six weeks post-injection (see Table 1 and Attachment C).

3.4 Conclusions and Full Scale Design Considerations

The monitoring objectives for the pilot study were:

- Determine the relationship between concentrations/dosages of non-activated persulfate and 1,4-dioxane mass destruction;
- Determine oxidant distribution and persistence over space and time;
- Observe the degree and persistence of any metals mobilization associated with ISCO;
- Observe the degree and persistence of changes in groundwater pH and other geochemical parameters associated with ISCO; and
- Observe the degree and persistence of increased levels of dissolved sulfate.

Overall, the dose of oxidant achieved during the pilot study matched the design target, but the decline in 1,4-dioxane was considerably less, ranging from 24 to 41% in the target treatment area. It is difficult to discern how much of this decrease in concentration is due to ISCO treatment since the distribution and reaction behavior did not meet design expectations. The long term trends for 1,4-dioxane were already decreasing, following a non-linear trend at CG-122-60. From February 2015 to June 2016, the 1,4-dioxane concentration in CG-122-60 was fairly stable, ranging from 330 to 310 ppb. However, from August 2014 to February 2015, the 1,4-dioxane concentration dropped by nearly 90 ppb. Therefore, while a reduction of 70 ppb is significant, it is not possible to determine what percentage of that decrease is in excess of the overall trend.

Given the variability of the results and the lag in the detection of notable changes in groundwater chemistry, the relationship between the dose of persulfate and 1,4-dioxane mass destruction cannot be accurately estimated or projected for full scale implementation.

The oxidant distribution did not occur according to the design ROI as suggested on Figure 3. The variable and/or delayed response results indicate that oxidant likely followed microchannels and distributed randomly around the target injection area, or even farther away. No consistent pattern was identified. Persulfate persistence documented in groundwater sample results was less than one week at high concentrations and approximately two weeks at lower concentrations (less than 1 ppm), but as noted previously, sulfate concentrations did not increase until many weeks later. This indicates that the majority of the persulfate was not immediately consumed, but more likely flowed away from the monitoring wells, reacted, and the resultant sulfate then flowed back to the monitoring wells later.

The high variance in 1,4-dioxane concentrations detected in the ISCO Pilot Study target area, and the delayed timing in detection of the high concentrations of sulfate indicate that the heterogeneous nature of the aquifer may limit the effectiveness of pressurized injections of oxidant. The oxidant is not likely to spread uniformly over the target treatment area and is unlikely to effectively contact the majority of the 1,4-dioxane mass before reacting with total organic carbon or other oxidant scavengers. Meanwhile, the unexpectedly low injection pressures and notably sandy soils for the area, indicate a slow release oxidant treatment has a higher chance of working than previously considered since flow may be more uniform at standard aquifer flows and pressures.

4.0 PHASE II ISB AND ISCO IMPLEMENTATION PLAN

Based on the results of the ISB Bench Scale Study and the ISCO Pilot Study, Stericycle has determined that further pilot testing is warranted before moving to full scale remediation. ISB and additional ISCO remediation piloting will be performed concurrently, to minimize the delay to the overall remediation schedule.

4.1 Slow Release ISCO Pilot Study Implementation Plan

Stericycle proposes to pilot test a slow release persulfate reagent in the area around CG-122-60. The combination of pressurized injections and heterogeneous soils in the target treatment zone led to uneven distribution of oxidant during the initial ISCO pilot study. Since the slow release persulfate reagent dissolves from the solid state into the site groundwater and is not injected under pressure, this may lead to more even distribution of oxidant. In addition, since the soils appear to be slightly sandier than the initial design presumed, wider spacing of the slow release reagent points may work better than when this technology was evaluated in the FFS. Iron concentrations were resampled in September 2016 and there appears to still be sufficient iron (from approximately 10 to 40 ppm, Table 1) for activation of the slow release persulfate.

The slow release persulfate reagent is a mixture of oxidant and paraffin wax, shaped into cylinders approximately 18 inches long. The cylinders are hung inside a mesh casing, covering the entire screened portion of a well. The cylinders release a small amount of persulfate directly into groundwater over a period of nine to twelve months (exact length of time depends on site specific groundwater chemistry and groundwater flow conditions). The manufacturer fact sheet, safety data sheet, and pictures of typical installation are provided in Attachment E. Three new semi-permanent wells will be installed upgradient of well CG-122-60 for the purpose of slow release persulfate distribution in the 50 to 60 feet bgs groundwater zone.

4.1.1 Construction Plan

This section describes the elements of construction and site mobilization for the Slow Release ISCO Pilot Study. Work will be completed per the Quality Assurance Project Plan provided with the Revised ISCO Pilot Study Work Plan. A summary outline is provided below, with details following.

The sequence of work will generally consist of:

1. Obtain required permit approvals outlined below and provide permit approvals to the Ecology site manager.
2. Work with Ecology to update the public notice for the Slow Release ISCO Pilot Study and distribute to residences and businesses in the immediate vicinity of the work area.
3. Mark the locations of the proposed slow release persulfate wells. Perform One-Call and a private locate to confirm utility locations if any of the borings are outside the previously cleared work areas.
4. Mobilize to the site and perform a tailgate health and safety meeting outlining all of the anticipated hazards and hazard mitigation with all workers.
5. Setup the work zone and traffic control components and spill prevention measures.
6. Install three semi-permanent wells upgradient of CG-122-60 for slow release of persulfate.
7. Develop the three new wells.
8. Perform groundwater monitoring at CG-122-60, IMW-1, and IMW-2.
9. Once monitoring event is complete, demobilize the work area and take down all temporary traffic control barriers and signage and move all equipment to the secure Stericycle properly. Decontaminate all monitoring equipment and manage waste appropriately.
10. Perform steps 4, 5, 8 and 9 for groundwater monitoring events over the next 9 to 12 months.
11. Meet with Ecology to review draft results.
12. Submit summary report with a full scale downgradient area remediation plan.

4.1.2 Permitting and Approval Requirements

The project will be conducted under AO No. DE 7347 between Stericycle and Ecology, and therefore is exempt from the procedural requirements of certain Washington State laws and all local permits (WAC 173 340-710[9][b]). However, the cleanup remedy and its implementation must comply with the substantive requirements of these permits and must comply with any federal permits that may be required. The permitting exemption is not applicable if Ecology determines that the exemption would result in the loss of approval from a federal agency that may be necessary for the state to administer any federal law. In addition to the permits required, a SEPA checklist was completed for the remedial action addressing the Downgradient Area of the site as detailed in the Revised ISCO Pilot Study Work Plan.

It is anticipated that the following permits will be required to complete the Slow Release ISCO Pilot Study:

- Work performed in the public right-of-way will require a 51A-Well Installation Permit and a Utility Major Permit from the City of Seattle, Department of Transportation (SDOT). The expected time to obtain these SDOT permits is 8–12 weeks.
- Three semi-permanent wells will be installed and monitored for the duration of the Slow Release ISCO Pilot Study injection monitoring period. The three semi-permanent wells will be abandoned after the last monitoring event. Ecology will require an Underground Injection Control Permit for each well installation. The expected time for obtaining these permits is 4 weeks.

Permit approvals will be obtained after Ecology approves this memorandum. The final permit approvals will be provided to Ecology prior to conducting any of the field work for the pilot study.

No Seattle Department of Development and Planning permits or additional site access permission will be required, as no work will be performed on private property. A traffic control plan is required as part of the SDOT Utility Major Permit. The plan used previously for the ISCO Pilot Study will be re-used for the Utility Major Permit application that will limit street closure on Lucile and Maynard Avenues to the extent practicable. All new well locations are off to the side of Maynard Avenue South. The traffic control plan will mitigate potential traffic issues that could result from the well installation and monitoring work that will occur in the public right of way.

The total area of disturbance is less than 100 square feet. This area of disturbed soils would not trigger state or county stormwater requirements or trigger a City of Seattle Drainage review.

4.1.3 Construction Activities

The construction components, elements, and approach to implementation in the field are described in this section. All geologic and hydrogeologic work will be performed under the supervision and direction of a geologist licensed in the State of Washington or under the direct supervision of an engineer licensed in the State of Washington. All engineering work will be performed by or under the direct supervision of an engineer licensed in the State of Washington.

Construction activities will include installation of three wells adjacent to CG-122-60 (Figure 3), and placement of slow release persulfate reagent in the three wells. Approximately four post-injection monitoring events at nearby wells will be performed.

Prior to mobilization to the site, Stericycle will update businesses/residences in the vicinity of the pilot study locations in accordance with the Public Participation Plan to provide the following information:

- A summary of work to be performed in relation to the 1,4-dioxane cleanup action proposed, a schedule of the work, the work duration, and potential site impacts;
- A summary of traffic control plans and plans to minimize impacts to local businesses;
- Hazards associated with the work being performed and hazard mitigation; and
- Project contact information.

Stericycle will work with businesses and residences in the immediate vicinity of the work area to minimize impacts to the local businesses and residences.

Subsurface utilities will be identified prior to the start of any subsurface drilling. Stericycle personnel will mark the proposed drilling locations on the ground. The utilities underground location center (1-800-424-5555) will be contacted, and a private utility locate will be conducted within the work areas to at least 20 feet beyond the limits of subsurface work, where possible. The intended well locations might be modified in the field if they interfere or appear to interfere with subsurface utilities.

Remediation personnel will mobilize to the site and complete site setup prior to starting construction activities. All equipment will be demobilized at the end of each day and all chemicals and wastes will be stored at the fenced in and secure Stericycle Georgetown facility.

Prior to commencing site setup, a health and safety tailgate meeting will be completed with all field personnel. The tailgate meeting will cover all known and anticipated hazards and mitigation or control of all hazards. Upon completion of the tailgate meeting, site setup will include establishing temporary facilities, implementing the traffic control plan, and installing stormwater controls. Temporary fencing or clear site delineation will be set up around the work area prior to implementation of drilling to prevent public access into dedicated work zones.

The slow release persulfate wells will be constructed based on the design and specifications presented in Figure 5.

The three new wells will be installed five to ten feet upgradient of CG-122-60 (IP5, 6, and 7, Figure 3) by a Washington State licensed well driller. The wells will be drilled using a hollow stem auger or sonic drill rig. Soil will be screened for contamination in the field using a hand-held PID. Each well will be screened from approximately 50 to 60 feet bgs.

The wells will be constructed using 2-inch-diameter, Schedule 40 flush-thread polyvinyl chloride casing. Sand pack around the screen will be coarse sand or pea gravel to facilitate flow of groundwater to and away from the slow release candles. The filter pack is approximately 2 feet above the top of the pre-pack well screen, the boring will be sealed using bentonite. A flush-mounted well monument will then be cemented around the well to protect it (WAC 173-360-420).

Contaminated soil, decontamination water, and purge water from the well installations will be managed at the Stericycle Georgetown facility in accordance with the Revised Waste Management Plan (Appendix K of the EDR).

RemOx® SR persulfate ISCO reagent cylinders will be installed in the three new wells per manufacturer instructions. Six, 1.5 foot long cylinders, will be placed in each well at the same depth as the screen, 50 to 60 feet below ground surface. The data sheet and Safety Data Sheet for the persulfate cylinders are attached (Attachment E).

To prevent potential spills or off-site migration of sodium persulfate, the cylinders will be covered and stored in secondary containment. In addition, a neutralization kit including sorbent materials (i.e., vermiculite or sand), a 5-gallon high density polyethylene bucket, and neutralization chemicals (such as sodium bisulfite) will be available within the staging area.

4.1.4 Monitoring

Groundwater monitoring will be performed at IMW-1, IMW-2, and CG-122-60 approximately one month after placement of the cylinders, six weeks later, and then quarterly for three additional events. Monitoring will be completed for field parameters and laboratory analysis as per Table 4, following the methods described in the Long Term Groundwater Monitoring plan in the EDR.

4.1.5 Demobilization and Waste Management

Once the persulfate reagent is spent (approximately 12 months after installation), the cylinders will be removed from the wells and placed into labelled 55 gallon drums pending characterization for waste disposal.

Stericycle will properly handle, accumulate and temporarily store, transport, and dispose of project derived wastes in accordance with local, state, and federal requirements. Trained and experienced personnel will be present during active pilot study activities to arrange initial waste segregation, storage, and coordination of both on-site and off-site disposal activities. The primary project activities will include early identification and pre-planning for expected waste sources, characterization of wastes (analytical data, source and generator knowledge), interim and centralized accumulation and storage at the secure Stericycle Georgetown facility, and timely transportation and disposal of wastes. The anticipated waste sources include:

- Spent disposable personal protective equipment;
- Soil from well installation activities;
- Spent persulfate reagent cylinders;
- Decontamination rinse water; and
- Groundwater sampling purge water.

Initial waste characterization will be carried out at the Stericycle Georgetown facility, based on the source or process generating the waste and the field staff's knowledge of the probable regulatory status of the wastes. All waste characterization and disposal for the pilot study will follow the Revised Waste Management Plan, Appendix K of the EDR.

4.2 ISB Bioaugmentation Pilot Study Implementation Plan

Recent groundwater monitoring data show concentrations of 1,4-dioxane have increased or only slightly declined in some portions of the downgradient area. These concentration trends may indicate that a secondary source is present. If a secondary source is present and due to mass flux from less permeable aquifer zones such as in silt lenses, higher concentrations may persist in groundwater.

If 1,4-dioxane is being released from low permeability units into sandier soils in the aquifer, bioaugmentation (via injection of 1,4-dioxane degrading bacteria) is unlikely to treat the finer grained units. This is a similar challenge as encountered during the ISCO pilot study injections. Since the 1,4-dioxane degrading bacteria do not exhibit motility (i.e. self-propelled motion), placement of the injection points for bacteria are likely to be most effective as a biobarrier, rather than used for targeted source removal. The ISB Bioaugmentation Pilot Study has been designed with this approach. General guidance on bioaugmentation types and procedures is provided in Attachment F.

A row of injections will be performed, to create a biobarrier, using a mixed culture of 1,4-dioxane degrading bacteria. 1,4-Dioxane within the injection radius should immediately start being consumed, but unlike ISCO, the bacteria may survive for long periods of time. 1,4-Dioxane desorbed from the low permeability units would be degraded as it flowed through the biobarrier. In-situ, the availability of oxygen will likely limit the effectiveness of 1,4-dioxane degraders, but groundwater flow should bring small amounts of oxygen to the bacteria in the biobarrier.

Even without motility, smaller bacteria may end up being able to travel with groundwater flow, slowly increasing the size and breadth of the biobarrier. CB1190 is known to aggregate and would most likely stay relatively close to the injection point. However, PH-06 is smaller and may travel a further distance from its original placement. As noted previously, these two 1,4-dioxane degraders also behave differently as far as 1,4-dioxane degradation rate and maximum removal concentration. A mixed culture injection provides the best chance for the fastest and most complete degradation of 1,4-dioxane in the aquifer, and the best chance for long term survivability of some 1,4-dioxane degraders for long term treatment.

Stericycle proposes to test ISB with bioaugmentation in a two-step process.

In Stage 1, baseline injection and sampling will both be conducted at a single well, CG-127-75, as a basic test of the viability of the 1,4-dioxane degrading cultures for use in-situ (Figure 4). CG-127-75 is ideal because it has the highest remaining concentration of 1,4-dioxane and effects of treatment should therefore be more notable. In addition, the greatest mass would be destroyed with successful implementation at this location.

If Stage 1 is successful, Stage 2 will be conducted in a similar manner to the ISCO Pilot Study, with 1,4-dioxane cultures injected by direct push around well CG-161-60. CG-161-60 has consistently had the second highest concentration of 1,4-dioxane in the downgradient area for several years, and is also located on a less busy side street with room for additional monitoring wells to be installed in the right of way. Monitoring during Stage 2 will be conducted at CG-161-60 and two new semi-permanent monitoring wells.

4.2.1 Construction Plan

This section describes the elements of construction and site mobilization for the ISB Bioaugmentation Pilot Study. Work will be completed per the Quality Assurance Project Plan provided with the Revised ISCO Pilot Study Work Plan. A summary outline is provided below, with details following.

The sequence as proposed in this memorandum will generally consist of:

1. Obtain required permit approvals outlined below and provide permit approvals to the Ecology site manager for work in Stage 1.
2. Work with Ecology to develop a Public Participation Plan for the Stage 2 work. Provide residences and businesses in the vicinity of the work area with handout notifications summarizing the work, hazards, and hazard mitigation.
3. Perform baseline groundwater monitoring at CG-127-75 and baseline sampling of the 1,4-dioxane culture prior to injection.
4. Perform injection of up to 10 liters of 1,4-dioxane degrading bacteria at CG-127-75.
5. Conduct groundwater monitoring events.
6. Meet with Ecology to review results.
7. If results suggest ISB Bioaugmentation may be a worthwhile remedial alternative to continue investigating, Stage 2 of the ISB Bioaugmentation pilot study will commence.
8. Mark the drilling locations for monitoring wells and injection points. Perform One-call and a private locate to confirm utility locations.
9. Mobilize to the site and perform a tailgate health and safety meeting outlining all of the anticipated hazards and hazard mitigation with all workers for Stage 2.
10. Setup the work zone and traffic control components and spill prevention.
11. Install and develop new semi-permanent groundwater monitoring wells near CG-161-60 (Figure 4).
12. Perform baseline groundwater monitoring and baseline sampling of the 1,4-dioxane culture prior to injection.
13. Install direct push temporary casings for injection locations (IP8 through IP11 on Figure 4).
14. Connect injection skid to the bioaugmentation solution and to the first two IPs (IP8 and IP9). Begin ramp up procedures and actively monitor pressure, flow rates, and total volumes during injection of substrate.
15. Connect injection skid to tote and to the next two IPs (IP10 and IP11). Repeat step #14.
16. Once injections are complete, demobilize the work area and take down all temporary traffic control barriers and signage and move all equipment to the secure Stericycle properly. Decontaminate all injection equipment and manage waste properly.
17. Perform four Stage 2 monitoring events.
18. Meet with Ecology to review draft results.

19. Submit final summary report with a full scale downgradient area remediation plan.

4.2.2 Permitting and Approval Requirements

The general requirements are as the same as noted above, in the Slow Release ISCO Pilot Study Implementation Plan.

It is anticipated that the following permits will be required to as part of Stage 1 and Stage 2 of the ISB pilot study:

- Work performed for Stage 1 in the public right of way will be covered under Stericycle's permits for groundwater monitoring with SDOT as no additional equipment will be necessary.
- Work performed for Stage 2 in the public right-of-way or the street will require a 51A-Well Installation Permit and a Utility Major Permit from the City of Seattle, Department of Transportation (SDOT). The expected time to obtain these SDOT permits is 8–12 weeks.
- Stage 2 work includes installation of two semi-permanent wells to be monitored for the duration of the ISB Pilot Study. In addition, four direct push injections will be performed and one injection will be performed at an existing monitoring well. The two semi-permanent monitoring wells will be abandoned after the last monitoring event. Ecology will require a variance to allow for well installation via direct push methods. Ecology will require a single Underground Injection Control Permit for all the injection locations. The expected time for obtaining these permits is 4-8 weeks.

Permit approvals will be obtained after Ecology approves this memorandum. The final permit approvals will be provided to Ecology prior to conducting any of the relevant field work for the ISB Pilot Study.

No Seattle Department of Development and Planning permits or additional site access permission will be required, as no work will be performed on private property. A traffic control plan is required as part of the SDOT Utility Major Permit for Stage 2. A plan covering Stage 2 work will be developed and included in the Utility Major Permit application that will limit street closure on South Findlay Street to the extent practicable. The traffic control plan will mitigate potential traffic issues that could result from the injection work that will occur in the street and the public right of way.

The total area of disturbance is less than 750 square feet. This area of disturbed soils would not trigger state or county stormwater requirements or trigger a City of Seattle Drainage review.

4.2.3 Construction Activities

The construction components, elements, and approach to implementation in the field are described in this section. All geologic and hydrogeologic work will be performed under the supervision and direction of a geologist licensed in the State of Washington or under the direct supervision of an engineer licensed in the State of Washington. All engineering work will be performed by or under the direct supervision of an engineer licensed in the State of Washington.

Stage 1

No new construction activities will be necessary as part of Stage 1. All work will be performed in an existing well, CG-127-75.

Prior to injection, a baseline groundwater sample will be collected at CG-127-75 as per Table 5.

Sentinel Environmental will overnight mail the 1,4-dioxane culture for injection the following day. The culture will be stored on ice under chain of custody until the time of mixing and injection. A sample of the 1,4-dioxane culture provided by Sentinel Environmental will be concurrently collected to gauge the viability of the culture before mixing with site groundwater. Up to 10 liters of a mixed culture of 1,4-dioxane degrading bacteria will be injected into CG-127-75 using a push pull method. Up to 10 gallons of groundwater will be extracted using the existing sampling pump, collected in a clean decontaminated 15 gallon plastic drum, mixed with the1,4-dioxane culture, and reinjected (via peristaltic pump) back into well. Prior to reinjection, a sample of the 1,4-dioxane inoculated groundwater will also be collected for analysis by Sentinel Environmental in order to gauge the viability of the culture at the time of injection. The extraction flow rate will be no greater than 2 liters per minute. The water level inside CG-127-75 will be manually monitored during both extraction and injection, and flow will be adjusted accordingly if the water level rises or drops more than 1 foot.

After the bacteria are injected monitoring will be performed at CG-127-75 approximately one week, two weeks, and one month later; then quarterly for a minimum of two rounds, for field parameters and laboratory analysis by Sentinel Environmental (Table 5). The objective of Stage 1 is to determine if 1,4-dioxane is successfully degraded in the vicinity of the well, identify which bacteria are thriving, and how long the 1,4-dioxane bacteria survive/thrive. If results indicate bioaugmentation is likely to work in-situ, Stage 2 of ISB piloting will be performed.

Stage 2

In Stage 2, a pilot study test will be performed around CG-161-60 (Figure 4). Similar to the setup around CG-122-60 for the ISCO pilot study, two semi-permanent wells (IMW-3 and IMW-4, screened from approximately 50 to 60 feet bgs) will be installed within 5 to 10 feet of CG-161-60. In addition, four direct push injections will be performed.

Approximately four post-injection monitoring events at CG-161-60, IMW-3, and IMW-4 will be conducted. Timing of the monitoring events will be determined based on the results of Stage 1 and communicated with Ecology prior to the sampling events. Stericycle will work with businesses and residences in the immediate vicinity of the work area to minimize impacts to the local businesses and residences.

Subsurface utilities will be identified prior to the start of any subsurface drilling. The proposed drilling locations will be marked on the ground. The utilities underground location center (1-800-424-5555) will be contacted, and a private utility locate will be conducted within the work areas to at least 20 feet beyond the limits of subsurface work, where possible. The intended drilling locations might be modified in the field if they interfere or appear to interfere with subsurface utilities.

Remediation personnel will mobilize to the site and complete site setup prior to starting construction activities. Stage 1 injection activities will cause minimal disturbance (as much as typical groundwater sampling events). Stage 2 injection activities will likely encroach on one lane of traffic on South Findlay

Street. The right-of-way along the Southern side of South Findlay Street just south of the proposed Stage 2 injection locations (Figure 4) could be used as a contractor staging area for the duration of the project as long as business access may be maintained for local businesses in the vicinity. All equipment will be demobilized at the end of each day and all chemicals and wastes will be stored at the fenced in and secure Stericycle Georgetown facility.

Prior to commencing site setup, a health and safety tailgate meeting will be completed with all field personnel. The tailgate meeting will cover all known and anticipated hazards and mitigation or control of all hazards. Upon completion of the tailgate meeting, site setup will include establishing temporary facilities, implementing the traffic control plan, and installing stormwater controls. Temporary fencing or clear site delineation will be set up around the work area prior to implementation of drilling or monitoring events to prevent public access into dedicated work zones. In addition, monitoring locations are along the right of way adjacent to South Findlay Street to minimize potential traffic impacts.

The semi-permanent groundwater monitoring wells will be constructed based on the design and specifications presented in Figure 5. The two new wells will be installed five to ten feet downgradient of CG-161-60 (IMW-3 and IMW-4, Figure 4) by a Washington State licensed well driller. The wells will be drilled using a direct push drill rig under the supervision of a Washington State licensed geologist. The borings will be continuously logged for lithology starting at approximately 40 feet bgs. The borings will be screened for contamination in the field using a hand-held PID. Wells will be screened from approximately 50 to 60 feet bgs. A detailed record or log of each groundwater monitoring well will be recorded.

The wells will be constructed using 0.75-inch-diameter, Schedule 40 flush-thread polyvinyl chloride casing. All of the wells will be constructed using pre-packed well screens, with 20/40 sized sand. Loose filter pack sand will be added slowly into the annulus as the core barrel is retracted. The filter pack sand is used to stabilize the well screen and casing as the core is removed. Once the loose filter pack is approximately 2 feet above the top of the pre-pack well screen, the boring will be sealed using bentonite. The flush-mounted well monument will then be cemented around the well to protect it.

Baseline samples will be collected from the two new wells, plus existing well CG-161-60 for microbial, nutrient, and 1,4-dioxane laboratory analysis by Sentinel Environmental using low flow sample collection methods consistent with the Long Term Monitoring Plan (Table 5).

The mobile injection skid will then be positioned near CG-161-60 during the Stage 2 ISB pilot study for injection at locations IP8 through IP11 (Figure 4). A diesel-powered generator or power provided by the injection rig or utility truck will power the injection pump. If a diesel generator is used, it will be running downwind of the injection area. All hoses will be secured by camlock adapters and placed within secondary containment to the extent practicable. Hoses will be securely fastened to the substrate storage, and leak checks will be performed prior to performing any injections. During push-probe injections, the drill rig and the injection skid will be located immediately adjacent to the injection location.

Substrate will be injected at the four injection points. Injection personnel will set up the substrate containers and injection skid in the vicinity of the injection area inside of a secondary containment area. The direct push tooling will be lowered to 60 feet bgs, and then substrate will be pumped into the aquifer. Concentration, dosing, and mixing details for the substrate based on the results of Stage 1 will be provided to Ecology for review. Due to the depth of the injection, daylighting of the substrate (either back up the annulus or to the ground surface/utility) is unlikely to occur. However, the pressures and flow rates during the injection event will be monitored, and should rapid changes in pressure occur, the causes will be identified prior to any further injections.

The Revised ISCO Pilot Study Work Plan provided templates for Standard Operating Procedures (SOPs), maximum injection pressures, and field form templates. Only minor simplifications are required since the substrate being injected in this case is non-hazardous. Since the formation and the depths of injection are the same, the overall pressures and flows should be similar to that for the June ISCO Pilot Study.

Control valves will be adjusted so that the pressure does not exceed 45 psi in order to prevent hydraulic fracturing. Flow rates and total flow quantities will be logged on field forms to monitor the total amount of substrate added at each injection location. As material is injected, the tooling will be slowly raised in increments of 2 feet, up to 50 feet bgs. Substrate solution will be added between 50 and 60 feet bgs until the total mass of substrate is added.

There are a total of four injection locations for Stage 2 of the pilot study. Substrate will be injected into two injection locations at a time. It is anticipated that IP8 and IP10 will be injected into first and any modifications to solution strength, injection volumes, or injection rates will be made prior to injecting into IP9 and IP11 (Figure 4). Dilution of the substrate with previously extracted groundwater may be performed per Sentinel recommendations based on Stage 1 results.

To prevent potential spills or off-site migration of bioaugmentation cultures, the storage containers will be covered and stored in secondary containment. In addition, a spill kit including sorbent materials (i.e., kitty litter, etc.), a 55-gallon high density polyethylene drum, and antiseptic chemicals (such as bleach) will be available within the staging area. These cultures are considered non-toxic and non-hazardous. However, upon identification of a spill of any cultures, Stericycle will immediately notify the Ecology site manager for the Stericycle Georgetown facility as per the SOP provided in the Revised ISCO Pilot Study Work Plan.

4.2.4 Monitoring

Monitoring for Stage 1 will be performed only at existing well CG-127-75. After the bacteria are injected, monitoring will be performed at CG-127-75 approximately one week, two weeks, and one month later; then quarterly for a minimum of two rounds (Table 5).

For Stage 2, monitoring will be performed at the three wells (IMW-3, IMW-4 and CG-161-60) approximately one week, one month, and then quarterly for a minimum of two rounds after injection (Table 5).

Monitoring for field parameters and sample collection procedures will follow the procedures as described in the Long Term Groundwater Monitoring plan in the EDR. All laboratory analysis will be performed by Sentinel Environmental and will include standard analysis for 1,4-dioxane as well as genetic analysis for assessing the health and population size of the 1,4-dioxane degrading bacteria.

4.2.5 Demobilization and Waste Management

Wastes will be managed as noted above in the Slow Release ISCO Pilot Study Implementation Plan (Section 4.1.5). The anticipated waste sources include:

- Spent disposable personal protective equipment;
- Soil from well installation activities;
- Decontamination rinse water; and
- Groundwater sampling purge water.

5.0 Updated Schedule

This section outlines a tentative schedule for implementation of the next stage ISCO and ISB pilot testing described in this memorandum.

Stage 1 of the ISB bioaugmentation pilot study will only require an Underground Injection Control (UIC) Permit, but otherwise can be performed under permits for groundwater sampling already established with Seattle Department of Transportation by Stericycle. Sentinel is likely to have enough 1,4-dioxane degrading bacteria produced for field testing by January 2017. Stage 1 ISB bioaugmentation pilot testing can feasibly be completed in January 2017, with monitoring completed by July 2017.

The slow release ISCO pilot study and Stage 2 of the ISB pilot study will require additional permitting with the SDOT. Typically this takes on the order of 12 weeks or more from the start of the permit application. However, Stericycle will endeavor to minimize this time since the work proposed will be very similar to work already completed under the previously permitted ISCO pilot study work. Ideally well installation for ISCO could begin as soon as April 2017 if permitting is expedited. Given the 9 to 12 month monitoring following treatment, it is expected the last round of monitoring would occur by April 2018.

If Stage 1 preliminary results for ISB are favorable for continued piloting, permitting for the Stage 2 ISB Pilot Study could be initiated as soon as February 2017, with installation of wells by July 2017. Given the 6 to 9 month monitoring following treatment, it is expected the last round of monitoring would occur as early as April 2018, depending on permitting and laboratory reporting schedules.

Within 45 days of receiving the last analytical data packages from the ISB and ISCO pilot studies, Stericycle will summarize the findings and present them to Ecology for review with recommendations on how to proceed for full scale remediation in the downgradient area. Once the best full scale remediation approach is agreed upon, Stericycle will prepare a separate full-scale downgradient area implementation work plan within 60 days, which will present full results of the pilot studies to support full-scale design and implementation of treatment in the downgradient area.

6.0 References

AMEC, 2015a, 1,4-Dioxane Remedial Design – Remedial Action (RD/RA) Work Plan, Stericycle Georgetown Facility, Seattle, Washington. October.

AMEC, 2015b, 1,4-Dioxane Remediation Approach Focused Feasibility Study, Stericycle Georgetown Site, Seattle, Washington. January.

AMEC Geomatrix, Inc., 2011, Revised Engineering Design Report, PSC Georgetown Facility, Seattle, Washington. September.

Dalton, Olmsted, and Fuglevand and AMEC, 2016. Revised In-Situ Chemical Oxidation Pilot Study Work Plan, Stericycle Georgetown Facility, Seattle, Washington, March 2016.

7.0 Closing and Signature

The services described in this report were performed consistent with generally accepted professional consulting principles and practices. No other warranty, expressed or implied, is made. This report is solely for the use and information of our client unless otherwise noted. Any reliance on this report by a third party is at such party's sole risk.

State of Washington Licensed Geologist

NATASYA GRAY

exp 3/14/17

Tasya Gray, LG

Senior Geologist

Patrick Hsieh, PE

Senior Engineer

Tables

TABLE 1

GROUNDWATER MONITORING DATA SUMMARY

Stericycle Georgetown Facility
Seattle, Washington

Well	**IMW-1**							**IMW-2**						
Parameter	6/21/2016	6/24/2016	6/30/2016	7/7/2016	7/14/2016	8/4/2016	9/29/2016	6/21/2016	6/24/2016	6/30/2016	7/7/2016	7/14/2016	8/4/2016	9/29/2016
initial water level (ft TOC)	8.6	--	8.69	8.76	8.85	9.19	9.85	8.73	--	8.8	8.87	8.94	9.26	10.0
pH (standard units)	7.4	--	7.6	7.4	7.4	7.2	7.22	7.3	--	7.4	7.4	7.4	7.2	6.93
Specific Conductivity (µs/cm)	1015	--	1024	989	1340	1714	1815	1040	--	1124	1068	1082	1890	3288
Temperature (°C)	15.9	--	17.6	16.8	16.9	16.4	16.7	15.9	--	17.2	16.8	16.9	16.1	16.65
Turbidity (NTU)	5	--	6.6	11.7	10.4	5.1	3	2.2	--	12.5	8.9	9	0.9	2.7
Dissolved Oxygen	0.4	--	0.5	0.2	0.1	0.1	0.01	0	--	0.4	0.1	0.1	0	0.02
Redox (mV)	-93.4	--	-100.8	-38.8	-48.7	-30.1	-3.6	-116.2	--	-103.6	-52.3	-56.9	-8.2	-4.2
Sulfate	0.69	--	0.68	73.6 J/ 192	301	457	454	0.46	--	0.37	0.39	27.2	519	1550
Sulfide	<0.05	--	<0.05	<0.05	<0.05	<0.05	0.031 J	0.031 J	--	<0.05	<0.05	<0.05	<0.05	0.035 J
1,4-Dioxane (µg/L)	210		300	290	300	240	160	370		330	340	380	310	220
Persulfate (ppm)	--	>70	0.5	0.5	0	0	0	--	>70	0.2	0.3	0	0	0
Arsenic	0.0004 J	--	0.0003 J	<0.0005	0.0003 J	<0.0005	--	0.0002 J	--	0.0003 J	0.0002 J	<0.0005	<0.0005	--
Cadmium	<0.000016	--	0.000015 J	<0.000020	<0.000010 J	<0.000020	--	<0.000025	--	0.00002 J	<0.000020	<0.000020	<0.000020	--
Chromium	0.00058	--	0.00064	0.00052	<0.00057	<0.00038	--	0.0005	--	0.00061	0.00058	<0.00057	<0.00047	--
Lead	<0.000031	--	0.000029	<0.000018 J	<0.000034	0.000012 J	--	<0.000032	--	0.000072	<0.000027	<0.000014 J	0.000009 J	--
Silver	<0.00002	--	<0.000020	--	--	<0.000020	--	<0.000020	--	<0.000015 J	--	--	<0.000020	--
Sodium	144	--	136	--	--	182	--	190	--	189	--	--	228	--
Selenium	<0.001	--	<0.00100	--	--	< 0.00100	--	<0.00100	--	< 0.00100	--	--	0.00054 J	--
Barium	0.015485	--	0.015064	--	--	0.027401	--	0.010919	--	0.011538	--	--	0.027709	--
Beryllium	<0.00002	--	<0.000020	--	--	<0.000020	--	<0.000020	--	<0.000020	--	--	<0.000020	--
Copper	0.00033	--	0.00023	--	--	0.0004	--	0.00018	--	0.00048	--	--	0.0005	--
Zinc	0.00164	--	0.00191	--	--	0.00089	--	0.00229	--	0.01022	--	--	0.0016	--
Nickel	0.00119	--	0.00098	--	--	0.0012	--	0.00123	--	0.00128	--	--	0.00161	--
Chromium (+3)	<0.024	--	<0.05 J	--	--	<0.05	--	<0.024	--	<0.05	--	--	<0.05	--
Chromium (+6)	<0.024	--	<0.05 J	--	--	0.004 J	--	<0.024 J	--	<0.05	--	--	0.005 J	--
Total Iron	--	--	--	--	--	--	9.9	--	--	--	--	--	--	37.4
Ferrous Iron	--	--	--	--	--	--	0.39	--	--	--	--	--	--	2.7
Iron (+2) field test	--	--	--	--	--	--	3.8	--	--	--	--	--	--	6.0

Notes:

1) metals are dissolved results, field filtered

2) units are in milligrams per liter (mg/L) unless otherwise noted

Definitions:

µg/L = micrograms per liter
°C = degrees centigrade
ppm = part per million
NTU = Nephelometric turbidity units

mV = millivolt
ft = feet
TOC = Top of casing
-- = not tested

µs/cm =microsiemens per centimeter
> = exceeds upper limit of test
< = not detected above reporting limit
J = the result is an estimated value

TABLE 1
GROUNDWATER MONITORING DATA SUMMARY
Stericycle Georgetown Facility
Seattle, Washington

Well	**CG-122-60**						**CG-122-75**					**CG-161-60**
Parameter	6/22/2016	6/30/2016	7/7/2016	7/14/2016	8/4/2016	9/29/2016	6/21/2016	6/30/2016	7/7/2016	7/14/2016	8/4/2016	9/29/2016
initial water level (ft TOC)	8.65	8.73	8.84	8.9	9.2	9.94	8.37	8.48	8.55	8.65	8.98	9.8
pH (standard units)	7.3	7.4	7.3	7.3	7.18	7.14	7.4	7.4	7.4	7.3	7.41	6.77
Specific Conductivity (µs/cm)	709	732	702	711	981	1170	576	590	580	578	591	968
Temperature (°C)	15.3	16.2	15.5	16	15.51	16.36	15	15.9	15.9	15.7	15.27	15.9
Turbidity (NTU)	1.6	2.5	2.5	5.9	0.83	1.3	1.3	1.3	1.5	6.3	0.8	2.6
Dissolved Oxygen	0	0	0	0	0.07	0.01	0	0.1	0	0.2	0.12	0.04
Redox (mV)	-80	-72.5	-35.9	-21.1	-10.3	5.3	-102.5	-82.4	42.8	-11.2	-9.3	40.9
Sulfate	0.33	0.29	0.29	0.33	324	324	0.24	0.2	0.22	0.22	0.12 J	< 0.20
Sulfide	<0.05	<0.05	<0.05	<0.05	<0.05	0.053	<0.05	<0.05	<0.05	<0.05	<0.05	0.030 J
1,4-Dioxane (µg/L)	310	310	210	360	280/240	240	160	150	150	130	110	530
Persulfate (ppm)	--	0.7	0.3	0.3	0	0	--	0	0	0	0	0
Arsenic	0.0001 J	<0.0005	<0.0005	<0.0005	<0.0005	--	0.0002 J	0.0003 J	0.0003 J	0.0003 J	0.0002 J	--
Cadmium	<0.000017 J	0.000013 J	<0.000020	<0.000020	<0.000020	--	<0.000016 J	0.000025	<0.000020	<0.000020	<0.000020	--
Chromium	0.00048	<0.00045	0.00042	<0.00049	<0.00034	--	0.00061	<0.00058	0.00058	<0.00057	<0.0006	--
Lead	<0.000043	0.000026	<0.000017 J	<0.000023	0.000008 J	--	<0.000021	0.000036	<0.000017 J	<0.000023	0.000023	--
Silver	<0.000020	<0.000015 J	--	--	<0.000020	--	<0.000020	<0.000015 J	--	--	<0.000020	--
Sodium	116	120	--	--	146	--	115	113	--	--	103	--
Selenium	<0.00100	<0.00100	--	--	<0.00100	--	0.00033 J	0.00042 J	--	--	0.00063 J	--
Barium	0.005084	0.004726	--	--	0.020056	--	0.002914	0.002758	--	--	0.002456	--
Beryllium	<0.000020	<0.000020	--	--	<0.000020	--	0.000010 J	0.000008 J	--	--	0.000006 J	--
Copper	0.00013	0.00015	--	--	0.00036	--	0.00019	0.00023	--	--	0.0002	--
Zinc	0.00082	0.02177 J	--	--	0.00075	--	0.00122	0.0116	--	--	0.00065	--
Nickel	0.00106	0.00103	--	--	0.00132	--	0.00043	0.00047	--	--	0.00046	--
Chromium (+3)	<0.025	<0.05	--	--	<0.05	--	<0.039	<0.05	--	--	<0.05	--
Chromium (+6)	<0.025 J	<0.05	--	--	<0.05	--	<0.039 J	<0.05	--	--	<0.05	--
Total Iron	--	--	--	--	--	18.6	--	--	--	--	--	8.09
Ferrous Iron	--	--	--	--	--	3.8	--	--	--	--	--	1.3
Iron (+2) field test	--	--	--	--	--	4.8	--	--	--	--	--	3.8

TABLE 1
GROUNDWATER MONITORING DATA SUMMARY
Stericycle Georgetown Facility
Seattle, Washington

Well	**DP-1**	**DP-2**	**DP-3**	**DP-4**	**DP-5**	**DP-6**	**DP-7**	**DP-8**
Parameter	7/1/2016	7/1/2016	7/8/2016	7/8/2016	7/15/2016	7/15/2016	8/5/2016	8/5/2016
initial water level (ft TOC)	--	--	--	--	--	--	--	--
pH (standard units)	7.2	7.3	6.9	7.1	7.4	7.2	7.1	6.9
Specific Conductivity (µs/cm)	791	1077	366	403	989	1002	1307	429
Temperature (°C)	19.5	18.6	18.9	17	23.3	20	17.8	22.5
Turbidity (NTU)	170	>1000	345	18.1	279	363	160	102
Dissolved Oxygen	0.4	0.3	0.1	0.2	0.4	0.4	0.05	0.17
Redox (mV)	-84.2	-61.3	-20.2	-6.2	-12.1	-7.6	-1.2	63
Sulfate	35.2	0.51	2.77	1.93	5.9	6.3	143	1.9
Sulfide	2.4 J	11 J	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
1,4-Dioxane (µg/L)	180	250	3.7	8.7	380	280	18	5.3
Persulfate (ppm)	0	0	0.3	1.4	6	3.5	0.7	2.8
Arsenic	0.0005	0.0012	0.0025	0.0016	0.0006	0.0004 J	0.0004 J	0.0013
Cadmium	<0.000013 J	<0.000013 J	<0.000028	<0.000020	<0.000010 J	<0.00002	<0.000020	<0.000020
Chromium	<0.00066	<0.00067	0.00055	0.00051	<0.00062	0.00077	<0.00048	<0.00036
Lead	<0.000093	<0.000055	0.000098	0.000062	<0.000022	<0.00004	0.000057	0.000038
Silver	<0.000007 J	<0.000007 J	--	--	--	--	<0.000020	<0.000020
Sodium	--	--	--	--	--	--	120	32.8
Selenium	0.00042 J	<0.0010	--	--	--	--	<0.0010	<0.0010
Barium	0.009267	0.013166	--	--	--	--	0.019278	0.004786
Beryllium	0.000009 J	0.000006 J	--	--	--	--	<0.000020	<0.000020
Copper	<0.00105	<0.00083	--	--	--	--	0.00045	0.00049
Zinc	0.00528	0.03338	--	--	--	--	0.00134	0.00214
Nickel	0.00201	0.00608	--	--	--	--	0.0031	0.00358
Chromium (+3)	--	--	--	--	--	--	<0.05	<0.05
Chromium (+6)	<0.05	0.025 J	--	--	--	--	0.36	<0.05
Total Iron	--	--	--	--	--	--	--	--
Ferrous Iron	--	--	--	--	--	--	--	--
Iron (+2) field test	--	--	--	--	--	--	--	--

TABLE 2
INJECTION DOSE SUMMARY
Stericycle Georgetown Facility
Seattle, Washington

Date	Sodium Persulfate (25%)	Water	Sodium Persulfate Injection Concentration
	gallon	**gallon**	**weight %**
6/23/2016	125	295	8.47
6/24/2016	181	422	8.53
Totals	**306**	**717**	**8.51**

Injection Point	Volume Injected sodium persulfate (8.5%) (gal)	Pressure Range (psi)
IP1	300	8-25
IP2	123	25-60
IP3	300	11-15
IP4	300	4-27
Total	**1023**	

Notes:

Target Dose was 250 gallons per point at 8.5%, for a total of 1,000 gallons.

TABLE 3
INJECTION TIMING, PRESSURE, AND FLOW DETAILS

Stericycle Georgetown Facility
Seattle, Washington

6/23/2016						
Injection Location	**Time**	**Depth (ft bgs)**	**Injection Rate (gpm)**	**Pressure (psi)**	**Volume Injected (gallons)**	**Average Injection Rate (gpm)**
IP-1	12:35	51-53	start [1]	start	60	1.0
	12:45	51-53	2.0	8		
	12:50	51-53	1.5	8		
	13:05	51-53	pause	pause		
	14:28	50-52	2.0	10		
	15:00	50-52	final	final		
	15:00	52-54	start	start	60	2.1
	15:28	52-54	final	final		
	15:40	54-56	start	start	60	1.0
	15:50	54-56	--	12		
	15:54	54-56	--	14		
	16:03	54-56	1.4	--		
	16:10	54-56	--	14		
	16:25	54-56	0.2	--		
	16:30	54-56	--	18		
	16:41	54-56	final	final		
	16:51	56-58	start	start	50	1.3
	16:59	56-58	1.3	--		
	17:09	56-58	1.3	--		
	17:11	56-58	0	0		
	17:26	56-58	--	8		
	17:30	56-58	final	final		
IP-3	12:35	50-52	start	start	60	1.2
	12:45	50-52	2.0	8		
	12:50	50-52	1.5	8		
	13:25	50-52	1.3	5		
	15:40	52-54	start	start	60	1.0
	15:50	52-54	--	12		
	15:54	52-54	--	14		
	16:03	52-54	1.4	--		
	16:25	52-54	--	14		
	16:25	52-54	0.2	--		
	16:30	52-54	--	18		
	16:41	52-54	1.00	16		
	16:51	54-56	start	start	50	1.3
	16:59	54-56	1.3	--		
	17:09	54-56	1.3	--		
	17:11	54-56	0	0		
	17:26	54-56	--	8		
	17:30	54-56	final	final		

Notes:

1) Injection start and stop as well as breaks for troubleshooting (pause) are noted rather than pressures or flows.

2) There was no flow at 45 psi. Pressure was increased to 65 psi to achieve 2 gpm, but pressure stayed elevated followed by leak at surface seal. No flow at next injection depth.

Definitions:

ft bgs =	feet below ground surface	psi =	pound per square inch
gpm =	gallon per minute	'--' =	No reading taken

TABLE 3
INJECTION TIMING, PRESSURE, AND FLOW DETAILS
Stericycle Georgetown Facility
Seattle, Washington

6/24/2016						
Injection Location	**Time**	**Depth (ft bgs)**	**Injection Rate (gpm)**	**Pressure (psi)**	**Volume Injected (gallons)**	**Average Injection Rate (gpm)**
IP-1	10:20	56-58	0.5-2.0	10-20	10	2.0
	10:25	56-58	0.5-2.0	10-20		
	10:40	58-60	1.8	22	60.01	2.1
	10:55	58-60	2.0	8		
	11:08	58-60	2.0	10		
IP-3	10:20	54-56	0.5-2 .0	10-20	10	2.0
	10:25	54-56	0.5-2.0	10-20		
	10:40	56-58	2.0	22	59.98	2.0
	10:55	56-58	2.0	8		
	11:10	56-58	2.0	10		
	11:12	58-60	2.0	11	60	2.1
	11:18	58-60	2.0	11		
	11:23	58-60	2.0	11		
	11:33	58-60	2.0	11		
	11:40	58-60	2.0	11		
IP-4	12:48	48-50	start	start	60.1	2.0
	12:55	48-50	2.0	--		
	13:00	50-52	2.0	5		
	13:18	50-52	final	final		
	13:20	52-54	start	start	60.05	2.1
	13:30	52-54	2.00	30		
	13:36	52-54	2.00	28		
	13:42	52-54	2.00	28		
	13:50	52-54	final	final		
	13:51	54-56	start	start	60.05	2.4
	14:00	54-56	2.0	8		
	14:05	54-56	2.0	7		
	14:10	54-56	2.0	--		
	14:18	54-56	2.0	8		
	14:18	56-58	start	start	60.21	2.2
	14:20	56-58	2.0	10		
	14:25	56-58	2.0	8		
	14:30	56-58	2.0	6		
	14:47	56-58	2.0	6		
	14:59	58-60	start	start	60.45	2.1
	15:28	58-60	2.0	7		
IP-2	13:51	50-52	start	start	59.99	2.2
	14:00	50-52	2.0	32		
	14:05	50-52	2.0	36		
	14:10	50-52	2.0	--		
	14:18	50-52	2.0	34		
	14:18	52-54	start	start	55.70	1.9
	14:20	52-54	2.0	22		
	14:25	52-54	2.0	30		
	14:30	52-54	2.0	34		
	14:47	52-54	2.0	22		
	14:59	54-56 [2]	2.0	65	7.3	1.2
	15:05	55-57	--	--		

TABLE 4
Slow Release ISCO Pilot Monitoring Summary
Stericycle Georgetown Facility
Seattle, Washington

Monitoring Event	Monitoring Location	Sample Depth	Media	Lab Sample Parameters	Field Sample Parameters[1]	Location Objective
Baseline	CG-122-60	50-60 ft bgs	GW	1,4-D, sulfate, iron (total, speciated)	conventionals	Provide baseline conditions pre-injections
	IMW-1	50-60 ft bgs	GW	1,4-D, sulfate, iron (total, speciated)	conventionals	Provide baseline conditions pre-injections
	IMW-2	50-60 ft bgs	GW	1,4-D, sulfate, iron (total, speciated)	conventionals	Provide baseline conditions pre-injections
Monitoring Event #1, through #4	CG-122-60	50-60 ft bgs	GW	1,4-D, sulfate, iron (total, speciated)	conventionals	Provides permanent monitoring location at downgradient location in target depth interval
	IMW-1	50-60 ft bgs	GW	1,4-D, sulfate, iron (total, speciated)	conventionals	Provides a semi-permanent location further downgradient than CG-122-60 to evaluate changes in 1,4-dioxane concentrations and changes in geochemistry as oxidant spreads downgradient
	IMW-2	50-60 ft bgs	GW	1,4-D, sulfate, iron (total, speciated)	conventionals	Provides an upgradient semi-permanent location as a control well for comparison to wells downgradient of slow release injections.

Notes:

1. Conventionals include: pH, DO, ORP, temperature, specific conductance.

Abbreviations:

1,4-D = 1,4-dioxane
GW= groundwater
ft bgs = feet below ground surface

TABLE 5
ISB Pilot Monitoring Summary
Stericycle Georgetown Facility
Seattle, Washington

Monitoring Event	Monitoring Location	Sample Depth	Media	Lab Sample Parameters [2]	Field Sample Parameters[1]	Location Objective
Stage 1						
Baseline	NA	NA	NA	genetic analysis	NA	Provide check on viability of cultures before mixing with groundwater.
	NA	NA	NA	1,4-D, genetic and nutrient analysis	NA	Provide check on viability of cultures after mixing with groundwater, prior to injection into well.
	CG-127-75	50-60 ft bgs	GW	1,4-D and nutrient analysis	conventionals	Provide baseline conditions pre-injections
Monitoring Event #1, through #4	CG-127-75	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Confirm reduction of 1,4-D and viability of bacteria in-situ.
Stage 2						
Baseline	CG-161-60	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Provide baseline conditions pre-injections
	IMW-3	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Provide baseline conditions pre-injections
	IMW-4	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Provide baseline conditions pre-injections
Monitoring Event #1, through #5	CG-161-60	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Provides permanent monitoring location in heart of ISB injection area at the target depth interval
	IMW-3	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Provides a semi-permanent location downgradient to the southwest to evaluate changes in 1,4-dioxane concentrations and changes in geochemistry as oxidant spreads downgradient
	IMW-4	50-60 ft bgs	GW	1,4-D, genetic and nutrient analysis	conventionals	Provides a semi-permanent location downgradient to the south to evaluate changes in 1,4-dioxane concentrations and changes in geochemistry as oxidant spreads downgradient

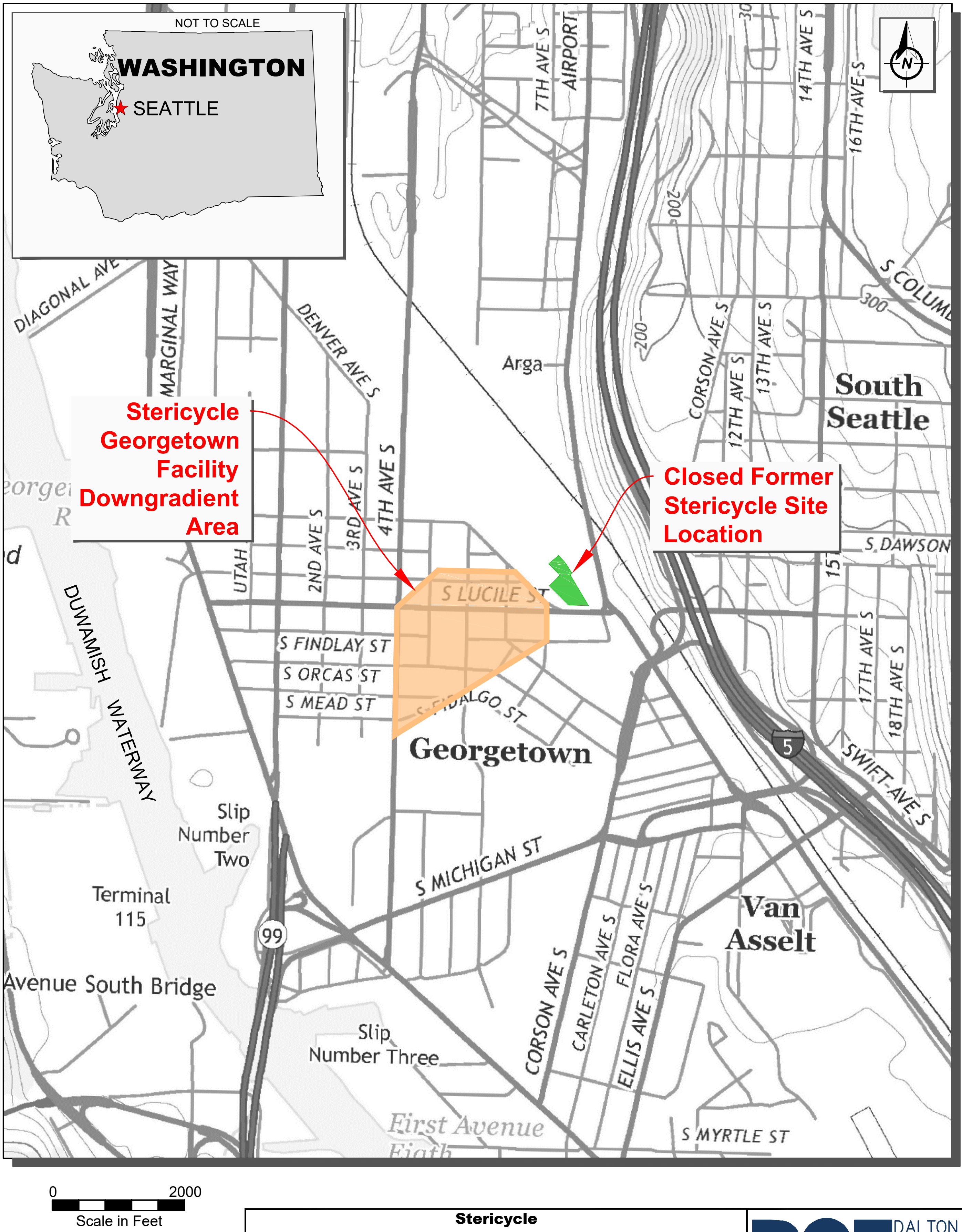
Notes:
1.) Conventionals include: pH, DO, ORP, temperature, specific conductance.
2.) Genetic and nutrient analysis will depend on the specific culture provided by Sentinel Environmental. A table of specific analyses to be performed will be provided for Ecology review prior to each injection event.

Abbreviations:

1,4-D = 1,4-dioxane	GW = groundwater
ft bgs = feet below ground surface	NA = not applicable

DOF

Figures



Stericycle

Georgetown Site Downgradient Area
Seattle, Washington

Site Location

DALTON OLMSTED FUGLEVAND

Figure
1

November 17, 2016

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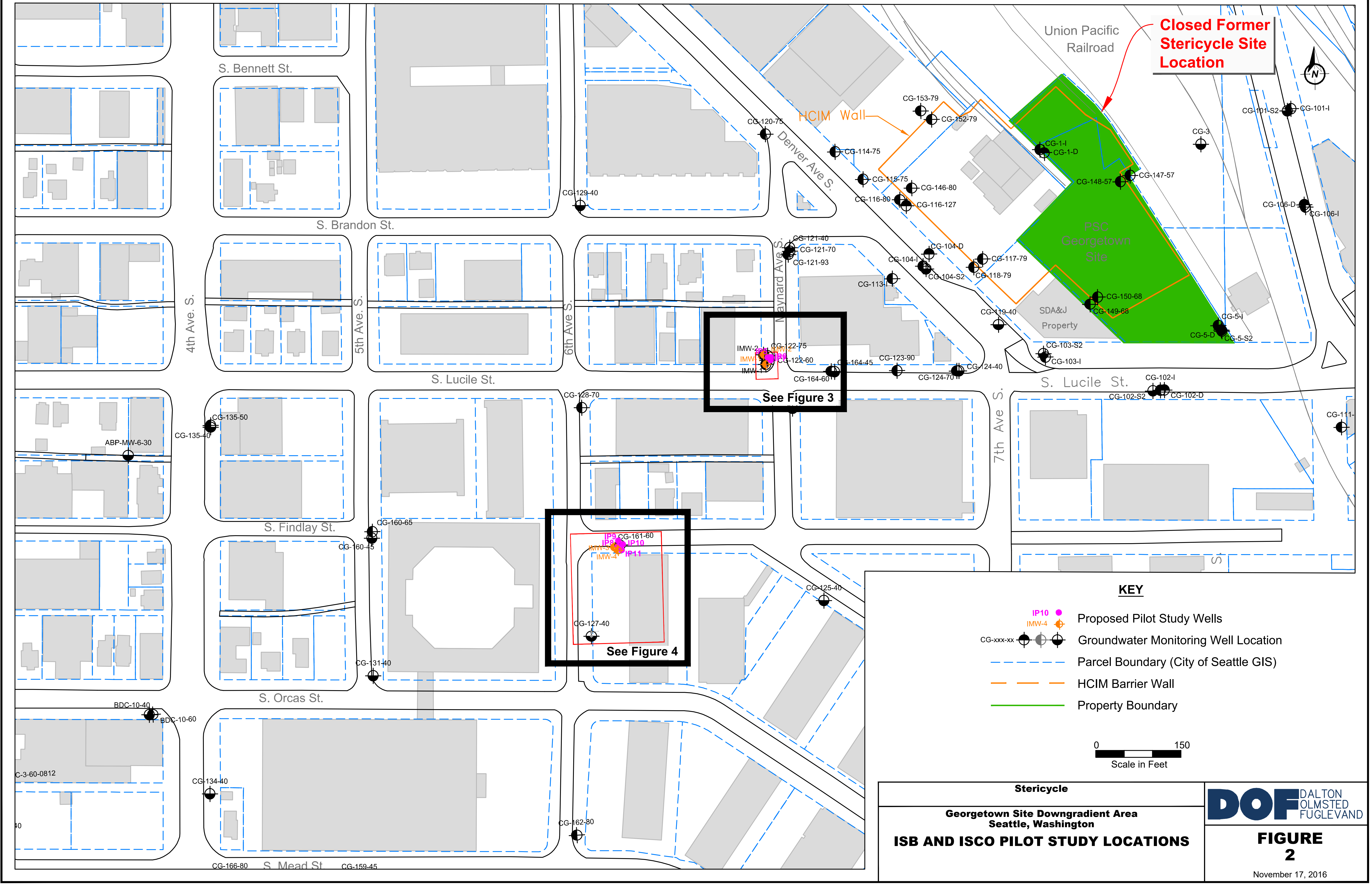

Stericycle

Georgetown Site Downgradient Area
Seattle, Washington

ISB AND ISCO PILOT STUDY LOCATIONS

DALTON OLMSTED FUGLEVAND

FIGURE
2

November 17, 2016

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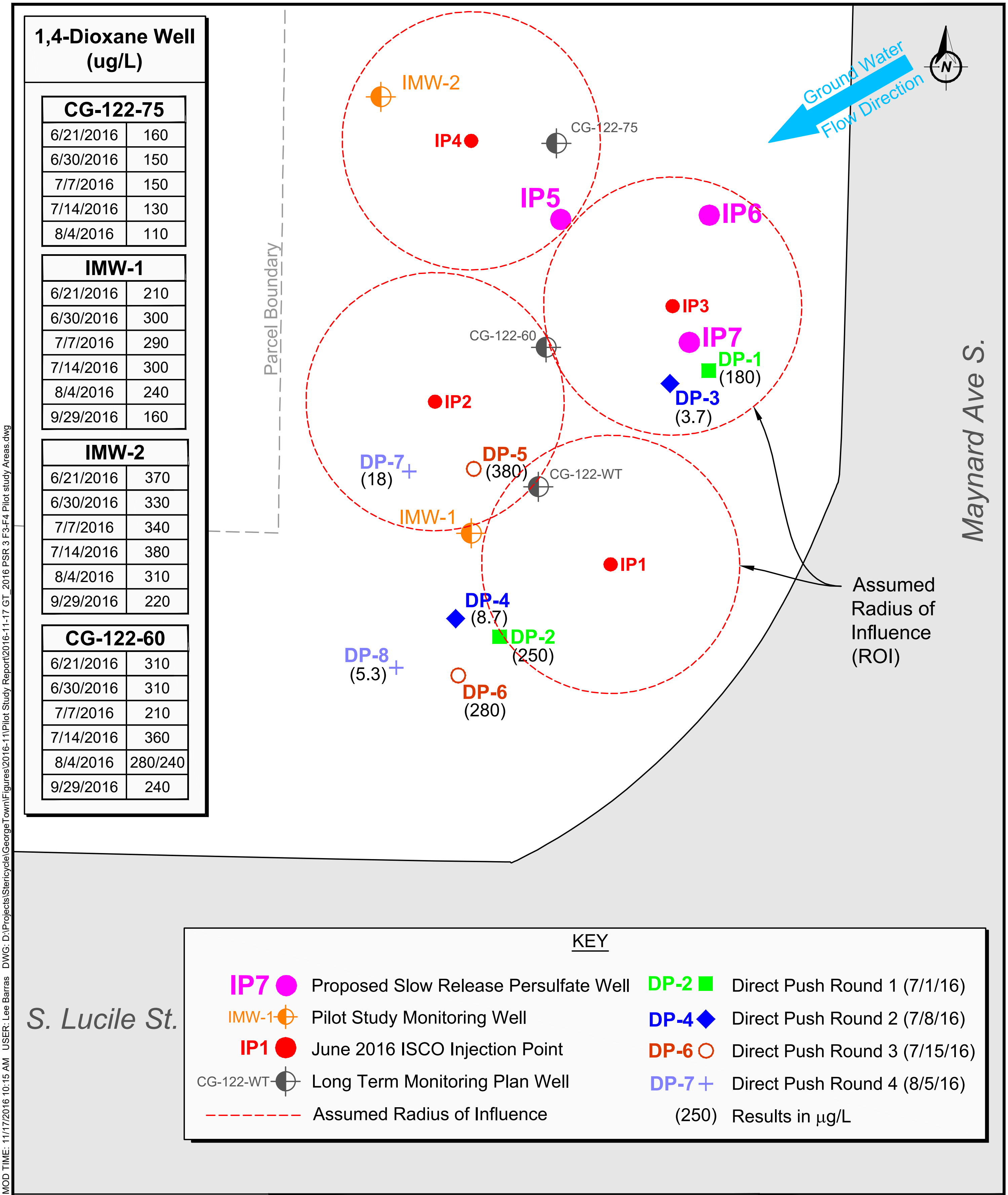


1,4-Dioxane Well (ug/L)

CG-122-75	
6/21/2016	160
6/30/2016	150
7/7/2016	150
7/14/2016	130
8/4/2016	110

IMW-1	
6/21/2016	210
6/30/2016	300
7/7/2016	290
7/14/2016	300
8/4/2016	240
9/29/2016	160

IMW-2	
6/21/2016	370
6/30/2016	330
7/7/2016	340
7/14/2016	380
8/4/2016	310
9/29/2016	220

CG-122-60	
6/21/2016	310
6/30/2016	310
7/7/2016	210
7/14/2016	360
8/4/2016	280/240
9/29/2016	240

KEY

IP7 ●	Proposed Slow Release Persulfate Well	DP-2 ■	Direct Push Round 1 (7/1/16)
IMW-1 ⊕	Pilot Study Monitoring Well	DP-4 ◆	Direct Push Round 2 (7/8/16)
IP1 ●	June 2016 ISCO Injection Point	DP-6 ○	Direct Push Round 3 (7/15/16)
CG-122-WT ⊕	Long Term Monitoring Plan Well	DP-7 +	Direct Push Round 4 (8/5/16)
- - - - - - -	Assumed Radius of Influence	(250)	Results in µg/L

0 5
Scale in Feet

Stericycle

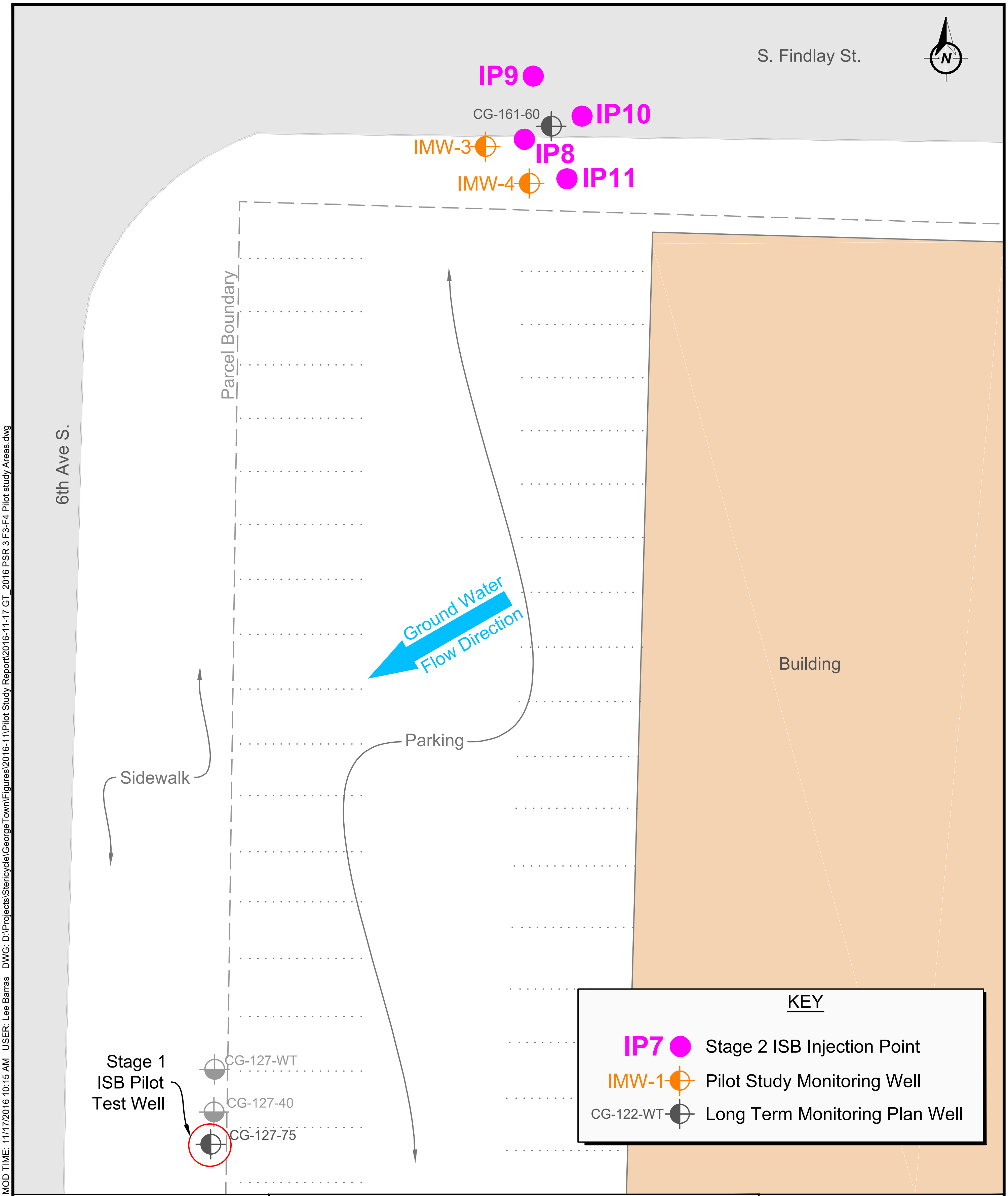
Georgetown Site Downgradient Area
Seattle, Washington

Proposed Slow Release Persulfate Wells

DOF DALTON OLMSTED FUGLEVAND

Figure 3

November 17, 2016



0 10
Scale in Feet

Stericycle

Georgetown Site Downgradient Area
Seattle, Washington

ISB Pilot Study Locations

DOF DALTON OLMSTED FUGLEVAND

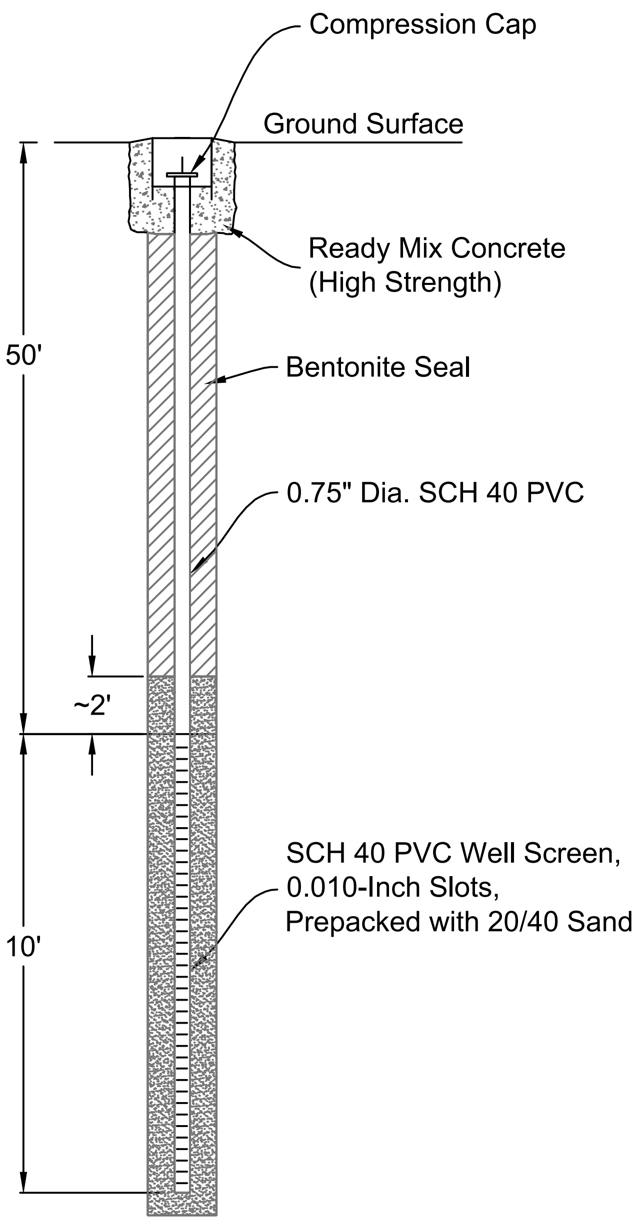
Figure 4

November 17, 2016

PLOT TIME: 11/17/2016 12:22 PM MOD TIME: 11/17/2016 10:15 AM USER: Lee Barras DWG: D:\Projects\Stericycle\GeorgeTown\Figures\2016-11\Pilot Study Report\2016-11-17 GT_2016 PSR 3 F3-F4 Pilot study Areas.dwg

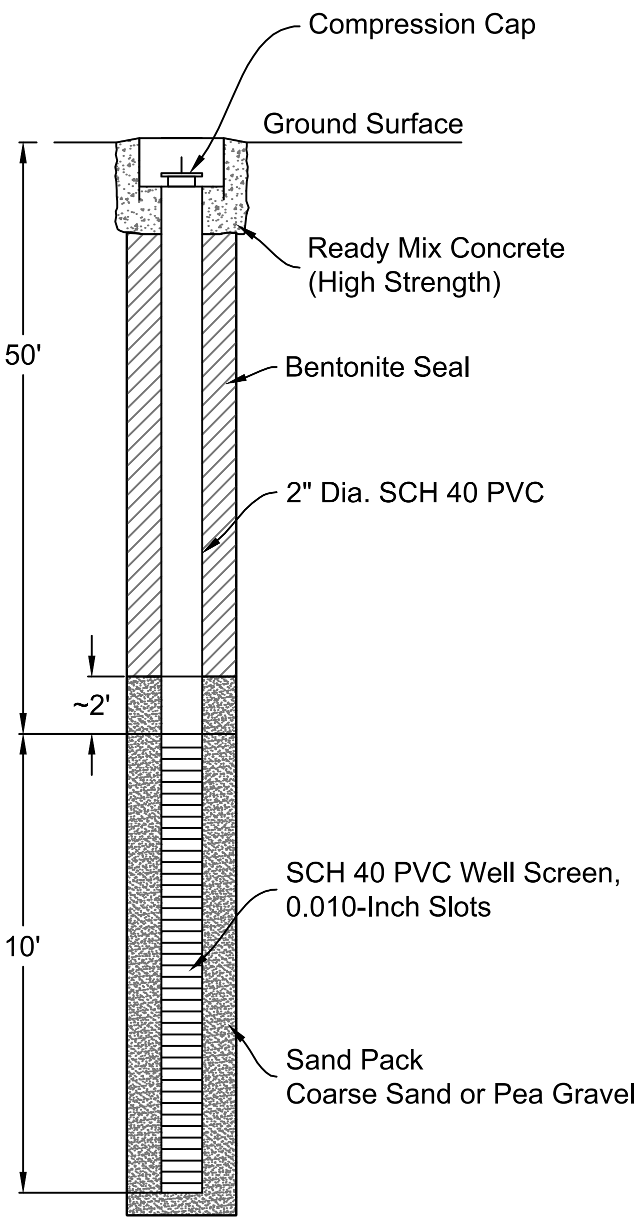
Semi-Permanent Monitoring Well

0.75-inch Diameter Well



Slow Release ISCO Well

2-inch Diameter Well



NOTE

1. Well depths and screen intervals are approximate. Final depth will be determined based on field observations.

Stericycle

Georgetown Site Downgradient Area
Seattle, Washington

New Well Details

DOF DALTON OLMSTED FUGLEVAND

Figure
5

November 17, 2016

PLOT TIME: 11/17/2016 12:22 PM MOD TIME: 11/17/2016 12:20 PM USER: Lee Barras DWG: D:\Projects\Stericycle\GeorgeTown\Figures\2016-11\Pilot Study Report\2016-11-17 GT_2016 PSR 5 F5 New Well Detail.dwg

Attachment A

Well Construction Diagrams, Boring Logs, and Survey Information

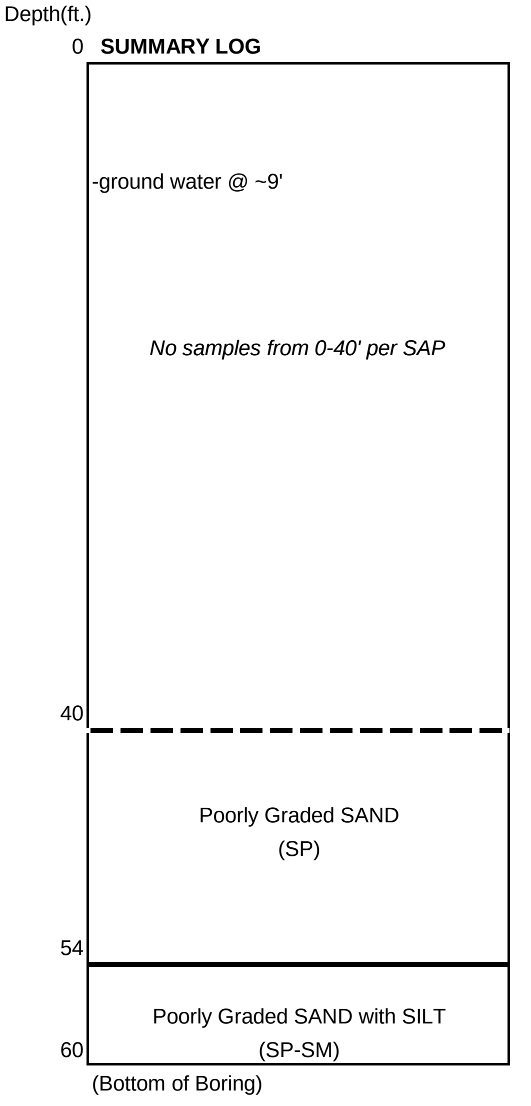
DESCRIPTION OF SAMPLES, TESTS, AND INSTALLATION - MONITORING WELL NO. IMW-1

Field Rep: D. Cooper
Reviewed by: D. Cooper, LG, LHG
Drilling Co.: Cascade
Location: N205475.6 E1271970.6 NAD83
Driller: Kyle
Ground surface elevation: 20.05 NAVD 88
Ground Surface:
Drill Type: GeoProbe 7730DT
Date Completed: 6/16/2016
Size/Type Casing: 2"
Drill Type: Direct-Push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic sleeve

Spl. No.	**Sample Interval (ft. bgs.)**	**PID (ppm)**	**Odor/ Sheen**	**Spl Depth (Ft.) From - To**	**Spl length (inches)**	**Time**	**Sample Description**
				0-40			No sampling from 0-40' according to SAP
	40	0.3	NO/NS	40-45	60		40.0-44.0' Sat, V Dk Gry (7.5YR-3/1), F-M SAND
	42	0.1	NO/NS				44.0-45.0' Sat, V Dk Gry, F SAND, w/trace silt
	44	0.2	NO/NS				F Sandy, SILT interbed @ 44.0-44.2'
	46	0.0	NO/NS	45-50	60		45.0-50.0' Sat, V Dk Gry, F-M SAND
	48	0.0	NO/NS				
	50	0.0	NO/NS				
	52	0.0	NO/NS	50-55	60		50.0-54.0' Sat, V Dk Gry, F-M SAND
	54	0.2	NO/NS				54.0-55.0' Sat, V Dk Gry, F SAND, w/trace to some silt
			NO/NS				
	56	0.2	NO/NS	55-60	60		55.0-60.0' Sat, V Dk Gry, F SAND, w/some silt
	58	0.1	NO/NS				1/4" silt interbeds @ 59.5'
	60	0.3	NO/NS				

Bottom of boring @ 60.0'

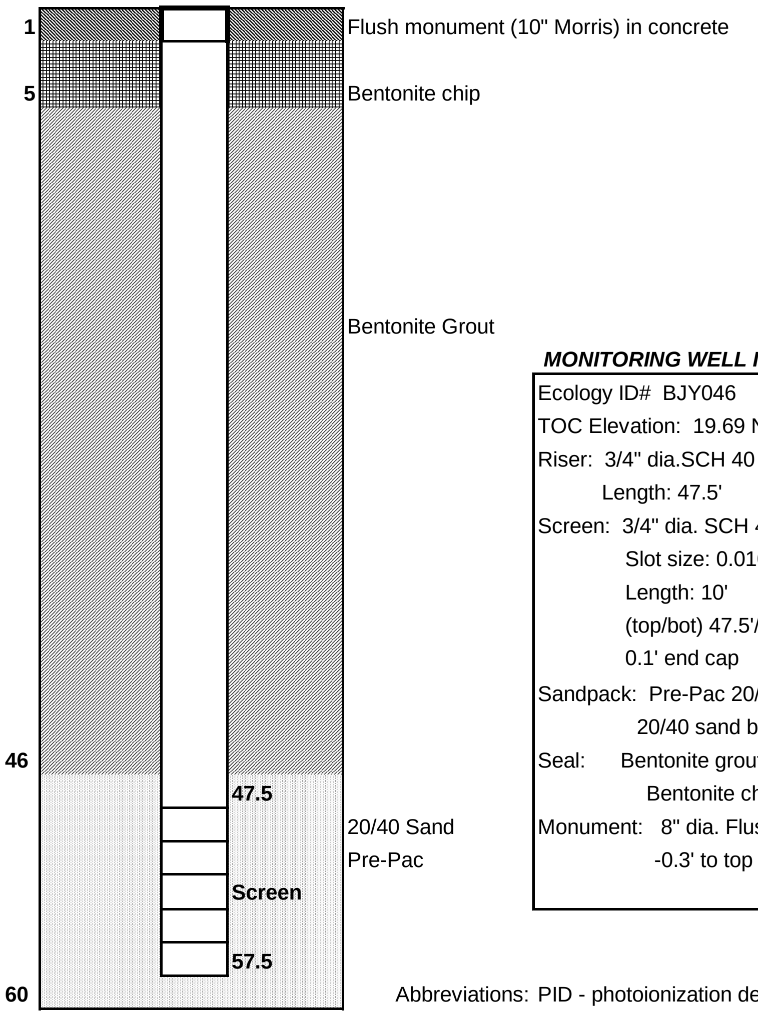
SUMMARY LOG



(Bottom of Boring)

NOTE: The summary log is an interpretation based on samples, drill action, and interpolation. Variations between what is shown and actual conditions should be anticipated.

MONITORING WELL DIAGRAM



MONITORING WELL INFORMATION

Ecology ID# BJY046
TOC Elevation: 19.69 NAVD 88
Riser: 3/4" dia.SCH 40 PVC
Length: 47.5'
Screen: 3/4" dia. SCH 40 PVC
Slot size: 0.010"
Length: 10'
(top/bot) 47.5'/57.5'
0.1' end cap
Sandpack: Pre-Pac 20/40 colorado sand
20/40 sand backfill (top/bot) 46'/58'
Seal: Bentonite grout (top/bot) 5'/46'
Bentonite chip (top/bot) 1'/5'
Monument: 8" dia. Flush Mount (Morris)
-0.3' to top of PVC/TOC

Abbreviations:
PID - photoionization detector - MiniRAE 3000
F - fine
M - medium
Sat. - saturated
mot - mottled
NS - no sheen
NO - no odor

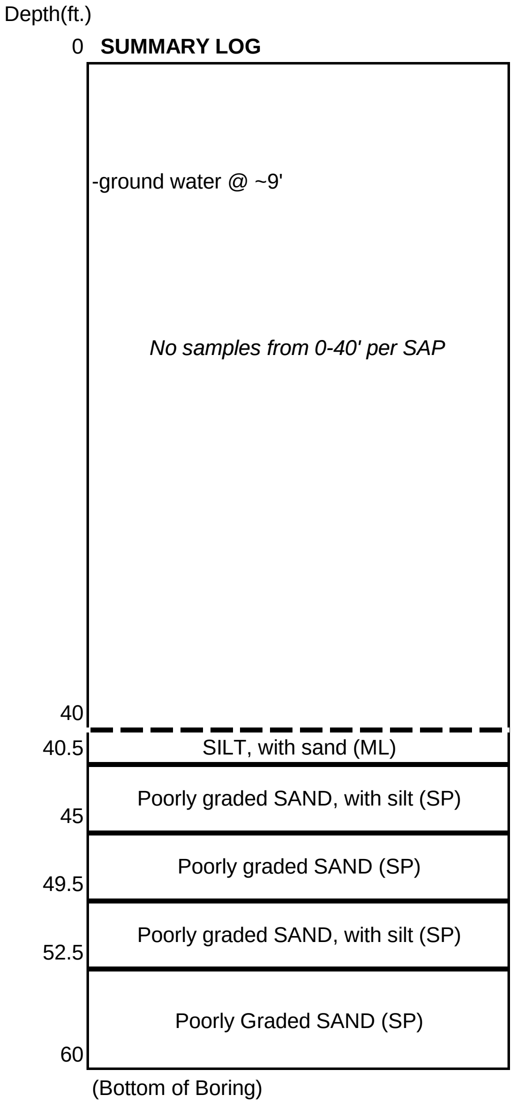
DESCRIPTION OF SAMPLES, TESTS, AND INSTALLATION - MONITORING WELL NO. IMW-2

Field Rep: D. Cooper
Drilling Co.: Cascade
Driller: Kyle
Drill Type: GeoProbe 7730DT
Size/Type Casing: 2"
Reviewed by: D. Cooper, LG, LHG
Location: N205474.5 E1271967.1 NAD83
Ground surface elevation: 20.14 NAVD 88 Ground Surface:
Date Completed: 6/16/2016
Drill Type: Direct-Push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic sleeve

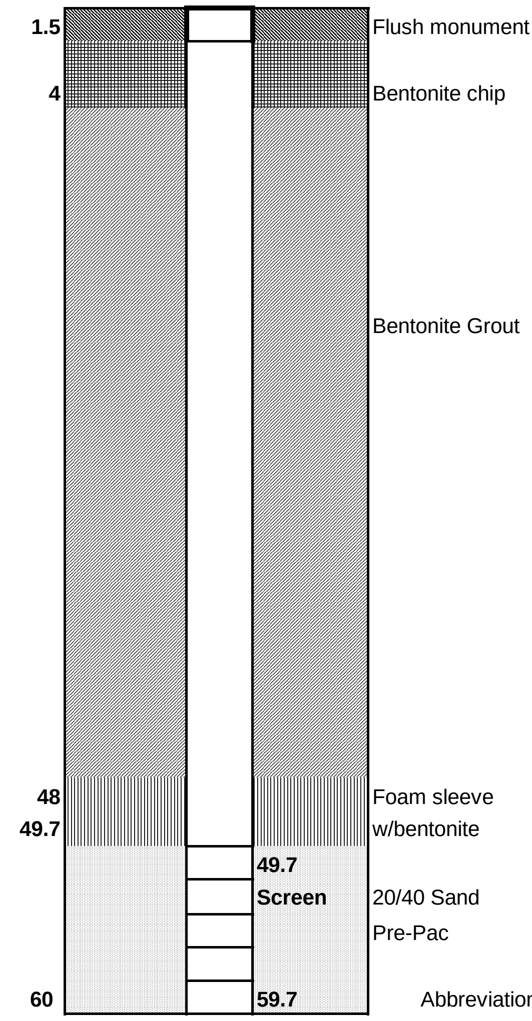
Spl. No.	Sample Interval (ft. bgs.)	PID (ppm)	Odor/ Sheen	Spl Depth (Ft.) From - To	Spl length (inches)	Time	Sample Description
				0-40			No sampling from 0-40' according to SAP
	40	1.6	NO/NS	40-45	60		40.0-40.5' Sat, V Dk Gry (7.5YR-3/1), SILT, w/some sand
	42	0.3	NO/NS				40.5-45.0' Sat, V Dk Gry, F SAND, w/some silt
	44	0.2	NO/NS				Thin SILT interbed @ 44.0-44.2'
	46	0.0	NO/NS	45-50	60		45.0-49.5' Sat, V Dk Gry, F-M SAND
	48	0.0	NO/NS				49.5-50' Sat, V DK Gry, F SAND, w/trace silt
	50	0.0	NO/NS				
	52	0.0	NO/NS	50-55	60		50.0-52.5' Sat, V Dk Gry, F SAND, w/trace silt
	54	0	NO/NS				52.5-55.0' Sat, V Dk Gry, F-M SAND, w/trace organics
			NO/NS				
	56	0.8	NO/NS	55-60	60		55.0-59.0' Sat, V Dk Gry, F-M SAND
	58	0.0	NO/NS				59.0-60.0' Sat, V Dk Gry, F SAND, w/silty F Sand interbeds
	60	0.0	NO/NS				

Bottom of boring @ 60.0'

SUMMARY LOG



MONITORING WELL DIAGRAM



MONITORING WELL INFORMATION

Ecology ID# BJY045
TOC Elevation: 19.82 NAVD 88
Riser: 3/4" dia.SCH 40 PVC
Length: 49.7'
Screen: 3/4" dia. SCH 40 PVC
Slot size: 0.010"
Length: 10'
(top/bot) 49.7'/59.7'
0.1' end cap
Sandpack: Pre-Pac 20/40 colorado sand
20/40 sand backfill (top/bot) 46'/58'
Seal: Bentonite grout (top/bot) 4'/49.7'
Bentonite chip (top/bot) 1.5'/4'
Monument: 8" dia. Flush Mount (Morris)
-0.3' to top of PVC/TOC

Abbreviations: PID - photoionization detector - MiniRAE 3000
F - fine
M - medium
Sat. - saturated
mot - mottled
NS - no sheen
NO - no odor

NOTE: The summary log is an interpretation based on samples, drill action, and interpolation. Variations between what is shown and actual conditions should be anticipated.

Dalton, Olmsted & Fuglevand, Inc.
Environmental Consultants

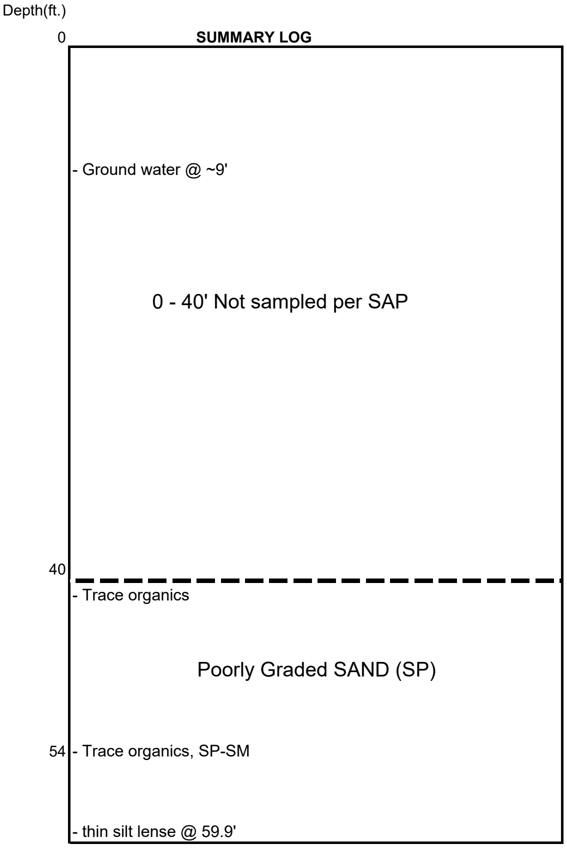
Stericycle GT

DP1

BORING - DESCRIPTION OF SAMPLES & DATA

Field Rep: DG Cooper L.G.
Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade
Location: N205463.9 E1271979.8 NAD83
Driller: Kyle
Elevation (Ft.): 19.82 NAVD88
Ground Surface: soil
Drill Type: Geoprobe 7730DT
Date Completed: 07/01/16
Size/Type Casing: 2"
Drill Type: Direct push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
	40		0	40-45	60		40.0-41.0' Sat, V Dk Gry (7.5YR-3/1), F SAND, w/trace organics
	42		0				41.0-45.0' Sat, V Dk Gry, F SAND
	44		0				
	46		0	45-50	40		45.0-50.0' Sat, V DK Gry, F SAND
	48		0				
	53	1.4	0	50-55	60		50-54.5' Sat, V DK Gry, F SAND
	55	0.7	0				54.5'-55.0' Sat, V Dk Gry, silty, F SAND, w/trace organics
							Milky / turbid pore water
	57	0-0.7	0	55-60	60		55.0-57.0' Sat, V Dk Gry, F SAND
	60	0-0.7	0				57.0-60.0' Sat, V Dk Gry, F-M SAND
							Thin silt lense @ 59.9'



60 (Bottom of Boring)
NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP1-070116 @ 1335

Groundwater parameters:

Temperature 19.5C
pH 7.2
Conductivity 791 uS/cm
Turbidity 170 ntu
ORP -84.2 mv
DO 0.4 mg/l
Sodium Persulfate 0 ppm

Completed boring backfilled with granular bentonite

Abbreviations:

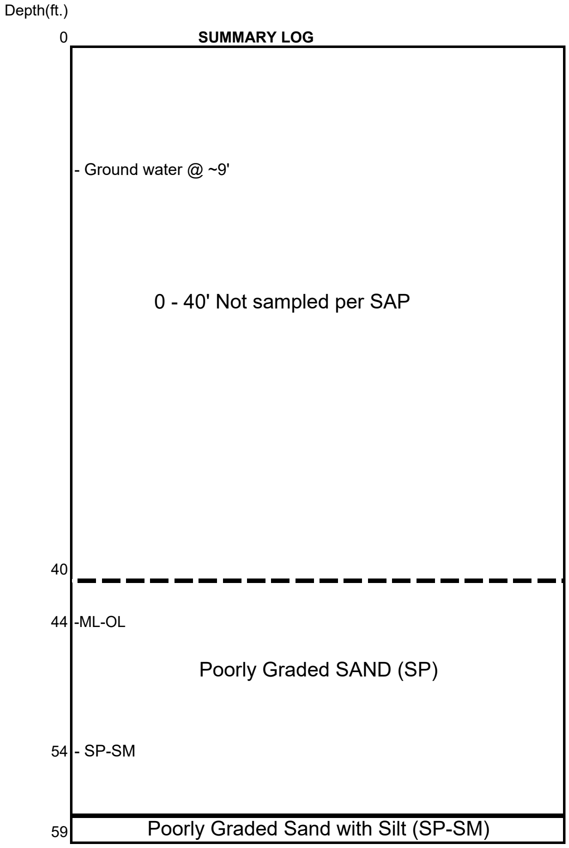
gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

BORING - DESCRIPTION OF SAMPLES & DATA

DP2

Field Rep: DG Cooper L.G.	Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade	Location: N205453.6 E1271971.7 NAD83
Driller: Kyle	Elevation (Ft.): 19.99 NAVD88 Ground Surface: Concrete sidewalk
Drill Type: Geoprobe 7730DT	Date Completed: 07/01/16
Size/Type Casing: 2"	Drill Type: Direct push Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
	40		0	40-45	60		40.0-41.0' Sat, V Dk Gry (7.5YR-3/1), F SAND, w/some organics
	42		0				41.0-45.0' Sat, V Dk Gry, F SAND
	44		0				Thin organic silt interbed @ 44.8'
	46		0	45-50	50		45.0-50.0' Sat, V DK Gry, F SAND
	48		0				Trace silt @ 49.5-50'
	50		0				
	51	0.7	0	50-55	50		50-55' Sat, V DK Gry, F SAND, w/trace silt
	53	0.7	0				Silty fine sand interbed @ 54.8'
	55	0-0.3	0				Milky / turbid pore water
	57	0.0	0	55-60	60		55.0-59.2' Sat, V Dk Gry, F SAND
	59.5	0-0.7	0				59.2-60.0' Sat, V Dk Gry, F SAND, w/some silt



60 (Bottom of Boring)

NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP2-070116 @ 1000

Groundwater parameters:

Temperature 18.6C
pH 7.3
Conductivity 1077 uS/cm
Turbidity >1000 ntu
ORP -61.3 mv
DO 0.3 mg/l
Sodium Persulfate 0 ppm

Completed boring backfilled with granular bentonite

Abbreviations:

gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

Dalton, Olmsted & Fuglevand, Inc.
Environmental Consultants

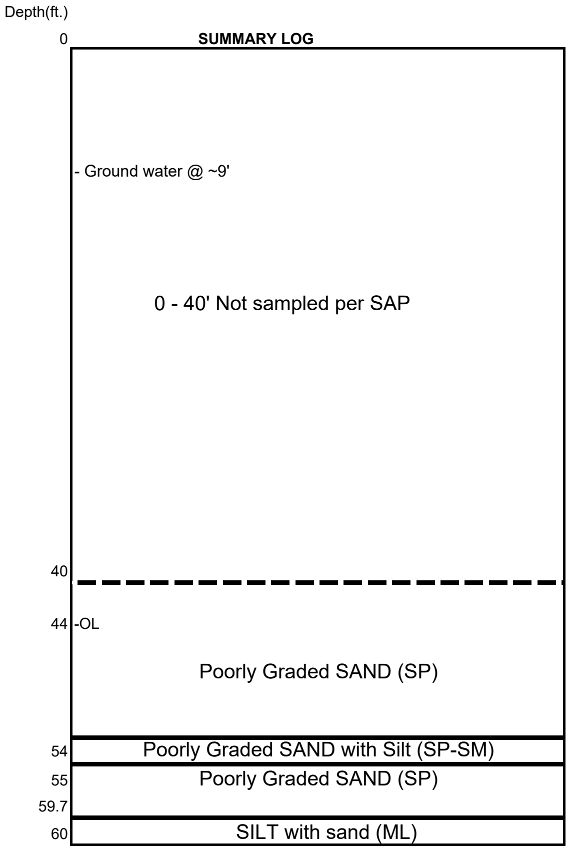
Stericycle GT

BORING - DESCRIPTION OF SAMPLES & DATA

DP3

Field Rep: DG Cooper L.G.
Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade
Location: N205463.4 E1271978.3 NAD83
Driller: Kyle
Elevation (Ft.): 19.94 NAVD88
Ground Surface: Soil
Drill Type: Geoprobe 6600
Date Completed: 07/08/16
Size/Type Casing: 2"
Drill Type: Direct push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
				40-45	60		40.0-41.5' Sat, V Dk Gry (7.5YR-3/1), F SAND, w/trace organics
	42		1.5				41.5-45.0' Sat, V Dk Gry, F SAND
	44		0				0.1' organic interbed @ 44'
	46		0.6	45-50	60		45.0-50.0' Sat, V DK Gry, F SAND
	48		0.8				
	50		0				
	52		0.7	50-55	60		50-55' Sat, V DK Gry, F SAND
	54		0.3				54-55' Sat, V Dk Gry, Silty, F SAND
	56		0.5	55-60	60		55.0-59.0' Sat, V Dk Gry, F-M SAND
	58		0.4				59.0-59.7' Sat, V Dk Gry, silty, F SAND, w/trace organics
							59.7-60.0' Sat, V DK Gry, F sandy, SILT



(Bottom of Boring)
NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP3-070816 @ 1300

Groundwater parameters:

Temperature	18.9C
pH	6.9
Conductivity	366 uS/cm
Turbidity	345 ntu
ORP	-20.2 mv
DO	0.1 mg/l
Sodium Persulfate	0.3 ppm

Completed boring backfilled with granular bentonite

Abbreviations:

gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

Dalton, Olmsted & Fuglevand, Inc.
Environmental Consultants

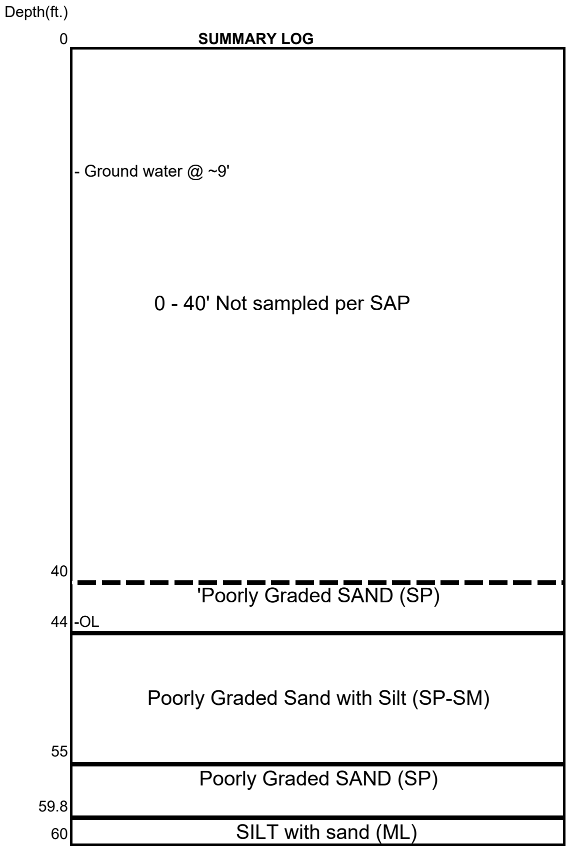
Stericycle GT

BORING - DESCRIPTION OF SAMPLES & DATA

DP4

Field Rep: DG Cooper L.G.
Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade
Location: N205454.3 E1271970.0 NAD83
Driller: Kyle
Elevation (Ft.): 20.00 NAVD88
Ground Surface: Concrete sidewalk
Drill Type: Geoprobe 6600
Date Completed: 07/08/16
Size/Type Casing: 2"
Drill Type: Direct push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
				40-45	60		40.0-45' Sat, V Dk Gry (7.5YR-3/1), F-M SAND
	42		0				Competent organic (twig) @ 43.8
	44		0				Organic silt interbed @ 44.8'
	46		1.3	45-50	60		45.0-44.5' Sat, V DK Gry, F SAND
	48		1.8				44.5-50' Sat, V Dk Gry, silty, F SAND
	50		0.8				
	52		0.3	50-55	60		50-54.6' Sat, V DK Gry, F SAND
	54		1.6				54.6-55.0' Sat, V Dk Gry, Silty, F SAND , w/thin silt interbeds
	56		0	55-60	60		55.0-59.8' Sat, V Dk Gry, F SAND
	58		0				59.8-60.0' Sat, V Dk Gry, F sandy, SILT
	60		0				



(Bottom of Boring)
NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP4-070816 @ 1030

Groundwater parameters:

Temperature	17.0C
pH	7.1
Conductivity	403 uS/cm
Turbidity	18 ntu
ORP	-6.2 mv
DO	0.2 mg/l
Sodium Persulfate	1.4 ppm

Completed boring backfilled with granular bentonite

Abbreviations:

gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

BORING - DESCRIPTION OF SAMPLES & DATA

DP5

Field Rep: DG Cooper L.G.	Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade	Location: N205460.1 E1271970.7 NAD83
Driller: Tim	Elevation (Ft.): 20.08 NAVD88 Ground Surface: Soil
Drill Type: Geoprobe 7730DT	Date Completed: 07/15/16
Size/Type Casing: 2"	Drill Type: Direct push Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
							No Soil sampling
							Direct-Push to reveal groundwater screen

Depth(ft.)

0 **SUMMARY LOG**

No Sampling due to Time limitations
Groundwater Sampling Only

(Bottom of Boring)

NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)

Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.

Water sample collected: DP4-071516 @ 1030

Groundwater parameters:

Temperature 23.3C
pH 7.4
Conductivity 989 uS/cm
Turbidity 279 ntu
ORP -12.1 mv
DO 0.4 mg/l
Sodium Persulfate 6 ppm

Completed boring backfilled with granular bentonite

Abbreviations:

gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

Dalton, Olmsted & Fuglevand, Inc.
Environmental Consultants

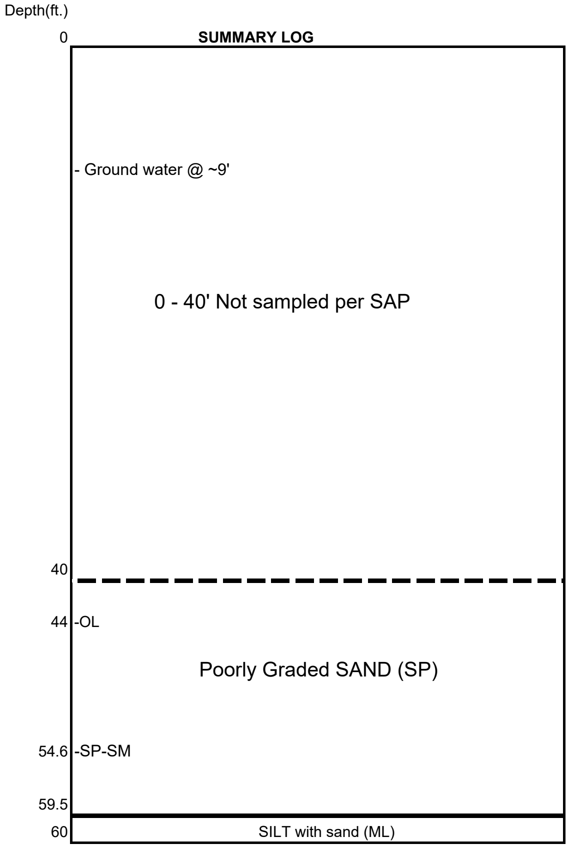
Stericycle GT

BORING - DESCRIPTION OF SAMPLES & DATA

DP6

Field Rep: DG Cooper L.G.
Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade
Location: N205452.2 E1271970.1 NAD83
Driller: Tim
Elevation (Ft.): 20.00 NAVD88
Ground Surface: Concrete sidewalk
Drill Type: Geoprobe 7730DT
Date Completed: 07/15/16
Size/Type Casing: 2"
Drill Type: Direct push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
				40-45	60		40.0-45' Sat, V Dk Gry (7.5YR-3/1), F-M SAND
	42		0				Competent organic (wood) @ 44'
	44		0				Silty Sand interbed @ 44.8'
				45-50	0		Sat, V DK Gry, F SAND observed
					Liner jammed		
	52		0.3	50-55	60		50-54.6' Sat, V DK Gry, F SAND
	54		1.6				54.6-55.0' Sat, V Dk Gry, Silty, F SAND , w/thin silt interbeds
	57		0	55-60	60		55.0-59.5' Sat, V Dk Gry, F-M SAND
	59		0				59.5-60.0' Sat, V Dk Gry, F sandy, SILT



(Bottom of Boring)

NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP6-071516 @ 1510

Groundwater parameters:

Temperature 20.0C
pH 7.2
Conductivity 1002 uS/cm
Turbidity 363 ntu
ORP -7.6 mv
DO 0.4 mg/l
Sodium Persulfate 3.5 ppm

Completed boring backfilled with granular bentonite

Abbreviations:

gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

Dalton, Olmsted & Fuglevand, Inc.
Environmental Consultants

Stericycle GT

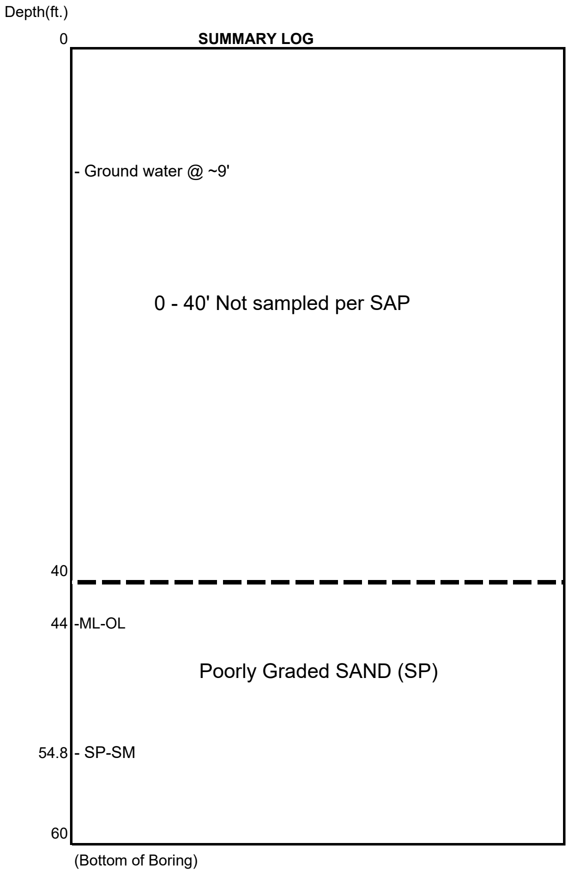
BORING - DESCRIPTION OF SAMPLES & DATA

DP7

Field Rep: DG Cooper L.G.
Drilling Co.: Cascade
Driller: Kyle
Drill Type: Geoprobe 6600
Size/Type Casing: 2"

Reviewed By: D. Cooper LG, LHG.
Location: N205460.0 E1271968.2 NAD83
Elevation (Ft.): 20.11 NAVD88 Ground Surface: Concrete sidewalk
Date Completed: 08/05/16
Drill Type: Direct push Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
				40-45	60		40.0-44.' Sat, V Dk Gry (7.5YR-3/1), F-M SAND
	42		0				44.6-45.0' Sat, V Dk Gry, F Sandy, SILT, interbedded, trace organics
	44		0				
	46		0.9	45-50	50		45.0-50.0' Sat, V DK Gry, F-M SAND, w/trace gravel
	48		1.2				
	50		1.3				
	52		0	50-55	50		50-55' Sat, V DK Gry, F-M SAND
	54		0.4				F Sandy Silt interbed @ 54.8'
			0.5				
	56		0.9	55-60	60		55.0-60.0' Sat, V Dk Gry, F-M SAND, w/trace gravel
	58		1.7				
	60		0.5				



(Bottom of Boring)
NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP7-080516 @ 1330

Groundwater parameters:
Temperature 17.8C
pH 7.1
Conductivity 1307 uS/cm
Turbidity 160 ntu
ORP -1.2 mv
DO 0.05 mg/l
Sodium Persulfate 0.7 ppm

Completed boring backfilled with granular bentonite

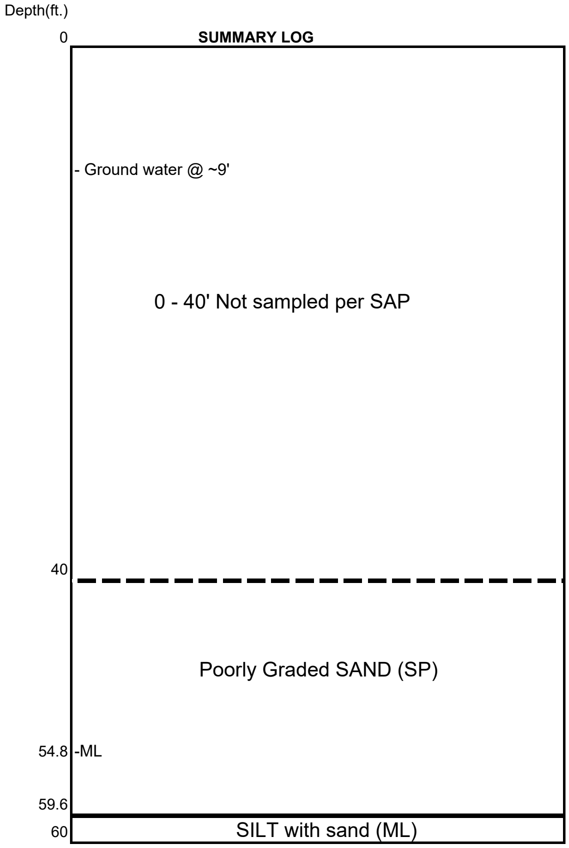
Abbreviations:
gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

BORING - DESCRIPTION OF SAMPLES & DATA

DP8

Field Rep: DG Cooper L.G.
Reviewed By: D. Cooper LG, LHG.
Drilling Co.: Cascade
Location: N205452.4 E1271967.7 NAD83
Driller: Tim
Elevation (Ft.): 20.05 NAVD88
Ground Surface: Concrete sidewalk
Drill Type: Geoprobe 7730DT
Date Completed: 08/05/16
Size/Type Casing: 2"
Drill Type: Direct push
Sampler Type: 5' long x 2" dia. Macro retained in an acrylic liner

Sample Number	Sample Interval (ft. bgs.)	Sodium Persulfate (ppm)	PID (ppm)	Spl Depth (Ft.) From - To	Spl length inches	Time	Sample Description
				0-40			No sampling from 0-40' per SAP
				40-45	60		40.0-45' Sat, V Dk Gry (7.5YR-3/1), F-M SAND
	42		0				
	44		0				
	46		0	45-50	60		45.0-49.0' Sat, V Dk Gry, F SAND, w/trace silt
	48		0				49.0-50.0' Sat, V Dk Gry, F-M SAND
	50		0				
	52		0	50-55	60		50-54.8' Sat, V DK Gry, F-M SAND
	54		0				54.8-55.0' Sat, V Dk Gry, F Sandy, SILT
	56		0	55-60	60		55.0-59.6' Sat, V Dk Gry, F-M SAND
	58		0				59.6-60.0' Sat, V Dk Gry, F sandy, SILT
	60		0				



(Bottom of Boring)
NOTE: The summary log is an interpretation based on samples, drill action and interpolation. Variations between what is shown and actual conditions should be anticipated.

Notes: Temporary Screen set @ 53-57' below ground surface consisting of Geoprobe SP16 SS screen (0.004 slot)
Water sample collected using peristaltic pump through 1/4" diameter polyethylene tubing with intake @ 55' bgs.
Water sample collected: DP8-080516 @ 1100

Groundwater parameters:

Temperature	23.5C
pH	6.9
Conductivity	429 uS/cm
Turbidity	102 ntu
ORP	63.0 mv
DO	0.17 mg/l
Sodium Persulfate	2.8 ppm

Completed boring backfilled with granular bentonite

Abbreviations:
gry = gray; bwn = brown; blk = black; mot = mottled
Sheen - NS= none, LS = Light, MS = Moderate, HS = Heavy
Odor - NO= None, SLO = Slight, MO = Moderate, STO = Strong
F = fine; M = medium
Sat = Pores saturated with water

GOLDSMITH
LAND DEVELOPMENT SERVICES

August 23, 2016

Dalton, Olmsted & Fuglevand
10827 NE 68th St.
Suite: B
Kirkland, WA 98033

Attention: Tasya Gray, LG

Re: Georgetown Facility (Geoprobe, Monitoring Well, and Injection Well Locations)

Dear Tasya,

At your request, we have obtained Y (northing), X (easting), and Z (elevation) coordinates for three (3) monitor well locations, two (2) injection well locations, and 12 geoprobe locations at the Georgetown Facility. The information was obtained on August 22, 2016 and reflects conditions at that time. The horizontal locations are either to the center of the existing monitor well / injection well casing or the approximate center of the existing geoprobes. The elevations shown reflect natural ground immediately adjacent (Z_1) to the monitor well or geoprobe site and the North rim of the pvc pipe in the casing (Z).

Geoprobe / Monitor Well / Injection Well Designation	**HGG Point Number**	**Northing (Y)**	**Easting (X)**	**Elevation (Z)** (TOP PVC PIPE)	**(Z_1)** (NAT. GRND)
DP-8	50000	205452.4	1271967.7		20.05
DP.6	50001	205452.1	11271970.1		20.00
DP-4	50002	205454.3	1271970.0		20.00
DP-2	50003	205453.6	1271971.7		19.99
DP-7	50004	205460.0	1271968.2		20.11
IP-2	50005	205462.7	1271969.2		20.02
DP-5	50006	205460.1	1271970.7		20.08
IP-1	50007	205456.4	1271976.0		19.91
DP-3	50008	205463.4	1271978.3		19.94
DP-1	50009	205463.9	1271979.8		19.82
IP-3	50010	205466.4	1271978.4		19.57
IP-4	50011	205472.8	1271970.6		20.12
IMW-2	50012	205474.5	1271967.1	19.82	20.14
IMW-1	50014	205457.6	1271970.6	19.69	20.05
CG122WT	50016	205459.4	1271973.2	19.60	20.13
CG-122-60	50018	205464.8	1271973.5	19.75	19.93
CG-122-75	50020	205472.7	1271973.9	19.52	19.97

For the purpose of this survey, we have utilized site benchmarks established by Goldsmith & Associates, Inc. in a prior survey. Enclosed with this letter is a copy of our letter (dated April 4, 2001) which discusses general control and datum utilized.

Should you have any questions regarding the nature of this survey, please do not hesitate to call.

Sincerely,

Mark A. Mauger

Mark A. Mauger, P.L.S. | GOLDSMITH

Sr. Survey Project Manager | 425.462.1080 |
mmauger@goldsmithengineering.com

8-23-16
MARK A. MAUGER
STATE OF WASHINGTON
29277
REGISTERED PROFESSIONAL LAND SURVEYOR
Mark A. Mauger

Attachment:
Letter dated 4/4/2001

Hugh G. Goldsmith
& Associates, Inc.

MAME WINNER
1995 Best Community Land Use
1994 Community of the Year
1994 Best Community Land Use
1992 Best Community Land Use
1990 Environmental Award
1990 Best Planned Community
1989 Best Community Land Use Plan
1987 Best Community Land Use Plan

April 4, 2001

Philip Services Corp.
955 Powell Avenue S.W.
Renton, WA 98055

Attention: Carolyn Mayer

Re: Georgetown Facility

Dear Carolyn:

At your request, we have obtained Y (Northing), X (Easting), and Z (Elevation) coordinates for the monitoring wells and soil sample locations at your Georgetown Facility. The information was obtained in March 2001 and reflects conditions at that time. All horizontal locations are to the approximate center of the existing monitor well or a painted location provided by Philip Services personnel. The elevations shown were obtained at the north side of the PVC pipe or blue cap affixed to said pipe (Z) of the wells and to either the rim, asphalt or natural ground immediately adjacent (Z_1) of the wells and soil sample locations.

For the purposes of this survey, we have utilized City of Seattle GPS survey control to bring horizontal and vertical control to the site. Horizontal information shown on Exhibit A (HGG data) is based on Washington State Plane Coordinate System, North Zone (North American Datum 1983/91). The basis of position is an existing 4″ diameter concrete monument with a ⅜″ diameter pin in case at the intersection of S. Stacy Street and 1st Avenue S. Monument has a ½″ brass tag stamped 1547 and is designated "City of Seattle GPS Survey Control Point #803," with a published coordinate of North 215869.69 (grid), East 1270024.19 (grid), Elevation 16.63 feet (NAVD 88). Units are expressed in U.S. survey feet. The basis of bearing is GPS derived Washington State Plane Coordinate System based on occupation of the above mentioned basis of position and simultaneous occupation of control points adjacent to the project area. A combination factor of 0.999992700 was applied to all GPS measurements to establish project coordinates for two control points within the project area resulting in the following values. Note: Only the basis of position is, therefore, a true grid state plane coordinate.

PST-2	Found 2½″ square concrete monument with nail in case at intersection of Maynard Avenue S. and S. Lucille Street North 205426.72, East 1271995.22, Elevation 19.25 feet (project coordinate)
PST-11	Set PK with flasher 8.0 southwest of southwest railroad tracks on southwest side E. Marginal Way S. and 7.0 northwest of southeast edge of pavement of drive to "J.A. Jack & Sons, Inc." approximately at the southwest corner of intersection of S. Brandon Street and E. Marginal Way North 205737.80, East 1278999.16, Elevation 16.29 feet (project coordinate)

The vertical information shown hereon is based on the North American Vertical Datum of 1988 (NAVD 88). The master benchmark utilized for this survey was the above noted City of Seattle GPS Survey Control Point #803.

A ground based traverse was then run through existing City of Seattle monumentation and HGG GPS Survey Control Points, at which time the monitor wells and soil sample locations were surveyed. Vertical information was obtained using trigonometric levels and a closed loop traversing method which resulted in closures within 0.1 foot vertically.

The information shown on Exhibit "B" (converted HDA data) was taken from a map labeled *"Chempro Georgetown Facility Well Locations"* by Horton Dennis & Associates (HDA) dated 4/07/95. For the purposes of this conversion we have accepted the monument found at the intersection of S. Lucille Street and Denver Avenue S. as the HDA Basis of Position (HDA coordinate value 10,000, 10,000). The Basis of Bearing was the monumented centerline of S. Lucille Street east of said Basis of Position, held as N 89°57′28″ E per HDA. A separate vertical comparison to the HDA data was obtained by running levels to the benchmark shown on the above referenced plan. Nine wells were then relocated as a check by Hugh G. Goldsmith & Associates, Inc. (HGG) personnel on 3/28/01. This resulted in a translation between HDA data and HGG data of:

Delta Y = +195414.589′
Delta X = +1262434.125′
Delta Z = +9.14′

In addition, HDA data was Rotated + 01°37′39″ to fit the HGG bearing system. As a result, all monitoring data (HGG and HDA) is now based on a common datum as described above.

If we can be of further assistance to you on this matter, please do not hesitate to call.

4-4-01
MARK A. MAUGER
29277
EXPIRES 8/21/01

Very truly yours,

HUGH G. GOLDSMITH & ASSOCIATES, INC.

Mark A. Mauger

Mark A. Mauger, P.L.S.

Attachment B

ISCO Pilot Study Field Forms

amec foster wheeler

CHEMICAL INJECTION LOGGING FORM
ISCO PILOT STUDY
Stericycle Georgetown Facility Downgradient Area

Field crew: L. Davidge, Cascade
Injection #: IP-1
Date: 6/23/2016 - 6/24/2016
Drilling rig: geoprobe
Probe injection Point (GPS): Lat / Lon — marked by DOF

Nearby Monitoring Well Monitoring

				(Initial)	(Final)
Well ID	IMW-2		Time	1046	1735
Distance from injection (ft)	20.5		DTW (ft BTOC)	8.63	NM
Direction from injection (N/S/E/W)	NW				

				(Initial)	(Final)
Well ID	CG-122-60*		Time		
Distance from injection (ft)	9.0		DTW (ft BTOC)		
Direction from injection (N/S/E/W)	NNW				

*cannot monitor due to geoprobe positioning

Well ID	IMW-1		Time	1048	1735
Distance from injection (ft)	5.5		DTW (ft BTOC)	8.74	NM
Direction from injection (N/S/E/W)	W				

Well ID			Time		
Distance from injection (ft)			DTW (ft BTOC)		
Direction from injection (N/S/E/W)					

NM - ~~Both~~ wells are under pressure so final WLs are not taken. Water is slowly leaking into monuments from leaking (but tightly sealed) casing. Water @ monument is >70 ppm persulfate by test kit at both wells.

SODIUM PERSULFATE wt%: 8.5%

each mix tan
45 gal 25%
105 gal wat

Sodium Persulfate Injection Monitoring

	Time	Injection depth (ft bgs) 50-60 ft	Injection Pressure (PSI) <45 psi	Persulfate Solution Flow Rate (gpm) 1-2 gpm	Dilution Water Flow Rate (gpm)	Notes	Pilot Study Depth (50-60 ft bgs)
6/23	13:05	51-53	8 psi	1.8 gpm	NA	Initial flow totalizer volume: 60 gal inj for 50-53 ft	lowered 1 ft
	15:00	50-52	10 psi	2.0 gpm			
	15:28	52-54	13 psi	2.6 gpm		60 gal injected	
	16:41	54-56	16 psi	1.0 gpm		60 gal injected	
	17:30	56-58	8 psi	1.0 gpm		50 gal injected	, 10 added on 6/24
6/24	11:08	58-60	10 psi	2.0 gpm			
						Final totalizer volume: 30283.1 Total volume injected (gal): 300 gals End injection time: 1108	

Comments

At 45 psi, initially no flow at 1st interval. With verbal approval from Ed (Ecy), onsite pressure was increased to 75 psi but still no flow. Cascade moved first interval to 51-53 ft then injected <10 psi and 1-2 gpm. Hole began leaking from tooling, so rods were removed at 1305 to reseal tooling. Reset @ 50-52 ft to continue injection interval.

amec foster wheeler

CHEMICAL INJECTION LOGGING FORM
ISCO PILOT STUDY
Stericycle Georgetown Facility Downgradient Area

Field crew: L. Davidge, Cascade
Injection #: IP-2
Date: 6/24/2016

Drilling rig: geoprobe
Probe injection Point (GPS): Lat / Lon: marked by DOF

Nearby Monitoring Well Monitoring

				(Initial)	(Final)
Well ID	1MW-2		Time	0848	1825
Distance from injection (ft)	12.0		DTW (ft BTOC)	8.58	NM
Direction from injection (N/S/E/W)	N				

NM-see note for IP-1 or field book

				(Initial)	(Final)
Well ID	CG-122-60		Time	0843	1825
Distance from injection (ft)	5.0		DTW (ft BTOC)	8.69	8.32
Direction from injection (N/S/E/W)	ENE				

Well ID	1MW-1		Time	0918	1825
Distance from injection (ft)	6.5		DTW (ft BTOC)	8.68	NM
Direction from injection (N/S/E/W)	SSE				

Well ID			Time		
Distance from injection (ft)			DTW (ft BTOC)		
Direction from injection (N/S/E/W)					

SODIUM PERSULFATE wt%: 8.5%

Sodium Persulfate Injection Monitoring

Time	Injection depth (ft bgs) 50-60 ft	Injection Pressure (PSI) <45 psi	Persulfate Solution Flow Rate (gpm) 1-2 gpm	Dilution Water Flow Rate (gpm)	Notes
14:18	50-52	34 psi	2gpm	NA	Initial flow totalizer volume: 17160.0 → 17220.8 (59.99)
14:47	52-54	22psi	2gpm		(55.7) 17275.4
15:05	54-56	65psi	2gpm		(7.21) 17282.7
					Final totalizer volume: 17287.0 Total volume injected (gal): 123 gals End injection time: 1505

Pilot Study Depth (50-60 ft bgs)

Comments

Second interval stopped at ~50 gal due to leak at the surface (slow drip from rods, contained by shop vac. Third interval doesn't inject <65psi. Cascade attempted to lower screen to 55-57 ft interval, but leak became more severe and injection location was abandoned. Flush 5 gals water through lines prior to probe removal.

CHEMICAL INJECTION LOGGING FORM
ISCO PILOT STUDY
Stericycle Georgetown Facility Downgradient Area

amec foster wheeler

Field crew: L. Davidge, Cascade

Injection #: IP-3

Date : 6/23/2016 – 6/24/2016

Drilling rig: : geoprobe

Probe injection: Lat / marked by

Point (GPS) Lon DOF

Nearby Monitoring Well Monitoring

Well ID	IMW-2
Distance from injection (ft)	13.5
Direction from injection (N/S/E/W)	NW

	(Initial)	(Final)
Time	1046	1755
DTW (ft BTOC)	8.63	NM

NM – see field form for IP-1 or field book.

Well ID	CG-122-60
Distance from injection (ft)	5.0
Direction from injection (N/S/E/W)	WSW

	(Initial)	(Final)
Time		
DTW (ft BTOC)		

cannot monitor due to geoprobe placement.

Well ID	IMW-1
Distance from injection (ft)	12.0
Direction from injection (N/S/E/W)	SW

Time	1048	1755
DTW (ft BTOC)	8.74	NM

Well ID	
Distance from injection (ft)	
Direction from injection (N/S/E/W)	

Time		
DTW (ft BTOC)		

SODIUM PERSULFATE wt%: 8.5%

Sodium Persulfate Injection Monitoring

	Time	Injection depth (ft bgs) 50-60 ft	Injection Pressure (PSI) <45 psi	Persulfate Solution Flow Rate (gpm) 1-2 gpm	Dilution Water Flow Rate (gpm)	Notes	Pilot Study Depth (50-60 ft bgs)
6/23	13:25	50-52	5 psi	1.3 gpm	NA	Initial flow totalizer volume: 60 gal injected	
	16:41	52-54	16 psi	1.0 gpm		60 gal inj.	
	17:30	54-56	8 psi	1.0 gpm		50 gal injected / add 10 gal on 6/24	
6/24		56-58	10 psi	2.0 gpm		60 gal	
		58-60	11 psi	2.0 gpm		60 gal	
						Final totalizer volume: 30343.7 Total volume injected (gal): 300 gals End injection time: 1140 @ 6/24	

Comments

Flush 6 gals potable water after injection – final totalizer reading 30349.2 ga

CHEMICAL INJECTION LOGGING FORM
ISCO PILOT STUDY
Stericycle Georgetown Facility Downgradient Area

amec foster wheeler

Field crew: L. Davidge, Cascade
Injection #: IP-4
Date: 6/24/2016

Drilling rig: geoprobe
Probe injection: ~~Lat~~ marked by
Point (GPS) ~~Lon~~ DOF

Nearby Monitoring Well Monitoring

Well ID	IMW-1
Distance from injection (ft)	16.0
Direction from injection (N/S/E/W)	S

	(Initial)	(Final)
Time	0918	1825
DTW (ft BTOC)	8.68	NM

NM - see note for IP-1 or field book

Well ID	CG-122-60
Distance from injection (ft)	9.0
Direction from injection (N/S/E/W)	~~NW~~ SSE

	(Initial)	(Final)
Time	0843	1825
DTW (ft BTOC)	8.69	8.32

Well ID	IMW-2
Distance from injection (ft)	4.0
Direction from injection (N/S/E/W)	NW

Time	0848	1825
DTW (ft BTOC)	8.58	NM

Well ID	
Distance from injection (ft)	
Direction from injection (N/S/E/W)	

Time		
DTW (ft BTOC)		

SODIUM PERSULFATE wt%: 815%

Sodium Persulfate Injection Monitoring

Time	Injection depth (ft bgs) 50-60 ft	Injection Pressure (PSI) <45 psi	Persulfate Solution Flow Rate (gpm) 1-2 gpm	~~Dilution Water Flow Rate (gpm)~~ volume injected	Notes
12:55	48-50	5psi	2gpm	12gals	Initial flow totalizer volume: 30349.2
13:18	50-52	5psi	2gpm	48 gals	(6006) 30409.3
13:50	52-54	28psi	2gpm	60.05gal	30469.4
14:18	54-56	8psi	2gpm	60.16gal	30529.4
14:47	56-58	6psi	2gpm	60.21gal	30592.6
15:28	58-60	7psi	2gpm	60.45gal	30649.9
					Final totalizer volume: 306538 Total volume injected (gal): 300 gals End injection time: 1528

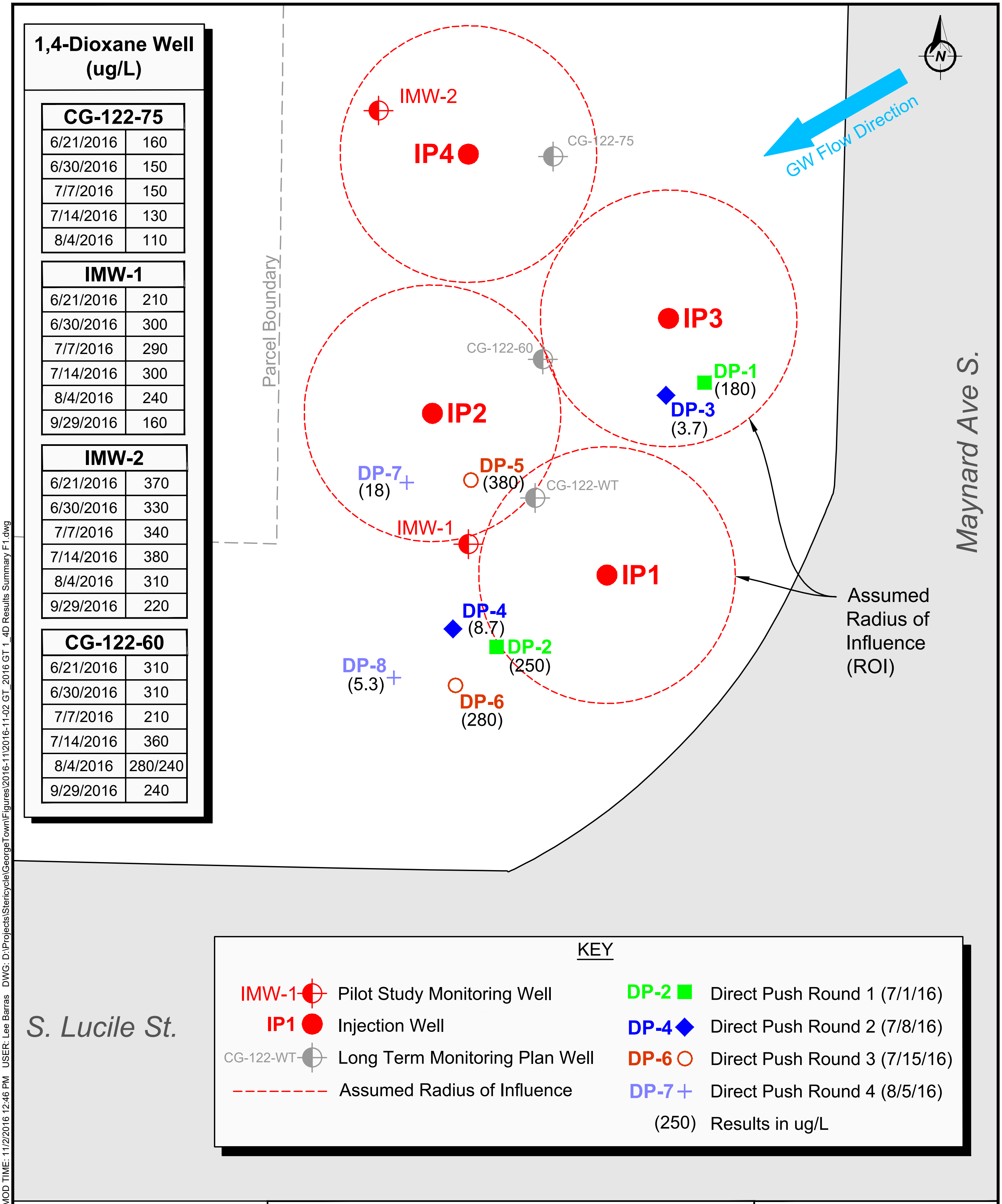
Pilot Study Depth (50-60 ft bgs)

Comments

Cascade crew accidentally began injection @ 48 ft, then moved to 50-52 ft when notified. Flush 4 gallons potable water through lines when finished.

Attachment C

ISCO Pilot Study Monitoring Summary



1,4-Dioxane Well (ug/L)

CG-122-75	
6/21/2016	160
6/30/2016	150
7/7/2016	150
7/14/2016	130
8/4/2016	110

IMW-1	
6/21/2016	210
6/30/2016	300
7/7/2016	290
7/14/2016	300
8/4/2016	240
9/29/2016	160

IMW-2	
6/21/2016	370
6/30/2016	330
7/7/2016	340
7/14/2016	380
8/4/2016	310
9/29/2016	220

CG-122-60	
6/21/2016	310
6/30/2016	310
7/7/2016	210
7/14/2016	360
8/4/2016	280/240
9/29/2016	240

0 5
Scale in Feet

Stericycle - Georgetown Facility
Seattle, Washington

1,4-Dioxane Groundwater Sampling
Summary of Pilot Study Results

DALTON OLMSTED FUGLEVAND

Figure 1

November 2, 2016

PLOT TIME: 11/2/2016 12:47 PM MOD TIME: 11/2/2016 12:46 PM USER: Lee Barras DWG: D:\Projects\Stericycle\GeorgeTown\Figures\2016-11\2016-11-02 GT_2016 GT 1_4D Results Summary F1.dwg

Figure 2. Sulfate Trends

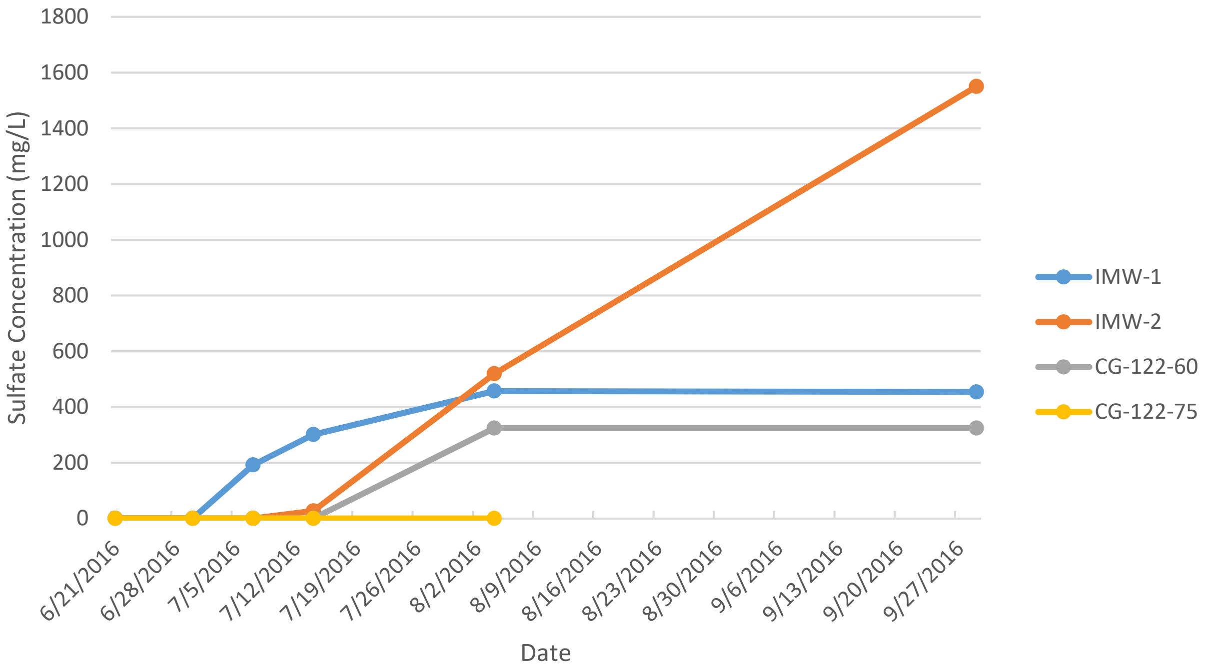
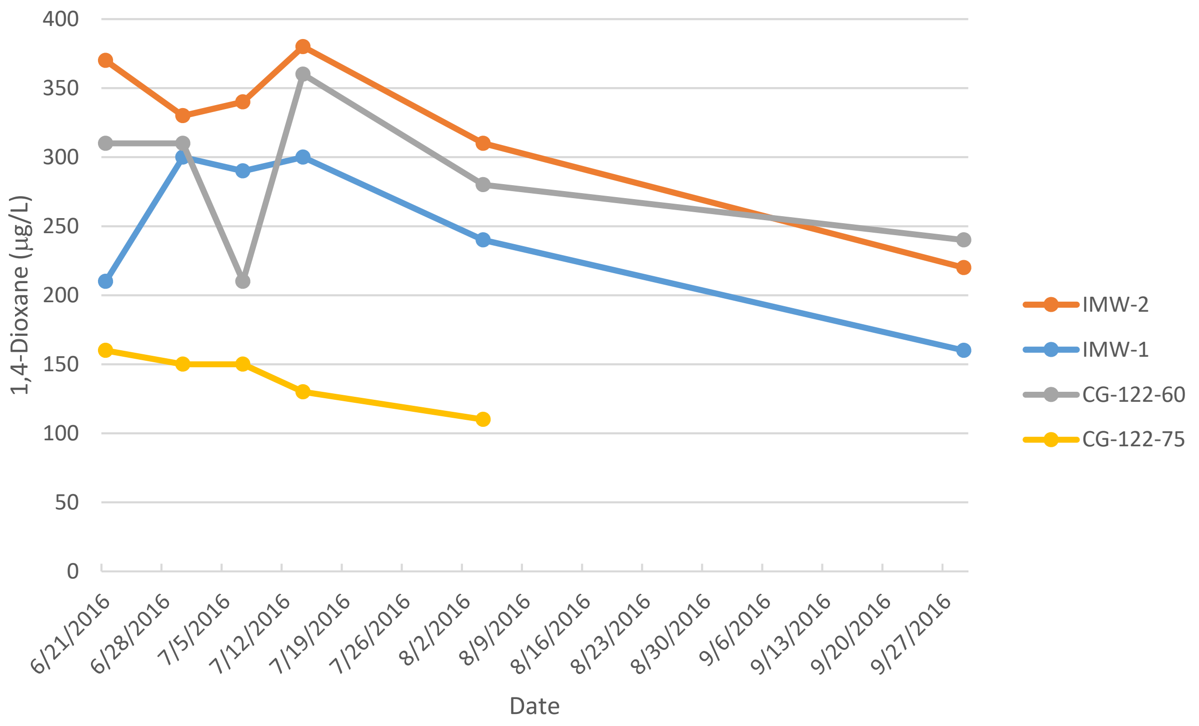


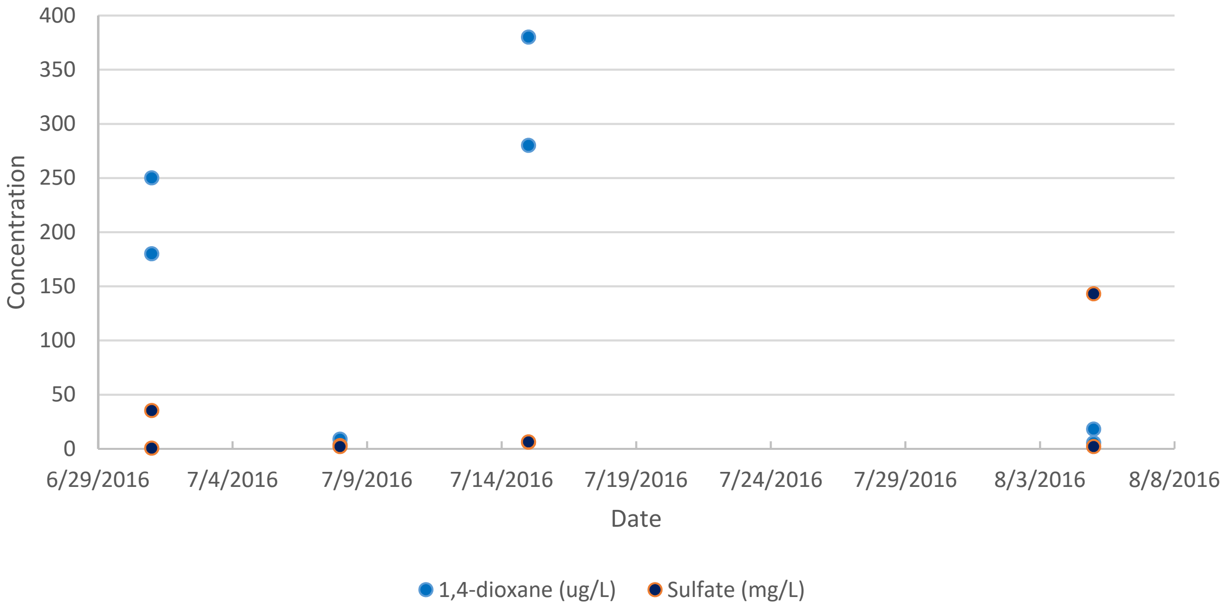
Figure 3. 1,4-Dioxane Trends



DOF

Stericycle Georgetown Facility
Seattle, Washington
2-Nov-16

Figure 4. Trends in Direct Push Samples (DP-1 through DP-8)



Stericycle Georgetown Facility
Seattle, Washington
2-Nov-16

Attachment D

ISCO Pilot Study Laboratory Data

(see attached CD)

Attachment E

Carus Specifications

SAFETY DATA SHEET

1. Identification

Product identifier	**Persulfate SR ISCO reagent**
Other means of identification	Not available.
Recommended use	In situ and ex situ chemical oxidation of contaminants and compounds of concern for environmental remediation applications.
Recommended restrictions	Use in accordance with supplier's recommendations.

Manufacturer/Importer/Supplier/Distributor information

Company name	CARUS CORPORATION
Address	315 Fifth Street, Peru, IL 61354, USA
Telephone	815 223-1500 - All other non-emergency inquiries about the product should be directed to the company
E-mail	salesmkt@caruscorporation.com
Website	www.caruscorporation.com
Contact person	Dr. Chithambarathanu Pillai
Emergency Telephone	For Hazardous Materials [or Dangerous Goods] Incidents ONLY (spill, leak, fire, exposure or accident), call CHEMTREC at CHEMTREC®, USA: 001 (800) 424-9300 CHEMTREC®, Mexico (Toll-Free - must be dialed from within country): 01-800-681-9531 CHEMTREC®, Other countries: 001 (703) 527-3887

2. Hazard(s) identification

Physical hazards	Oxidizing solids	Category 3
Health hazards	Acute toxicity, oral	Category 4 (30 % of the mixture consists of component(s) of unknown toxicity.)
	Skin corrosion/irritation	Category 2
	Serious eye damage/eye irritation	Category 2A
	Sensitization, respiratory	Category 1
	Sensitization, skin	Category 1
	Specific target organ toxicity, single exposure	Category 3 respiratory tract irritation
OSHA defined hazards	Not classified.	

Label elements

Signal word	Danger
Hazard statement	May intensify fire; oxidizer. Harmful if swallowed. Causes skin irritation. Causes serious eye irritation. May cause allergy or asthma symptoms or breathing difficulties if inhaled. May cause an allergic skin reaction. May cause respiratory irritation.

Precautionary statement

Prevention	Keep away from heat. Keep/Store away from clothing and other combustible materials. Take any precaution to avoid mixing with combustibles. Wear protective gloves/eye protection/face protection. Wash thoroughly after handling. Do not eat, drink or smoke when using this product. Avoid breathing dust/fume. In case of inadequate ventilation wear respiratory protection. Contaminated work clothing must not be allowed out of the workplace. Use only outdoors or in a well-ventilated area.

Response	In case of fire: Use foam, carbon dioxide, dry powder or water fog for extinction. If swallowed: Call a poison center/doctor if you feel unwell. Rinse mouth. If on skin: Wash with plenty of water. If skin irritation or rash occurs: Get medical advice/attention. Take off contaminated clothing and wash before reuse. If in eyes: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing. If eye irritation persists: Get medical advice/attention. If inhaled: If breathing is difficult, remove person to fresh air and keep comfortable for breathing. If experiencing respiratory symptoms: Call a poison center/doctor.
Storage	Store in a well-ventilated place. Keep container tightly closed. Store locked up.
Disposal	Dispose of contents/container in accordance with local/regional/national/international regulations.
Hazard(s) not otherwise classified (HNOC)	None known.

3. Composition/information on ingredients

Mixtures

Chemical name	CAS number	%
Sodium persulfate	7775-27-1	70

Composition comments	All concentrations are in percent by weight unless ingredient is a gas. Gas concentrations are in percent by volume.

4. First-aid measures

Inhalation	Move to fresh air. Do not use mouth-to-mouth method if victim inhaled the substance. For breathing difficulties, oxygen may be necessary. Call a physician or poison control center immediately.
Skin contact	Remove and isolate contaminated clothing and shoes. Immediately flush skin with plenty of water. Get medical attention immediately. For minor skin contact, avoid spreading material on unaffected skin. Wash clothing separately before reuse.
Eye contact	Immediately flush eyes with plenty of water for at least 15 minutes. Remove contact lenses, if present and easy to do. Continue rinsing. Get medical attention if irritation develops and persists.
Ingestion	Rinse mouth. Do not induce vomiting without advice from poison control center. If vomiting occurs, keep head low so that stomach content doesn't get into the lungs. Do not use mouth-to-mouth method if victim ingested the substance. Induce artificial respiration with the aid of a pocket mask equipped with a one-way valve or other proper respiratory medical device. Get medical attention if any discomfort continues.
Most important symptoms/effects, acute and delayed	May cause redness and pain. Symptoms may include coughing, difficulty breathing and shortness of breath.
Indication of immediate medical attention and special treatment needed	Provide general supportive measures and treat symptomatically.
General information	Ensure that medical personnel are aware of the material(s) involved, and take precautions to protect themselves.

5. Fire-fighting measures

Suitable extinguishing media	Water fog. Foam. Dry chemical powder. Carbon dioxide (CO2).
Unsuitable extinguishing media	None known.
Specific hazards arising from the chemical	Contact with combustible material may cause fire.
Special protective equipment and precautions for firefighters	Self-contained breathing apparatus and full protective clothing must be worn in case of fire.
Fire-fighting equipment/instructions	In the event of fire, cool tanks with water spray.
General fire hazards	May intensify fire; oxidizer.

6. Accidental release measures

Personal precautions, protective equipment and emergency procedures	Keep unnecessary personnel away. Keep people away from and upwind of spill/leak. Wear appropriate protective equipment and clothing during clean-up. Do not touch damaged containers or spilled material unless wearing appropriate protective clothing. Avoid skin contact and inhalation of vapors during disposal of spills. Ventilate closed spaces before entering them. Local authorities should be advised if significant spillages cannot be contained. For personal protection, see Section 8 of the SDS.
Methods and materials for containment and cleaning up	Stop the flow of material, if this is without risk. Prevent entry into waterways, sewer, basements or confined areas. Following product recovery, flush area with water. For waste disposal, see Section 13 of the SDS.
Environmental precautions	Avoid discharge into drains, water courses or onto the ground.

7. Handling and storage

Precautions for safe handling	Avoid inhalation of vapors/dust and contact with skin and eyes. Wash thoroughly after handling. Keep away from clothing and other combustible materials. Use only with adequate ventilation. Do not taste or swallow. Wear appropriate personal protective equipment (See Section 8). Observe good industrial hygiene practices.
Conditions for safe storage, including any incompatibilities	Store in original tightly closed container. Store away from incompatible materials (See Section 10). Keep locked up.

8. Exposure controls/personal protection

Occupational exposure limits

US. ACGIH Threshold Limit Values

Components	Type	Value
Sodium persulfate (CAS 7775-27-1)	TWA	0.1 mg/m3

Biological limit values	No biological exposure limits noted for the ingredient(s).
Appropriate engineering controls	Observe occupational exposure limits and minimize the risk of exposure. Ensure adequate ventilation, especially in confined areas.

Individual protection measures, such as personal protective equipment

Eye/face protection	Wear safety glasses with side shields (or goggles).
Skin protection	
Hand protection	Wear protective gloves.
Other	Neoprene or rubber gloves are recommended. Apron and long sleeves are recommended.
Respiratory protection	Wear positive pressure self-contained breathing apparatus (SCBA).
Thermal hazards	Wear appropriate thermal protective clothing, when necessary.
General hygiene considerations	Always observe good personal hygiene measures, such as washing after handling the material and before eating, drinking, and/or smoking. Routinely wash work clothing and protective equipment to remove contaminants.

9. Physical and chemical properties

Appearance	White solid.
Physical state	Solid.
Form	Solid.
Color	White.
Odor	Paraffinic.
Odor threshold	Not available.
pH	Not applicable.
Melting point/freezing point	140 °F (60 °C)
Initial boiling point and boiling range	Not applicable.
Flash point	Not available.
Evaporation rate	Not available.
Flammability (solid, gas)	Not available.

Upper/lower flammability or explosive limits

Flammability limit - lower (%)	Not available.
Flammability limit - upper (%)	Not available.
Explosive limit - lower (%)	Not available.
Explosive limit - upper (%)	Not available.
Vapor pressure	Not applicable.
Vapor density	Not applicable.
Relative density	1.18 (25°C)
Solubility(ies)	
Solubility (water)	Not available.
Partition coefficient (n-octanol/water)	Not available.
Auto-ignition temperature	Not available.
Decomposition temperature	Not available.
Viscosity	Not available.
Other information	
Oxidizing properties	Oxidizing.

10. Stability and reactivity

Reactivity	The product is stable and non-reactive under normal conditions of use, storage and transport.
Chemical stability	Material is stable under normal conditions.
Possibility of hazardous reactions	No dangerous reaction known under conditions of normal use.
Conditions to avoid	Contact with combustibles.
Incompatible materials	Combustible material. Oxidizing material. Reducing agents.
Hazardous decomposition products	No hazardous decomposition products are known.

11. Toxicological information

Information on likely routes of exposure

Ingestion	Harmful if swallowed.
Inhalation	May cause irritation to the respiratory system.
Skin contact	Causes skin irritation.
Eye contact	Causes serious eye irritation.
Symptoms related to the physical, chemical and toxicological characteristics	May cause redness and pain. Exposed individuals may experience eye tearing, redness, and discomfort. Symptoms may include coughing, difficulty breathing and shortness of breath. Exposed individuals may experience eye tearing, redness, and discomfort.

Information on toxicological effects

Acute toxicity	Harmful if swallowed.
Skin corrosion/irritation	Causes skin irritation.
Serious eye damage/eye irritation	Causes serious eye irritation.
Respiratory or skin sensitization	
Respiratory sensitization	May cause allergy or asthma symptoms or breathing difficulties if inhaled.
Skin sensitization	May cause an allergic skin reaction.
Germ cell mutagenicity	No data available.
Carcinogenicity	This product is not considered to be a carcinogen by IARC, ACGIH, NTP, or OSHA.

OSHA Specifically Regulated Substances (29 CFR 1910.1001-1050)

Not listed.

Reproductive toxicity	No data available.

Specific target organ toxicity - single exposure	May cause respiratory irritation.
Specific target organ toxicity - repeated exposure	No data available.
Aspiration hazard	Not applicable.
Chronic effects	Prolonged exposure may cause chronic effects.

12. Ecological information

Ecotoxicity	This product’s components are not classified as environmentally hazardous. However, this does not exclude the possibility that large or frequent spills can have a harmful or damaging effect on the environment.
Persistence and degradability	No data is available on the degradability of this product.
Bioaccumulative potential	No data available for this product.
Mobility in soil	Not available.
Other adverse effects	No data available.

13. Disposal considerations

Disposal instructions	Consult authorities before disposal. Dispose in accordance with all applicable regulations.
Hazardous waste code	The Waste code should be assigned in discussion between the user, the producer and the waste disposal company.
Waste from residues / unused products	Dispose of in accordance with local regulations.
Contaminated packaging	Empty containers should be taken to an approved waste handling site for recycling or disposal.

14. Transport information

DOT

UN number	UN1479
UN proper shipping name	Oxidizing solid, n.o.s. (Sodium persulfate)
Transport hazard class(es)	
Class	5.1
Subsidiary risk	-
Label(s)	5.1
Packing group	II
Environmental hazards	
Marine pollutant	No
Special precautions for user	Read safety instructions, SDS and emergency procedures before handling.
Special provisions	62, IB5, IP1
Packaging exceptions	None
Packaging non bulk	211
Packaging bulk	242

IATA

UN number	UN1479
UN proper shipping name	Oxidizing solid, n.o.s. (Sodium persulfate)
Transport hazard class(es)	
Class	5.1
Subsidiary risk	-
Label(s)	5.1
Packing group	II
Environmental hazards	No
ERG Code	5L
Special precautions for user	Read safety instructions, SDS and emergency procedures before handling.

IMDG

UN number	UN1479
UN proper shipping name	OXIDIZING SOLID, N.O.S. (Sodium persulfate)
Transport hazard class(es)	
Class	5.1
Subsidiary risk	-
Label(s)	5.1

Packing group	II
Environmental hazards	
Marine pollutant	No
EmS	F-A, S-Q
Special precautions for user	Read safety instructions, SDS and emergency procedures before handling. Read safety instructions, SDS and emergency procedures before handling.
Transport in bulk according to Annex II of MARPOL 73/78 and the IBC Code	This product is not intended to be transported in bulk.

15. Regulatory information

US federal regulations

This product is a "Hazardous Chemical" as defined by the OSHA Hazard Communication Standard, 29 CFR 1910.1200.
All components are on the U.S. EPA TSCA Inventory List.

TSCA Section 12(b) Export Notification (40 CFR 707, Subpt. D)

Not regulated.

OSHA Specifically Regulated Substances (29 CFR 1910.1001-1050)

Not listed.

CERCLA Hazardous Substance List (40 CFR 302.4)

Not listed.

Superfund Amendments and Reauthorization Act of 1986 (SARA)

Hazard categories

Immediate Hazard - Yes
Delayed Hazard - No
Fire Hazard - Yes
Pressure Hazard - No
Reactivity Hazard - No

SARA 302 Extremely hazardous substance

Not listed.

SARA 311/312 Hazardous chemical Yes

SARA 313 (TRI reporting)

Not regulated.

Other federal regulations

Clean Air Act (CAA) Section 112 Hazardous Air Pollutants (HAPs) List

Not regulated.

Clean Air Act (CAA) Section 112(r) Accidental Release Prevention (40 CFR 68.130)

Not regulated.

Safe Drinking Water Act (SDWA) Not regulated.

US state regulations

This product does not contain a chemical known to the State of California to cause cancer, birth defects or other reproductive harm.

US. Massachusetts RTK - Substance List

Not regulated.

US. New Jersey Worker and Community Right-to-Know Act

Sodium persulfate (CAS 7775-27-1)

US. Pennsylvania Worker and Community Right-to-Know Law

Not listed.

US. Rhode Island RTK

Not regulated.

US. California Proposition 65

US - California Proposition 65 - Carcinogens & Reproductive Toxicity (CRT): Listed substance

Not listed.

International Inventories

Country(s) or region	Inventory name	On inventory (yes/no)*
Australia	Australian Inventory of Chemical Substances (AICS)	Yes

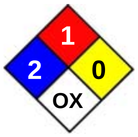
Country(s) or region	Inventory name	On inventory (yes/no)*
Canada	Domestic Substances List (DSL)	Yes
Canada	Non-Domestic Substances List (NDSL)	No
China	Inventory of Existing Chemical Substances in China (IECSC)	Yes
Europe	European Inventory of Existing Commercial Chemical Substances (EINECS)	Yes
Europe	European List of Notified Chemical Substances (ELINCS)	No
Japan	Inventory of Existing and New Chemical Substances (ENCS)	No
Korea	Existing Chemicals List (ECL)	Yes
New Zealand	New Zealand Inventory	Yes
Philippines	Philippine Inventory of Chemicals and Chemical Substances (PICCS)	Yes
United States & Puerto Rico	Toxic Substances Control Act (TSCA) Inventory	Yes

*A "Yes" indicates this product complies with the inventory requirements administered by the governing country(s).
A "No" indicates that one or more components of the product are not listed or exempt from listing on the inventory administered by the governing country(s).

16. Other information, including date of preparation or last revision

Issue date	12-August-2014
Revision date	-
Version #	01
Further information	NFPA Ratings: Health: 2 Flammability: 1 Physical hazard: 0 Hazard Scale: 0 = Minimal 1 = Slight 2 = Moderate 3 = Serious 4 = Severe HMIS® is a registered trade and service mark of the NPCA.
HMIS® ratings	Health: 2* Flammability: 0 Physical hazard: 1

NFPA ratings



List of abbreviations	NFPA: National Fire Protection Association.
References	Registry of Toxic Effects of Chemical Substances (RTECS) HSDB® - Hazardous Substances Data Bank
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CARUS
REMEDIATION

CAS Registry No. 7775-27-1 EINECS No. 231-892-1
CAS Registry No. 64742-51-4 EINECS No. 265-154-5

RemOx® SR Persulfate ISCO Reagent
FACT SHEET

RemOx® SR persulfate ISCO reagent has been specifically manufactured for environmental applications such as remediation of soils and associated groundwater. This product can be used to degrade a variety of contaminants including chlorinated ethenes, chlorinated ethanes, chlorinated methanes, benzene, toluene, ethylbenzene, and xylene, methyl tertiary butyl ether, polyaromatic hydrocarbons, petroleum hydrocarbons, 1,4-dioxane and pesticides.

REMEDIATION GRADE

RemOx SR persulfate is manufactured with sodium persulfate. Sodium persulfate meets specifications for assay.

Assay	>98.2% as $Na_2S_2O_8$

CHEMICAL/PHYSICAL DATA

Formula	$Na_2S_2O_8$ in paraffin wax
Formula Weight	$Na_2S_2O_8$: 238.1 g/mol
	Wax: not determined
Form	Extruded solid of granular crystalline inside wax

Congealing point of wax is 54-57° C/ 129-134° F

Paraffin wax will start to melt at 55° C/ 132° F

DESCRIPTION

Sodium persulfate crystals or granules are white encapsulated in a clear wax.

Standard sizes are 1.35 in (3.4 cm) or 2.5 in (6.4 cm) diameter by 18 in (45.7 cm) long with 70-75 % by weight $Na_2S_2O_8$.

APPLICATIONS

RemOx SR persulfate was developed to provide a sustained release of sodium persulfate for soil and groundwater treatment. RemOx SR persulfate can be emplaced in the subsurface using direct push technology or suspended into existing wells. This technology can be used for source treatment as well as barrier applications.

SHIPPING CONTAINERS

1.35 in (3.4 cm) by 18 in (45.7 cm) cylinders - Qty 12/box Corrugated box that is 12.5 in (31.75 cm) by 10.625 in (26.987 cm) by 22 in (55.88 cm) with foam insert. Weight of box is 3.383 lbs (1.534 kg). Weight per cylinder is 1.931 lbs (0.875 kg) or 23.172 lbs (10.510 kg) per box. Total weight of box and cylinders is 26.555 lbs (12.045 kg). (Domestic and international)

2.5 in (6.4 cm) by 18 in (45.7 cm) cylinder - Qty 6/box Corrugated box that is 12.5 in (31.75 cm) by 10.625 in (26.987 cm) by 22 in (55.88 cm) with foam insert. Weight of box is 3.303 lbs (1.498 kg). Weight per cylinder is 6.348 lbs (2.879 kg) or 38.088 lbs (17.276 kg) per box. Total weight of box and cylinders is 41.391 lbs (18.774 kg). (Domestic and international)

Specialty packaging above was designed to insure delivery of cylinders without breakage.

Orders can only be placed as full boxes in multiples of 6 or 12 depending on the cylinder dimensions.

Packaging meets UN performance-oriented packaging requirements.

SHIPPING

RemOx SR persulfate is classified as an oxidizer in accordance with the classification requirements of the Hazardous Materials Transportation regulations. It is shipped under Interstate Commerce Commission's (ICC) Tariff 19.

Proper Shipping Name:	Oxidizing solid, n.o.s. (sodium persulfate) (RQ- 100)
Hazard Class:	Oxidizer
Identification Number:	UN 1479
Label Requirements:	Oxidizer
Packaging Requirements:	49 CFR Parts 100 to 199
Sections:	173.152, 173.153, 173.194

Shipping Limitations:

Minimum quantities:

Rail car: See Tariff for destination

Truck: No minimum

Postal regulations:

Information applicable to packaging of oxidizers for shipment by the U.S. Postal Service to domestic and foreign destinations is readily available from the local postmaster. United Parcel Service accepts 25 lbs as largest unit quantity properly packaged; (consult United Parcel Service). Regulations concerning shipping and packing should be consulted regularly due to frequent changes.

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CARUS
REMEDIATION

CAS Registry No. 7775-27-1 EINECS No. 231-892-1
CAS Registry No. 64742-51-4 EINECS No. 265-154-5

RemOx® SR Persulfate ISCO Reagent
FACT SHEET

CORROSIVE PROPERTIES

RemOx® SR persulfate ISCO reagent is compatible with materials including butyl rubber, EPDM, fiber reinforced plastic, glass, neoprene, plexiglass, polyethylene, PVC, stainless steel, Teflon®, viton. Incompatible materials include aluminum, carbon steel, galvanized pipe, monel, nitrile rubber, brass, copper, iron, and nickel. Refer to Material Compatibility Chart.

Actual studies should be made under the conditions in which RemOx SR persulfate will be used.

HANDLING, STORAGE, AND INCOMAPTIBILITY

Protect containers against physical damage. Eye protection should also be worn when handling RemOx SR persulfate. Avoid breathing vapors or mists of the wax. Exposure or inhalation may cause irritation.

Store in a cool, clean, dry place away from point of sources of heat. Concrete floors are preferred to wooden decks. To clean up spills and leaks, follow the steps recommended in the MSDS or eSDS. Be sure to use goggles, rubber gloves, and respirator when cleaning up a spill or leak.

Avoid contact with acids, halides, combustible materials, most metals and heavy metals, oxidizable materials, other oxidizers, reducing agents, cleaners, and organic or carbon containing compounds. <u>Fires may be controlled and extinguished by using large quantities of water. Refer to the MSDS or eSDS for more information.</u>

RemOx SR persulfate is stable under normal conditions. Do not expose to sparks, heat, open flames, or hot surfaces. It is important that smoking is not allowed in proximity to RemOx SR persulfate. Do not cut with any cutting tool which could produce friction (i.e. hand saws, circular saws, reciprocal saws, etc.) as it may cause ignition of the material.

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Attachment F

Bioagumentation Guidance

93 Bioaugmentation

M. L. B. da Silva · P. J. J. Alvarez
Department of Civil and Environmental Engineering, Rice University,
Houston, TX, USA
silva@ens.ufsc.br
alvarez@rice.edu

K. N. Timmis (ed.), *Handbook of Hydrocarbon and Lipid Microbiology*, DOI 10.1007/978-3-540-77587-4_356,

Abstract: Bioaugmentation is receiving increasing attention as an approach to augment the catabolic potential at contaminated sites and enhance the biodegradation of recalcitrant priority pollutants. This chapter discusses the merits and limitations of bioaugmentation, and presents case studies and guidelines for its successful implementation as a bioremediation approach.

1 Introduction

Bioaugmentation consists of the addition (augmentation) of specialized microbial cultures, which are typically grown separately under well defined conditions, to perform a specific remediation task in a given environment (in situ or in a bioreactor) (Alvarez and Illman, 2006). This approach has been utilized in agriculture since the 1800s (e.g., addition of nitrogen-fixing *Rhizobium* spp. to legume roots (Gentry et al., 2004) and is now increasingly being use to enhance biodegradation of recalcitrant organic pollutants in groundwater and soils.

Two distinct bioaugmentation approaches have been developed. One is based on the injection of microorganisms with the desired catabolic potential to complement or replace native microorganism's population. In this case, the selected bacteria or consortia are capable of surviving and outcompeting native microorganisms, and occupy a specific metabolic niche within the contaminated environment (Vogel and Walter, 2002). The second bioaugmentation approach consists of the addition of a large concentration of cells that act momentarily as biocatalysts and degrade a significant amount of the target contaminant before becoming inactive or perishing (Duba et al., 1996; Krumme et al., 1994). In this case the inoculated microorganisms are not capable of establishing because of inherent abiotic and biological stress found in the new environment. These include fluctuations or extreme temperature, pH, water activity, low nutrient levels toxic pollutant concentrations, and competition with indigenous microorganisms (Gentry et al., 2004). In such cases, frequent biomass re-injection is required over time because the inoculated cells are incapable of flourishing in situ. Biostimulation (i.e., addition of nutrients and other stimulatory substrates and/or electron acceptors as appropriate) is generally used concomitantly with bioaugmentation to improve survival of the added cells and/or to optimize their metabolic capabilities (➲ *Table 1*), thus resulting in robust long term biodegradation efficiency.

Bioaugmentation in wastewater activated sludge systems is relatively easy to accomplish because the added microorganisms can be readily mixed in the reactor and reaction conditions can be manipulated to enhance their survival and performance (e.g., improved flocculation and settling of biomass, faster nitrification, and enhanced degradation of recalcitrant compounds). On the other hand, bioaugmentation of aquifers is more challenging and should anticipate challenges related to the survival of the added strains, their distribution throughout the contaminated zone (which is often affected by biomass growth near the injection wells), and low concentration of nutrients and target contaminants that serve as substrates to the added microorganisms. Even so, the benefits of bioaugmentation have been demonstrated in field trials for a wide variety of recalcitrant contaminants (➲ *Table 1*) and thus has become of increasing commercial interest over the past decade. For example, the Green Pages (www.eco-web.com) lists 632 companies that match the keyword "bio-augmentation." Nonetheless, the success of bioaugmentation cannot always be demonstrated due to the difficulty to assess

Table 1

Selected bioaugmentation case studies

Reference	Inoculum	Scale	Results and conclusions
Duba et al. (1996)	*Methylosinus trichosproium* OB3b	Field-scale	A buffer phosphate solution (10 mM) containing bacteria (1,800 L; 5 × 10^4 cells/mL) were injected into aerobic (2–7 mg/L dissolved oxygen) groundwater (425 ppb TCE) through a single well. Approximately 50% of the bacteria attached to sediment forming a fixed-bed reactor removed 40% of the mass of TCE (20 g) in 40 days. TCE concentrations met regulatory limits only during 2 days
Imamura et al. (1997)	strain JM1	Pilot-scale	A lysimeter was filled with sandy soil and contaminated with TCE. Strain JM1, which cometabolically transforms TCE, was injected into the lysimeter. Degradation of TCE were monitored. Growth of strain JM1 was hindered by low oxygen and TCE concentrations in the soil
Bourquin et al. (1997)	*Burkholderia cepacia* PR1301	Field-scale	First injection of a cometabolic TCE degrading bacterium that constitutively expresses toluene ortho-monooxygenase degraded TCE to a non-detect level in 24 h and maintained for 4 days. Bacterial concentration was too high (10^9 cells/mL, grown on glucose) and clogged the aquifer interfering with groundwater flow. Second step-wise injections at lower microbial concentrations resulted in complete degradation when cell concentrations reached 10^8/mL
Dybas et al. (1998)	*Pseudomonas stutzeri* KC	Field-scale	Bacteria (1,500 L; 2.3±1.3 × 10^7cells/mL of strain KC) were injected into a carbon tetrachloride (CT) contaminated aquifer. The pH (8.3) was buffered with acetate (1,600 mg/L), phosphate (10mg/L), NaOH (0.75 mequiv/L) amended groundwater. CT levels decreased ∼65% through aerobic and cometabolic transformations. Final sediment analysis indicated a 60–88% removal and persistence of *P. stutzeri* KC
Weiner and Lovley (1998)	Benzene-oxidizing, sulfate-reducing enrichment from aquatic sediments.	Pilot-scale	Benzene, which was persistent in sulfate-reducing sediments collected from a petroleum-contaminated aquifer, was degraded only after incubation with freshwater sediment adapted to benzene-oxidation coupled to sulfate reduction 1 mM. The results showed that the lack of measurable benzene degradation in the sulfate-reducing zones of some aquifers may be due to the absence of specific benzene-degrading sulfate reducers

Table 1 (Continued)

Reference	Inoculum	Scale	Results and conclusions
Steffan et al. (1999)	*Burkholderia cepacia* ENV 435	Field-scale	*B. cepacia* aerobically and cometabolically transforms chlorinated ethenes except PCE. Bacteria (550 L; $\cong 8 \times 10^{10}$ cells/L) were injected with oxygen (20 mg/L) into an aquifer contaminated with chlorinated ethenes at concentrations of 1,000 to 2,500 μg/L. The added strain migrated through the test plot at similar linear velocities to the bromide tracer. Total mass of TCE, *cis*-DCE, and vinyl chloride was reduced by as much as 78% within 2 days
El Fantroussi et al. (1999)	*Desulfomonile tiedjei*	Pilot-scale	*D. tiedjei* was injected ($\cong 1.6 \times 10^{8}$ cells/L) into soil bioreactors contaminated with 3-chlorobenzoate (313 mg/L). Acetate plus formate were used as primary substrates. Complete dechlorination was observed. First demonstration of applicability and limitations of pilot-scale soil bioaugmentation with a pure anaerobic dechlorinating strain of bacterium
Ellis et al. (2000)	Mixed enrichment culture (DOE's Pinellas culture)	Field-scale	Aquifer contaminated with TCE (4,800 μg/L) and cis-DCE (1,200 μg/L) was bioaugmented (350 L; 2×10^{11} cells/L) with a microbial enrichment culture capable of dechlorinating TCE to ethene. Groundwater was fed 200 mg/L lactate 1 day after bioaugmentation. Natural attenuation was observed at the site previous to bioaugmentation with an accumulation of *cis*-DCE. Within 90 days, vinyl chloride and ethene appeared in monitoring wells. By day 509, TCE and *cis*-DCE were fully dechlorinated to ethene
Salanitro et al. (2000)	Mixed consortium (MC-100)	Field-scale	MC-100 is a microbial consortium capable of aerobically degrading MTBE. Within 30 days of bioaugmentation with MC-100 and oxygen gas injection, and through 261 days, MTBE was degraded to non-detect levels. A byproduct, tert-butyl alcohol, was also degraded to non-detect levels
Henssen et al. (2001)	Mixed culture	Pilot-scale	Bioreactors anaerobically dechlorinated PCE to approximately 60% ethene. Effluent was allowed to infiltrate into a contaminated aquifer along with a carbon source. Natural attenuation of PCE to *cis*-DCE occurred. Complete dechlorination (ethene production) was observed after 4 weeks in monitoring wells 3.5 m and after 8 weeks in monitoring wells 7 m from infiltration point
Lendvay et al. (2001)	*Dehalococcoides* and *Desulfuromonas*	Field-scale	Natural attenuation of PCE was occurring with TCE, *cis*-DCE, and vinyl chloride observed in the plume. Lactate (9 mg/L) and nutrients were added prior to bioaugmentation and continued throughout study. Approximately 210 L of culture ($1.12 \pm 0.06 \times 10^{11}$ cells/L) was added. Complete dechlorination to ethene was observed in less than 50 days

Major et al. (2002)	Mixed culture KB-1 (*Dehalococcoides ethenogenes*)	Field-scale	Site was contaminated with PCE and lesser amounts of TCE and *cis*-DCE. A closed loop recirculation test plot was bioaugmented with KB-1 (13L $\cong 10^9$ cells/L) mixed culture containing *Dehalococcoides ethenogenes*. Methanol (115.3 mg/L) and acetate (216.2 mg/L) were added as electron donors. Molecular analysis prior to bioaugmentation showed no *D. ethenogenes*. Trace amounts of vinyl chloride were present after 16 days, and ethene was detected after 52 days. By day 142, ethene was the dominant product. Molecular analysis showed *D. ethenogenes* was present throughout the test plot
Straube et al. (2003)	*Pseudomonas aeruginosa* strain 64 (a biosurfactant producer)	Pilot-scale	Soil from the POPILE, Inc. Superfund site (PAHs at 13,000 mg/kg, average and PCP at 1,500 mg/kg, average) was used. Microcosms biostimulated with ground rice hulls as a bulking agent and dried blood as a slow-release nitrogen showed a 34% decrease in total PAHs, while the biostimulated and bioaugmented microcosms revealed an 87% decrease
Da Silva and Alvarez (2004)	Methanogenic consortia enriched with benzene (Ulrich and Edwards, 2003) or toluene and *o*-xylene (Ficker et al., 1999)	Pilot-scale	Flowthrough aquifer columns were used to investigate the potential of bioaugmentation to enhance anaerobic BTEX degradation in groundwater contaminated with ethanol-blended gasoline. Anaerobic benzene biodegradation was only observed after bioaugmentation (15 L; 3.1×10^{12} cells/L), and this removal efficiency was sustained for 1 year with no significant decrease in permeability due to bioaugmentation
Yu et al. (2005)	PAH-degrading bacterial consortium enriched from mangrove sediments.	*Pilot-scale*	Microcosms amended with 10‰ synthetic groundwater showed removal of over 97% PAHs. Bioaugmentation (5.8×10^7 cells/L) did not show significant effects compared to natural attenuation. Inhibitory effects were observed in the bioaugmented treatments. The results suggested that indigenous microorganisms may out compete with the enriched consortium during PAH biodegradation
Da Silva et al. (2006); Adamson et al. (2003)	Anaerobic dechlorinating consortium (Zheng et al., 2001)	*Pilot-scale*	Two 11.7 m^3 Experimental Controlled Release Systems (ECRS) packed with sand were contaminated with (PCE). One ECRS was bioaugmented directly into the source zone (15 L; 3.1×10^{12} cells/L). The other ECRS was only biostimulated. HRC®, and later dissolved lactate served as the electron donor. Bioaugmentation enhanced PCE mass removal compared to biostiumualtion alone
Atagana (2006)	Enrichment of indigenous microorganisms	Pilot-scale	The combination of biostimulation with ammonium-phosphate and H_2O_2 and bioaugmentation ($4.5\text{–}5.6 \times 10^7$ cells/L) enhanced PAH reduction by 100% compared to biostimulation only (between 90% and 100%)

Table 1 (Continued)

Reference	Inoculum	Scale	Results and conclusions
Maes et al. (2006)	*Desulfitobacterium dichloroeliminans* strain DCA1	Field-scale	1,2-dichloroethane (1,2-DCA)-contaminated groundwater was treated at an industrial site using bioaugmentation ($\cong 5 \times 10^{10}$ cells/L) and biostimulation (lactate: 3,603.1 mg/L, yeast extract: 50,000 mg/L, $NaHCO_3$: 84,000 mg/L). The groundwater flow distribution and migration of strain DCA1 were assessed using transport model MOCDENS3D. 1,2-DCA concentration decreased from 93 to 0.089 mg/L in 35 days
Malina and Zawierucha (2007)	Enrichment of indigenous or exogenous bacteria	*Pilot-scale*	The effects of bioaugmentation on the biodegradation of hydrocarbons were compared to biostimulation (by H_2O_2 or $KMnO_4$). Bioaugmentation enhanced biodegradation rates by two to four times higher than the rates of intrinsic biodegradation
Jacques et al. (2008)	Enrichment of PAH-degrading bacteria from the contaminated site (*Mycobacterium fortuitum*, *Bacillus cereus*, *Microbacterium* sp., *Gordonia polyisoprenivorans*, *Microbacteriaceae bacterium*)	*Pilot-scale*	The effects of bioaugmentation on the biodegradation of anthracene, phenanthrene and pyrene (PAH) was investigated. PAH mineralization (78%) was observed only in the bioaugmented reactors ($\cong 3.2 \times 10^{11}$ cells/L). No significant mineralization was observed in the reactors not bioaugmented

whether the inoculated cells are responsible for the increased removal and degradation of the target contaminant as compared to non-bioaugmented controls.

Whereas a competent indigenous consortium could develop in the long run at some contaminated sites (resulting in the eventual degradation of the targeted pollutants), bioaugmentation results in shorter acclimation periods and faster degradation, often with less objectionable byproducts. Thus, if a rapid response is needed, relying on indigenous microbial activity, which may experience a relatively long lag phase, may not be appropriate.

2 Types of Cultures Used

For practical purposes, different types of microorganisms can be used for bioaugmentation. These are usually bacteria, although lignolytic fungi can also be used to treat contaminated soil ex situ. Common inocula used for bioaugmentation include:

1. *Mixed cultures*. Collection of indigenous bacteria that have been highly enriched on the contaminant(s) of interest (Steffan et al., 1999; Ulrich and Edwards, 2003; Zheng et al., 2001). The seed culture to be enriched is usually obtained from the contaminated soil or wastewater treatment plants.
2. *Pure cultures*. Enrichment of single strain or syntrophic bacteria capable of degrading the contaminant. Many strains are available in bacterial banks (e.g., http:/www.atcc.org). Examples include *Dehalococcoides ethenogenes* or *Desulfomonile tiedjei* (that dechlorinate tetrachloroethene and chlorobenzoate, respectively) and *Pseudomonas stutzeri* KC (ATCC# 55595), which degrades carbon tetrachloride.
3. *Genetic elements*. Introduction of naturally occurring gene vectors (e.g., plasmids, which are extra-chromosomal DNA molecules separate from the chromosomal DNA that are capable of replicating independently and transferring catabolic capacity from one strain to another) instead of bacteria (Mohan et al., 2009; Pepper et al., 2002). The plasmid coding for enzymes with the desired catabolic potential is transferred to indigenous bacteria (horizontal gene transfer). Such approach minimizes the difficulties associated with the injection and distribution of (larger) bacterial cells throughout the contaminated area. Indigenous bacteria that acquire the plasmid may also be less susceptible to biotic or abiotic stresses than introduced (exogenous) microorganisms.
4. *Genetically modified microorganisms* (GMOs). About two decades have passed since it was first proposed to introduce specific traits into microbial communities via genetic manipulation (Brokamp and Schmidt, 1991; Fulthorpe and Wyndham, 1991). Examples of the use of GMOs to enhance biodegradation include the degradation of 2,4-D (Dejonghe et al., 2000), phenol (Watanabe et al., 2002), toluene, chlorobenzene, indole, and transformation of mercury ion to elemental mercury (II), its less toxic form (Lange et al., 1998). The above types of inocula are frequently available commercially and can be acquired from numerous companies as freeze-dried microorganisms that can be re-hydrated and revived in suspension just before inoculation. Nevertheless, whereas GMOs have been extensively used in laboratory scale and agriculture (Moza, 2005), little research has been conducted to assess their robustness and associated long-term life cycle impacts, which could include transfer of the exogenous gene across species, potentially affecting biodiversity and biological community structure. This gives rise to much speculation and polarization regarding the consequences of in vitro genetic manipulation, which represents a significant political

barrier to the use of GMOs in bioremediation. In fact, many countries have placed legal barriers on the release of GMOs for site cleanup applications. Therefore, country-specific laws should be consulted prior to the consideration of GMO's as bioaugmentation agents. In the USA, for example, the use of GMO's are examined for human and environmental risks using data and other information received in accordance with the U.S. Environmental Protection Agency's (EPA's) "Points to Consider" guidance document under the Toxic Substances Control Act (TSCA).

3 Inoculation

There are several options for introducing microorganisms into the contaminated zone. The principal delivery methods are:

1. *Liquid injection*. High microbial concentrations, typically 10^9–10^{12} cells/mL of the inoculum, are mixed with the nutrient solution that is introduced using liquid delivery pumps. To enhance microbial transport following bioaugmentation, researchers have tested various techniques, including the use of adhesion-deficient bacteria, starved bacteria, and surfactants (for review, see Gentry et al., 2004). These techniques hold significant potential, but must address specific challenges such as surfactant toxicity or the loss of biodegradation capabilities (e.g., plasmid curing) due to starvation or mutation. Once the appropriate culture is chosen for bioaugmentation, it can be obtained commercially when available (www.siremlab.com; EPA, 2004; www.atcc.org) in stainless steel vessels. These vessels can be shipped overnight to the site (➲ *Fig. 1*). The vessels are designed to maintain anaerobic conditions (when required) using pressurized inert gas. The positive pressure inside the vessels aid to bioaugmentation that takes place passively by pressurizing the vessel's opening port with inert gas (e.g., nitrogen) (➲ *Fig. 1*). This set up avoids the need for more complex engineering pumps minimizing also oxygen intrusion that could kill anaerobes.
2. *Immobilization and then injection*. This approach consists of mixing the cells into carriers such as biosolids, charcoal-amended soil, clay, lignite, gel beads, and peat prior mixing with contaminated surface soil (Gardin and Pauss, 2001; Gentry et al., 2004). The carrier material provides a temporary shelter and nutrition for the introduced microorganism that otherwise may not be able to outcompete indigenous microorganisms. The sterilization of the carrier material usually increases the inocula shelf life and enhances its survival in the environment.
3. *Encapsulation and then injection*. Microorganisms can be encapsulated in microbeads (e.g., agar, alginate, or polyurethane) or in porous ceramics (e.g., isolite) to enhance their survival (Gentry et al., 2004; Mertens et al., 2006; Moslemy et al., 2002, 2003). Some of these products can be injected as "hydraulic fracturing" fluids to remediate more relatively impermeable formations. The matrix that is non-toxic to the microorganism facilitates the diffusion of gases and liquids. This capsule protects the cells against the toxic effects of high concentrations of the chemicals usually found at the source zone. Additionally, carbon sources can be added into the composition of the capsule as substrate to promote growth of the inoculum during its adaptation to the new environment. Nonetheless, some negative effects from adding carbon to the capsule may occur if cells grow preferentially at the expenses of the added carbon rather than the target pollutant.

Figure 1

Pressurized vessels used to transport cultures for bioaugmentation (a). Bioaugmentation is conducted by transferring the culture from the sealed vessels into the wells directly. The process is accomplished pressurizing the vessels with inert gas (e.g., N_2) (b). Source: EPA, 2004; Site Recovery and Management (SiREM: www.siremlab.com/).

The increase in cell biomass resulting from bioaugmentation should not significantly decrease soil permeability and affect nutrient and substrate transport to the growing cells (Clement et al., 1996; Cunningham et al., 1991; Vandevivere and Baveye, 1992). For example, the pore volume fraction occupied by the microorganisms (η) is given as (Clement et al., 1996):

$$\eta = (X \times \mathrm{DCW} \times \rho_{\mathrm{bulk}})/\rho_{\mathrm{cell}}$$

where X is the microbial concentration (cells/L), DCW is the dry cell weight (g/cell), ρ_{bulk} is the soil bulk density (g/L), and ρ_{cell} is the biomass density (g/L). Thus, a microbial concentration on the order of 10^{12} cells/g of soil would decrease soil porosity by only about 2%, assuming a DCW value of 1.33×10^{-13} g (Bratbak, 1985), a soil bulk density of 1,600 g/L, and a biomass density of 1,100 g/L (Bratbak and Dundas, 1984). This calculation, however, ignores decreases in porosity caused by excessive production of extra cellular polysaccharides (EPS), which could result in pore clogging. Whereas pore clogging is undesirable for bioremediation, it can be a valuable process in microbial enhanced oil recovery (MEOR) (Pfiffner et al., 1986). For example, the injection of microorganisms such as *Bacillus* spp. that produces EPS can plug the high-permeability zones of the aquifer and divert fluid flow to the low-permeability zones to increase oil sweep efficiency (Raiders et al., 1985, 1986, 1989).

Following bioaugmentation, process monitoring (often supplemented by modeling efforts) must be implemented to ensure that the added microorganisms thrive and perform

Table 2

Bioaugmentation troubleshooting (adapted from Devinny and Chang, 2000)

Conditions	Comments
Microorganisms with catabolic potential present but not active	Bioaugmentation may not be required. Biostimulation should be used to provide optimum conditions for growth and expression of desired biodegradation activity
Bacteria known to degrade a recalcitrant contaminant of interest not present	Bioaugmentation with specific degraders may be a good idea
Catabolic potential is unidentified or unknown to exist	Directed evolution of catabolic enzymes and use of vectors to promote genetic breeding might be necessary
Low indigenous bacterial concentrations	Bioaugmentation may be necessary if biostimulation does not provide conditions to promote growth of specific degraders
Biostimulation cannot support bacterial growth and maintain high concentrations	May need to repeat bioaugmentation frequently to surpass unfavorable environmental conditions
Slow growth and/or lag phase	Bioaugmentation with a large biomass to minimize lag phase
Degradation occurring only near inoculation wells	Bioaugmentation with starved cells to enhance bacteria transport in the soil. Distribute inoculation wells
Low concentrations of contaminant to promote growth (threshold)	Biostimulation with specific inducers to promote simultaneously removal and/or cometabolism
Accumulation of toxic contaminant byproducts	Bioaugmentation with species capable of degrading specific contaminants byproducts
Adverse biological environmental conditions	Bioaugmentation may aid to change environmental conditions (mutualism, synthrophism, homoacetogens, hydrogenotrophic, etc)

their intended function. This can be accomplished by determining whether contaminant removal rates increase and expected metabolites appear, and by using molecular probes and quantitative PCR to target specific biomarkers from the added strains (e.g., phylogenetic or catabolic gene; Beller et al., 2002; Da Silva and Alvarez, 2007; Ritalahti et al., 2006; Van der Meer et al., 1998) to establish that the added organisms are present, and that their concentrations are higher in the treatment zone compared to background samples, which is an important line of evidence to demonstrate that bioremediation is working (*Table 2*).

4 Costs

The costs associated with bioaugmentation (as well as with any other remediation technology) may vary depending on type and concentration of contaminants present, hydro-geochemical characteristics of the soil/aquifer, size and heterogeneity of the contaminated area, depth to contamination and availability of specific equipment to implement the proposed remediation

Table 3

Typical costs of selected remediation technologies. Source: U.S. Federal Remediation Technologies Roundtable (2008) (http://www.frtr.gov)

Remediation technology	US$/m^3 of groundwater treated
Biostimulation/Bioaugmentation	30–100
Air sparging	24–84
Ex-situ bioreactors	5.6–45
Granular activated carbon (GAC)	0.3–1.7
UV/Oxidation	0.03–3

scheme. *Table 3* exemplifies some costs associated with conventional remediation technologies. Note that although the unit costs of pump-and-treat approaches may be lower, overall costs are typically higher because of the inability to pump out relatively hydrophobic contaminants that remain adsorbed to the aquifer material and serve as a source for sustained groundwater contamination.

5 Research Needs

Although considerable progress has been made is selecting appropriate inocula and advancing recipes to induce their activity for a wide variety of bioremediation applications, and on the understanding of how environmental factors and growth conditions influence bacterial transport and adhesion, further research is needed to advance our incomplete understanding of factors that hinder the distribution, survival and sustained performance of exogenous microorganisms. One research challenge is to enhance the transport and distribution of the inoculum throughout the contaminated zone. This requires improved understanding of bacterial adhesion and filtration through the porous medium, as well as chemotaxis towards or away from target pollutants, and the regulation of such processes, which may lead to better strategies to enhance microbial perfusion and distribution.

There is significant opportunity for natural genetic breeding to produce strains that not only exhibit broad catabolic specificity and can degrade mixtures of priority pollutants, but are also tolerant to environmental stress such as unfavorable pH or redox conditions that may be encountered in situ. In addition to such abiotic stress, the performance of the added strains may be hindered by biological stress such as competition for nutrients with indigenous strains and amensalistic or predatory microbial interactions. Thus, exploring approaches to selectively inhibit species that hinder the performance of the added strains (e.g., using strain specific bacteriophages) might be a fruitful avenue of research. There is also a need for improved mathematical modeling and forensic analysis tools such as transcription analysis of catabolic genes and other biomarkers to assess the performance of the added strains and confirm their participation in the cleanup process.

Overall, as our empirical database for the implementation of bioaugmentation is growing fast, as is our mechanistic understanding of the physico-chemical, ecological and genetic factors that influence the long-term efficacy of the added strains. This should ultimately lead us to better informed decisions on when and how to apply bioaugmentation in a reliable fashion to address a wide variety of remediation needs.

References

Adamson DT, McDade JM, Hughes JB (2003) Inoculation of DNAPL source zone to initiate reductive dechlorination of PCE. Environ Sci Technol 37: 2525–2533.

Alvarez PJJ, Illman WA (2006) Bioremediation and Natural Attenuation-Process Fundamentals and Mathematical Models. New York: Wiley.

Atagana HI (2006) Biodegradation of PAHs in contaminated soil by biostimulation and bioaugmentation in the presence of copper ions. World J Microbiol Biotechnol 22: 1145–1153.

Beller HR, Kane SR, Legler TC, Alvarez PJJ (2002) A real-time polymerase chain reaction method for monitoring anaerobic, hydrocarbon degrading bacteria based on a catabolic gene. Environ Sci Technol 36: 3977–3984.

Bourquin AW, Mosteller DC, Olsen RL, Smith MJ, Reardon RF (1997). Aerobic biorremediation of TCE-contaminated groundwater: bioaugmentation with *Burkholderia cepacia* PR1. In The Fourth International In situ and On-Site Bioremediation Symposium, New Orleans, LA, vol. 4(40), pp. 513–518.

Bratbak G (1985) Bacterial biovolume and biomass estimations. Appl Environ Microbiol 49: 1488–1493.

Bratbak G, Dundas I (1984) Bacterial dry-matter content and biomass estimations. Appl Environ Microbiol 48: 755–757.

Brokamp A, Schmidt FRJ (1991) Survival of *Alcaligenes xylosoxidans* degrading 2,2-dichloropropionate and horizontal transfer of its halidohydrolase gene in a soil microcosm. Curr Microbiol 22: 299–306.

Clement TP, Hooker BS, Skeen RS (1996) Macroscopic models for predicting changes in saturated porous media properties caused by microbial growth. Ground Water 34: 934–942.

Cunningham AB, Characklis WG, Abedeen F, Crawford D (1991) Influence of biofilm accumulation on porous-media hydrodynamics. Environ Sci Technol 25: 1305–1311.

Da Silva MLB, Alvarez PJJ (2004) Enhanced anaerobic biodegradation of benzene-toluene-ethylbenzene-xylene-ethanol mixtures in bioaugmented aquifer columns. Appl Environ Microbiol 70(8): 4720–4726.

Da Silva MLB, Alvarez PJJ (2007) Assessment of anaerobic benzene degradation potential using 16S rRNA gene-targeted real-time PCR. Environ Microbiol 9(1): 72–80.

Da Silva MLB, Da Prato R, Gómez DE, Hughes J, Alvarez PJJ, Ward H (2006) Reductions in DNAPL longevity through biological flux enhancement. Water Environ Res 78(13): 2456–2465.

Dejonghe W, Goris J, Fantroussi SE, Höfte M, De Vos P, Verstraete W, Top EM (2000) Effect of dissemination of 2,4-dichlorophenoxyacetic acid (2,4-D) degradation plasmids on 2,4-d degradation and on bacterial community structure in two different soil horizons. Appl Environ Microbiol 66: 3297–3304.

Devinny JS, Chang S-H (2000). Bioaugmentation for soil bioremediation. In: Bioremediation of contaminated soils. D Wise, DJ Trantolo, EJ Cichon, HI Inyang, U Stottmeister (eds.). New York, NY, ISBN 0-8247-0333-2, pp. 903.

Duba AG, Jackson KJ, Jovanovich MC, Knapp RB, Taylor RT (1996) TCE remediation using in situ, resting-state bioaugmentation. Environ Sci Technol 30: 1982–1989.

Dybas MJ, Barcelona M, Bezborodnikov S, Davies S, Forney L, Heuer H, Kawka O, Mayotte T, Sepulveda-Torres L, Smalla K, Sneathen M, Tiedje J, Voice T, Wiggert DC, Witt ME, Criddle CS (1998) Pilot-scale evaluation of bioaugmentation for in-situ remediation of a carbon tetrachloride-contaminated aquifer. Environ Sci Technol 32: 3598–3611.

El Fantroussi S, Belkacemi M, Top EM, Mahillon J, Naveau H, Agathos SN (1999) Bioaugmentation of a soil bioreactor designed for pilot-scale anaerobic biorremediation studies. Environ Sci Technol 33: 2992–3001.

Ellis DE, Lutz EJ, Odom JM, Buchanan J, Ronald J, Bartlett CL, Lee MD, Harkness MR, Deweerd KA (2000) Bioaugmentation for accelerated in situ anaerobic biorremediation. Environ Sci Technol 34: 2254–2260.

EPA (2004) Demonstration of biodegradation of DNAPL through biostimulation and bioaugmentation at launch complex 34 in Cape Canaveral Air Force station, Florida. EPA/540/R-07/007.

Fulthorpe RR, Wyndham RC (1991) Transfer and expression of the catabolic plasmid pBRC60 in wild bacterial recipients in a freshwater ecosystem. Appl Environ Microbiol 57(5): 1546–1553.

Gardin H, Pauss A (2001) (-carrageenan/gelatin gel beads for the co-immobilization of aerobic and anaerobic microbial communities degrading 2,4,6-trichlorophenol under air-limited conditions. Appl Microbiol Biotechnol 56: 517–523.

Gentry TJ, Rensing C, Pepper IL (2004) New approaches for bioaugmentation as a remediation technology. Crit Rev Environ Sci Technol 34(5): 447–494.

Henssen MJC, van der Werf AW, Keuning S, Hubach C, Blokzijl R, van Keulen E, Alblas B, Haasnoot C, Boender H, Meijerink E (2001) Engineered full scale biorremediation of chlorinated ethylenes.

In The Sixth International In situ and On-Site Biorremediation Symposium, San Diego, CA.

Imamura T, Kozaki S, Kuriyama A, Kawaguchi M, Touge Y, Yano T, Sugawa E, Kawabata Y, Iwasa H, Watanabe A, Iio M, Senshu Y (1997) Inducer-free microbe for TCE degradation and feasibility study in bioaugmentation. In The Fourth International In situ and On-Site Biorremediation Symposium, New Orleans, LA.

Jacques RJS, Okeke BC, Bento FM, Teixeira AS, Peralba MCR, Camargo FAO (2008) Microbial consortium bioaugmentation of a polycyclic aromatic hydrocarbons contaminated soil. Bioresour Technol 99(7): 2637–2643.

Krumme ML, Smith RL, Egestorff J, Thiem SM, Tiedje JM, Timmis KN, Dwyer DF (1994) Behavior of pollutant-degrading microorganisms in aquifers: predictions for genetically engineered organisms. Environ Sci Technol 28: 1134–1138.

Lange CC, Wackett LP, Minton KW, Daly MJ (1998) Engineering a recombinant *Deinococcus radiodurans* for organopollutant degradation in radioactive mixed waste environments. Nat Biotechnol 16: 929–933.

Lendvay J, Adriaens P, Barcelona M, Major CL Jr, Tiedje J, Dollhopf M, Loffler F, Fathepure B, Petrovskis E, Gebhard M, Daniels G, Hickey R, Heine R, Shi J (2001). Preventing contaminant discharge to surface waters: plume control with bioaugmentation. In The Sixth Internation In situ and On-Site Biorremediation Symposium, San Diego, CA.

Maes A, Raemdonck HV, Smith K, Ossieur W, Lebbe L, Verstraete W (2006) Transport and activity of *Desulfitobacterium dichloroeliminans* strain DCA1 during bioaugmentation of 1,2-DCA-contaminated groundwater. Environ Sci Technol 4: 5544–5552.

Malina G, Zawierucha I (2007) Potential of bioaugmentation and biostimulation for enhancing intrinsic biodegradation in oil hydrocarbon-contaminated soil. Bioremed J 11(3): 141–147.

Major DW, McMaster ML, Cox EE, Lee BJ, Gentry EE, Hendrickson E, Edwards E, Dworatzek S (2002). Successful field demonstration of bioaugmentation to degrade PCE and TCE to ethene. The Sixth International In situ and On-Site Remediation Symposium, San Diego, CA.

Mertens B, Boon N, Verstraete W (2006) Slow-release inoculation allows sustained biodegradation of (-hexachlorocyclohexane. Appl Environ Microbiol 1(72): 622–627.

Mohan SV, Falkentoft C, Nancharaiah YV, Sturm BSM, Wattiau P, Wilderer PA, Wuertz S, Hausner M (2009) Bioaugmentation of microbial communities in laboratory and pilot scale sequencing batch biofilm reactors using the TOL plasmid. Bioresour Technol 100: 1746–1753.

Moslemy P, Guiot SR, Neufeld RJ (2002) Production of size-controlled gellan gum microbeads encapsulating gasoline-degrading bacteria. Enzyme Microb Technol 30: 10–18.

Moslemy P, Neufeld RJ, Millette D, Guiot SR (2003) Transport of gellan gum microbeads through sand: an experimental evaluation for encapsulated cell bioaugmentation. J Environ Manage 69: 249–259.

Pepper IL, Gentry TJ, Newby DT, Roane TM, Josephson KL (2002) The role of cell bioaugmentation and gene bioaugmentation in the remediation of co-contaminated soils. Environ Health Perspect 110(6): 943–946.

Pfiffner SM, McInerney MJ, Jenneman GE, Knapp RM (1986) Isolation of halotolerant, thermotolerant, facultative polymer-producing bacteria and characterization of the expolymer. Appl Environ Microbiol 51: 1224–1229.

Raiders RA, Freeman DC, Jenneman GE, Knapp RM, McInerney MJ, Menzie DE (1985). The use of microorganisms to increase the recovery of oil from cores. SPE 14336. In Proceedings of the SPE Annual Technical Conference. Society of Petroleum Engineers, Richardson, Tex.

Raiders RA, McInerney MJ, Revus DE, Torbati HM, Knapp RM, Jenneman GE (1986) Selectivity and depth of microbial plugging in Berea sandstone cores. J Ind Microbiol 1: 195–203.

Raiders RA, Knapp RM, McInerney MJ (1989) Microbial selective plugging and enhanced oil recovery. J Ind Microbiol 4: 215–230.

Ritalahti KM, Amos BK, Sung Y, Wu QZ, Koenigsberg SS, Löffler FE (2006) Quantitative PCR targeting 16S rRNA and reductive dehalogenase genes simultaneously monitors multiple *Dehalococcoides* strains. Appl Environ Microbiol 72(4): 2765–2774.

Salanitro JP, Johnson PC, Spinnler GE, Maner PM, Wisniewski HL, Bruce C (2000) Field-scale demonstration of enhanced MTBE biorremediation through aquifer bioaugmentation and oxygenation. Environ Sci Technol 34: 4152–4162.

Steffan RJ, Sperry KL, Walsh T, Vainberg S, Condee CW (1999) Field-scale evaluation of in situ bioaugmentation for remediation of chlorinated solvents in groundwater. Environ Sci Technol 33: 2771–2781.

Straube WL, Nestler CC, Hansen LD, Ringleberg D, Pritchard PH, Jones-Meehan J (2003) Remediation of polyaromatic hydrocarbons (PAHs) through landfarming with biostimulation and bioaugmentation. Acta Biotechnol 23: 179–196.

Ulrich AC, Edwards EA (2003) Physiological and molecular characterization of anaerobic benzene-degrading mixed cultures. Environ Microbiol 5: 92–102.

Van der Meer JR, Werlen C, Nishino SF, Spain JC (1998) Evolution of a pathway for chlorobenzene metabolism leads to natural attenuation in contaminated groundwater. Appl Environ Microbiol 64(11): 4185–4193.

Vandevivere P, Baveye P (1992) Relationship between transport of bacteria and their clogging efficiency in sand columns. Appl Environ Microbiol 58: 2523–2530.

Vogel TM, Walter MV (2002). Bioaugmentation. In Manual of Environmental Microbiology 2nd edn. CJ Hurst, RL Crawford, GR Knudsen, MJ McIrney, LD Stezenback (eds.). ASM, Washington.

Watanabe K, Teramoto M, Harayama S (2002) Stable augmentation of activated sludge with foreign catabolic genes harboured by an indigenous dominant bacterium. Environ Microbiol 4: 577–583.

Weiner JM, Lovley DR (1998) Anaerobic benzene degradation in petroleum-contaminated aquifer sediments after Inoculation with a benzene-oxidizing enrichment. Appl Environ Microbiol 64(2): 775–778.

Yu KSH, Wong AHY, Yau KWY, Wong YS, Tam NFY (2005) Natural attenuation, biostimulation and bioaugmentation on biodegradation of polycyclic aromatic hydrocarbons (PAHs) in mangrove sediments. Mar Pollut Bull 51: 1071–1077.

Zheng D, Carr CS, Hughes JB (2001) Influence of hydraulic retention time on extent of PCE dechlorination and preliminary characterization of the enrichment culture. Biorem J 5: 159–168.