1,4-DIOXANE REMEDIATION APPROACH TECHNICAL MEMORANDUM

PSC Georgetown Facility

Seattle, Washington

Prepared for:

Burlington Environmental, LLC
A wholly owned subsidiary of PSC Environmental Services, LLC
Kent, Washington

Prepared by:

AMEC Environment & Infrastructure, Inc.
600 University Street, Suite 600
Seattle, Washington 98101
(206) 342-1760

September 2014

Project No. 0087700080.7040

TABLE OF CONTENTS

TABLES

TABLE OF CONTENTS
(Continued)

FIGURES

1,4-DIOXANE REMEDIATION APPROACH
TECHNICAL MEMORANDUM
PSC Georgetown Facility
Seattle, Washington

1.0 INTRODUCTION

AMEC Environment & Infrastructure, Inc. (AMEC), prepared this memorandum on behalf of Burlington Environmental LLC, a wholly owned subsidiary of PSC Environmental Services LLC (PSC) for the Georgetown facility located in Seattle, Washington (the site) (Figure 1). Over the last year, PSC has had multiple discussions with the Washington State Department of Ecology (Ecology) regarding 1,4-dioxane. This memorandum fulfills PSC's obligations regarding the implementation of a contingent remedy for 1,4-dioxane for the area east of 4th Avenue South and downgradient from the PSC Georgetown facility (the Outside Area), as outlined in the Washington State Department of Ecology (Ecology) letter dated June 19, 2014 and discussed in phone conferences held in August and September 2014 (Figures 2 and 3). As requested by Ecology, this memorandum proposes action to expeditiously attain 1,4-dioxane cleanup levels in the shallow and intermediate groundwater zones, by reducing 1,4-dioxane mass in the most problematic parts of the Outside Area.

This memorandum also serves to fulfill the preliminary requirements for a contingent remedy as outlined in Agreed Order #DE 7347 and the 2010 Cleanup Action Plan (CAP) (Ecology, 2010) to implement a contingent remedy for the sections of the Outside Area with 1,4-dioxane concentrations over 400 micrograms per liter (µg/l).

This page intentionally left blank.

2.0 BACKGROUND

In accordance with the Agreed Order and appended CAP, and based on discussions with Ecology, the evaluations performed to date indicate that natural attenuation of 1,4-dioxane will not achieve cleanup levels by 2015; thus, a contingent remedy is now required. Under Section 6.3.2 of the CAP, PSC is to “propose actions, such as implementation of the contingent remedy, which should result in expeditious cleanup level attainment.” As discussed in recent documents and conference calls with Ecology, monitoring data indicate that, contrary to what was assumed in the 2010 CAP, more mechanisms than dispersion and diffusion are contributing to the fate and transport of 1,4-dioxane in the shallow and intermediate groundwater zones (DOF, 2013). It appears as though a secondary source, either from an as yet unidentified source or from back diffusion of residual concentrations held in the fine grained units within the aquifer, is contributing to 1,4-dioxane concentrations in the Outside Area groundwater. Thus, 1,4-dioxane concentrations in the Outside Area remain elevated at concentrations above cleanup levels.

Recent monitoring data indicate that the areas with the highest concentrations of 1,4-dioxane (defined as concentrations over 400 µg/L) now includes wells CG-127 and CG-161 located downgradient of well CG-122, as well as CG-122 itself (Figure 2). Concentrations from the third quarter of 2013 and the first quarter of 2014 are shown on Figure 2. The highest concentrations (400 µg/L and greater) are observed in wells screened in the intermediate groundwater zone from approximately 65 to 75 feet below ground surface (bgs). Concentrations at shallower depths are generally lower, though still greater than 200 µg/L in the vicinity of wells CG-165, CG-127, CG-128, and CG-131 in the 45 feet bgs shallow groundwater zone. CG-127 is the area with the highest concentrations measured recently in the shallow and intermediate groundwater zone (400 and 560 µg/L, respectively), while CG-122-60 (approximately 2 blocks upgradient) also remains quite high (503 µg/L).

This page intentionally left blank.

3.0 OBJECTIVES

The objective of the remedial action as outlined in the Agreed Order, the CAP, and the Ecology letter is to hasten the attainment of 1,4-dioxane cleanup levels throughout the Outside Area. This memorandum presents alternatives to achieve this objective and select a preferred alternative that cost-effectively meets the objective. The primary objectives relevant to 1,4-dioxane in groundwater as outlined in the CAP were:

- Protect human and ecological receptors by reducing constituent of concern (COC) concentrations in Outside Area groundwater to cleanup levels based on protection of surface water;
- Attain, or otherwise comply with, the cleanup standards; and
- Reduce COC concentrations to achieve groundwater cleanup levels at the conditional point of compliance and downgradient locations in a reasonable time frame.

In order to address Ecology's requirements, at a minimum this memo will cover the following items:

- A summary of remedial technologies and approaches evaluated (Sections 4 and 5);
- A description of the action to be taken (Section 6) ;
- The action's performance goals (Section 6); and
- A schedule for future deliverables and meetings related to developing and submitting a remedial design of the proposed action (Section 7).

This page intentionally left blank.

4.0 TECHNOLOGY AND ALTERNATIVE CONSIDERATIONS

The contingent remedy in the CAP consisted of installing an extraction well in the vicinity of CG-122 to remove two pore volumes from the surrounding area. The extracted water was to be treated and discharged to the sanitary sewer or to the storm sewer with an appropriate permit. The extraction well and treatment system would need to operate for approximately 1.3 years of continuous pumping.

However, recent monitoring data show concentrations have not declined as fast as expected at CG-122-60. This combined with concentration trends in Outside Area wells, indicates that a secondary source is present. If the secondary source is due to back diffusion from less permeable zones such as in silt and/or clay lenses, pumping two pore volumes would not likely obtain cleanup levels in CG-122-60 or in the other areas that need to be addressed. As a result, other remedial action options were considered, as summarized in Sections 5 and 6.

Several considerations must be addressed in the development of a remedial action for the Outside Area for 1,4-dioxane. The extent of the highest contamination for 1,4-dioxane primarily lies within the intermediate and shallow groundwater zones downgradient of the site and CG-122 (Figure 2). The recent highest concentrations have been observed in the intermediate zones in CG-127 and CG-122. Concentrations over 400 µg/L also have been observed in CG-161 (screened partially in a silty layer near the upper portion of the intermediate zone) and CG-127 (shallow zone). The treatment alternatives presented were developed to address these areas within the shallow and intermediate groundwater zones.

The remedial action response selected will also consider risk to human and ecological receptors for both the remedial approach and the existing extent and migration of the 1,4-dioxane plume. Given that the contaminated groundwater is primarily 35 feet deep or more and that the nearest well with detections of 1,4-dioxane over the cleanup level (CI-9-70) is over 1,500 feet from the Duwamish Waterway (the potential exposure pathway), there are no current risks to human or ecological health.

The Outside Area is located in a densely populated urban area. Several of the streets running through the Outside Area act as primary arterials for traffic in the Georgetown area. The properties located within the Outside Area are residential, industrial, and commercial. As a result, the remedial action selected must be able to address the objectives discussed above while minimizing impacts to residents and businesses. Any work completed on private property will require access agreements and permitting through the Seattle Department of Planning and Development (DPD). Work taking place on City of Seattle property and in the public right of way will require permitting through the Seattle Department of Transportation (SDOT).

Permitting across multiple parcels of private property will result in longer remedy time frames and additional costs for permitting, thus affecting PSC's ability to provide a timely remedy implementation. As a result, minimizing permitting is an important factor in the evaluation of the treatment technologies and the remedial alternatives. Table 1 summarizes the permitting required for the remedial technologies considered in Section 5. Working exclusively in the public right of way and permitting solely with SDOT will reduce cleanup time by at least 3 to 4 months over working on private property and permitting through DPD. In addition, this option would decrease costs associated with permitting. To expedite the cleanup of the 1,4-dioxane plume, only technologies and alternatives that entail working entirely in the public right of way were considered. It is assumed that all work will be conducted outside of the privately-owned property boundaries for the Outside Area shown in Figure 3.

5.0 TECHNOLOGY SCREENING

This section describes the criteria used to screen potential treatment technologies and the technologies that will be retained to develop a comprehensive contingent remedy for the Outside Area.

5.1 SCREENING CRITERIA

Remedial actions for 1,4-dioxane feasible for the site were identified using a two-step screening process, consistent with U.S. Environmental Protection Agency guidance (EPA, 1994). The first step, as outlined in this section, was to identify potentially applicable remedial technologies appropriate for 1,4-dioxane that have been proven in full-scale applications or that have been used in pilot-scale programs and appear to be potentially feasible for use at the site. The potentially applicable remedial technologies were subsequently screened using appropriate criteria to prepare a “short list” of potentially applicable remedial technologies, which were then used to develop appropriate remedial action alternatives to address 1,4-dioxane in the Outside Area. The criteria used to screen the selected technologies were as follows:

- **Technology Development Status:** This criterion refers to the level of development for the technology (bench, pilot, or full-scale). Technologies with full-scale implementation were favored over less developed technologies. Technologies successfully implemented in a variety of environmental and geologic settings were favored over technologies with a more restricted application record.

- **Performance Record:** This criterion refers to the technology’s record of successfully attaining the remediation objectives established for the technology in prior implementations. Technologies with a more successful performance record were favored over technologies with fewer successes or more failures.

- **Implementability within the Constraints of the Site:** This criterion refers to the expected ability to successfully implement the technology within the Outside Area in a reasonable time frame. Technologies requiring minimal access and simpler permitting were favored over technologies requiring extensive permitting or access to numerous locations. Technologies requiring significant infrastructure (permanent wells, extensive piping runs, public and private easements, and access agreements) might be difficult to implement due to the associated logistical and administrative challenges; it is possible that in some cases certain technologies might not be implementable. Non-invasive technologies were favored over highly invasive technologies, due to the extensive development in the Outside Area and the complications involved in gaining property access for conducting remediation.

5.2 TREATMENT TECHNOLOGIES CONSIDERED

As part of the preliminary screening process, potentially applicable remedial technologies were identified based on professional experience, professional literature, and other technical resources such as the Federal Remediation Technologies Roundtable and Contaminated Site Clean-Up

Information website. All the remedial technologies considered for screening are discussed in this section. The technologies that have been proven in field applications or where pilot/bench scale testing indicated a high potential of successful application for 1,4-dioxane were retained for further consideration. The remediation technologies considered potentially applicable for the Outside Area for 1,4-dioxane, summarized in Sections 5.2.1 through 5.2.4 are described in detail in Table 2. Technologies retained for further consideration were used to build remedial action alternatives to address 1,4-dioxane in the Outside Area.

5.2.1 In Situ Biological Treatment

Four in situ biological treatment technologies were considered, three of which were retained for further consideration.

5.2.1.1 Enhanced Bioremediation

In situ bioremediation (ISB) may be used to degrade 1,4-dioxane with the enhancement of existing or planted microbes that can degrade 1,4-dioxane. Recently, 1,4-dioxane has been shown in biotraps and in bench scale studies to be biologically degraded using in situ co-metabolic processes (Li et al., 2010 and 2013). Co-metabolic degradation can be accomplished by injecting a fuel or alcohol substrate such as tetrahydrofuran, propane, methane, 1-butanol, or 1-propanol into the groundwater. The biodegradation of 1,4-dioxane through co-metabolic processes is a relatively new development in the environmental remediation field. Drawbacks of the technology include the potential for indigenous microorganisms to outcompete 1,4-dioxane degraders for substrate. Depending on the substrate used, potentially explosive or hazardous conditions can be created. This technology has not been implemented within fully developed urban areas and has not been applied in source areas.

This technology may be used to assist in expedited cleanup of the 1,4-dioxane plume in the Outside Area. Depending on the substrate used, potential for environmental releases, explosion hazards, or migration off-site in groundwater may be encountered; therefore, no fuels or toxic compounds will be considered. PSC is currently working with Rice University to set up treatability studies for Outside Area groundwater using various substrates. Based on its suitability for treating source areas and more specifically diffuse areas throughout the 1,4-dioxane plume, enhanced bioremediation is retained for further consideration.

5.2.1.2 Bioaugmentation

Bioaugmentation is an in situ remedial technology in which microorganisms, specifically adapted for degradation of the constituent of interest are introduced to the affected groundwater. Bioaugmentation could be conducted using anaerobic or aerobic biological microorganisms. Under aerobic conditions, the microorganisms *Mycobacterium vaccae* JOB5 and *Pseudonocardia* K1 have been observed degrading 1,4-dioxane in industrial sludge. Both bacterial strains *Pseudonocardia dioxanivorans*

CB1190 and *Rhodococcus* strain 219 have been shown to be capable of using 1,4-dioxane as a sole carbon source or to co-metabolically degrade 1,4-dioxane with another substrate (Mahendra and Alvarez-Cohen, 2006). Any microorganisms that may degrade 1,4-dioxane would need to be evaluated prior to the introduction of the microorganism. Injection wells or push probes are typically used for injecting the microorganisms. The culture added to the subsurface would then need to be capable of competing with indigenous organisms for nutrients and substrate. In many bioaugmentation applications, the added organisms do not compete successfully with indigenous organisms and require the addition of substrate to favor the target microorganisms.

Bioaugmentation has been retained for further consideration for the Outside Area due to its potential to address diffuse locations over the long term. This technology could be implemented in the event that existing colonies are insufficient to fully degrade 1,4-dioxane or if no known colonies are present at the site. PSC is currently working with Rice University to evaluate the options for bioaugmentation for Outside Area groundwater.

5.2.1.3 Monitored Natural Attenuation

Monitored natural attenuation (MNA) is a proven technology that has been effective in reducing contaminant concentrations in groundwater when appropriate conditions are present. This process relies on the attenuation of groundwater COCs by natural processes including biodegradation, abiotic degradation, adsorption, and dilution. Due to the passive nature of this remedial technology, it can be readily implemented with a minimum amount of institutional issues such as permitting or arranging for access permissions, and also has minimal potential for implementation problems such as well fouling. One potential drawbacks of sole reliance on this technology is potentially longer remediation periods compared to active groundwater remediation technologies.

MNA was the remedial technology selected in the CAP and appears to be working for the Outside Area, but at a rate slower than projected in the CAP. Given the low permeability lenses throughout the shallow and intermediate zones in the Outside Area any remedial design must consider the possible back diffusion of 1,4-dioxane from low permeability lenses as a potential long term source. MNA will be retained for further considerations for lower concentration parts of the Outside Area and combined with other more aggressive treatment technologies to remove 1,4-dioxane.

5.2.1.4 Phytoremediation

Phytoremediation is a set of processes that uses plants to destroy or remove contamination in groundwater. Plants use several mechanisms in phytoremediation, including enhanced rhizosphere biodegradation, phyto-degradation, and phyto-volatilization. Enhanced rhizosphere biodegradation utilizes natural substances released by plant roots to supply nutrients to microorganisms, which enhances their ability to biodegrade organic contaminants. Phyto-degradation is the metabolism of contaminants within plant tissues and phyto-volatilization occurs as plants take up water containing organic contaminants and release the contaminants into the air through their leaves. Phytoremediation through the use of plants such as poplars has been shown to be effective to remediate 1,4-dioxane in soil and groundwater (Aitchison et al., 2000).

The potential for application of phytoremediation in the Outside Area is extremely limited by the depth of groundwater contamination, the current land use, and the expected future land use. The heavy urban development would prevent application of the technology within the entire Outside Area. This technology would not be effective for groundwater below the water table depth interval. Therefore, this technology has been rejected for the Outside Area.

5.2.2 In Situ Chemical Treatment

In situ chemical oxidation (ISCO) has been successfully used for treatment of 1,4-dioxane. The oxidant primarily used to address 1,4-dioxane in situ has been activated persulfate (Regenesis, no date). This technology is based on the injection of the chemical oxidant into the affected groundwater. Persulfate is typically injected with an activator such as high pH compounds, reduced iron, or in high temperature solutions. The activator reacts with the persulfate, forming the sulfate radical, which is one of the strongest oxidants used in environmental remediation. Injection of the chemicals can be accomplished using direct-push techniques, injection wells, or recirculation wells. This technology is typically only considered for treatment of highly affected source areas; the technology is not well suited for use in dilute groundwater plumes because oxidation of the target COC depends on direct contact with 1,4-dioxane and the persulfate will be consumed rapidly by other oxidant-demanding sources. High reactant chemical doses and low utilization efficiencies would be required for dilute plumes, which would result in high remediation costs.

Persulfate is a reactive, hazardous chemical that requires proper design and management to be used safely. This technology could be used to target plume areas with 1,4-dioxane concentrations over 400 μg/L in the Outside Area over the required depths. However; the depths of the chemical impacts, the complex geology and geochemistry (including the presence of metals in a highly reductive environment), the dispersed 1,4-dioxane, and the difficulties of delivery of the oxidant within interbedded soils limit the potential use of this technology. Additionally, the technology would not effectively remediate 1,4-dioxane that has diffused into the interbedded silt layers. Due to the generally diluted nature of the Outside Area, chemical oxidation would not be cost-effective for the majority of the area. This technology was retained for potential application to target areas with 1,4-dioxane concentrations over 400 μg/L for immediate mass reduction.

5.2.3 Groundwater Extraction and Treatment (Pump and Treat)

Groundwater extraction and treatment was originally selected as the contingent remedy in the CAP for the area adjacent to CG-122. To implement this technology under current conditions, several additional recovery wells would be required to target areas with 1,4-dioxane concentrations over 400 µg/L. Groundwater extraction followed by ex situ treatment would be used for 1,4-dioxane mass removal in the vicinity of the extraction wells. Extracted groundwater would then be treated and discharged either to the King County publicly owned treatment works (POTW) or to the Duwamish Waterway via a NPDES permit. Discharge to the King County POTW would be the preferred option for the Outside Area due to the expense required to treat the extracted groundwater to the more stringent NDPES discharge limits, and the potential difficulty in obtaining property to house the treatment system.

Groundwater extraction for COC mass removal would likely be costly within the Outside Area due to the dilute 1,4-dioxane concentrations and the areal extent of affected groundwater. In addition, long-term pumping would be required to remove sufficient mass to obtain cleanup levels due to the presence of a secondary source for the 1,4-dioxane. This would result in a long-term cleanup time frame and significant operation and maintenance (O&M) costs. The use of a groundwater pump and treatment system along the public right of way would likely require long-term storage of potentially hazardous materials to treat the extracted groundwater to levels required for discharge. Technologies such as bioreactors that use propane injection for co-metabolic degradation and ex-situ chemical oxidation with activated persulfate, hydrogen peroxide, and ozone require the long-term storage of hazardous materials. Permitting for these options has several unknowns. While SDOT has noted they would find a way to permit it, additional spill requirements, fire prevention devices, and security would likely be required. As a result, treatment technologies storing hazardous chemicals in the right of way will likely more than double the time and cost of permitting. Adsorption media may be a feasible option for treatment of the extracted groundwater but would result in substantial waste generation and O&M costs to maintain the media. In addition, only a single vendor provides proven adsorption media and treatment systems, resulting in costs that are an order of magnitude greater than the other remedial alternatives. Due to the permitting issues, the extent of the contamination and the secondary source, the long term storage of equipment and the long term O&M costs; groundwater extraction and treatment was rejected from further consideration.

5.2.4 Subsurface Injection Technologies

Three methods of injecting chemicals to the subsurface were screened: push probe injection, recirculation wells, and hydraulic fracturing. Recirculation wells and hydraulic fracturing are not ideal for the soil types in the target injection zones. Recirculation wells will cover permeable areas but will result in incomplete distribution in less permeable areas. Fracturing uses high pressures to create large flow channels in the aquifer. The large flow channels could result in transport of the injected substance outside of the target area resulting incomplete coverage. As such, both were rejected from further consideration. Push probes were retained to be used in conjunction with ISCO and ISB as push probes can be used to target specific areas and depth intervals more effectively.

6.0 REMEDIAL ALTERNATIVES

This section presents the criteria used to formulate and evaluate the potential remedial alternatives identified for the Outside Area and select the preferred alternative to address 1,4-dioxane in the Outside Area. The potential remedial alternatives were developed from the initial screening of potentially applicable remediation technologies and were designed to attain the remediation objectives presented in Section 3.0.

During conference calls with Ecology in August and September, general outlines for remedial alternatives were developed. The remedial alternatives are designed to expeditiously attain 1,4-dioxane cleanup levels in the shallow and intermediate groundwater zones by reducing 1,4-dioxane mass in the most problematic areas of the Outside Area. Due to the additional time and cost of permitting necessary for working on both private property and in the City of Seattle right of way, it was agreed that working on the public right of way alone would be preferable.

6.1 REMEDIAL ALTERNATIVE EVALUATION CRITERIA

Each of the remedial alternatives presented below was evaluated relative to the relevant criteria specified in Washington Administrative Code 173-340-360 to select the preferred alternative. The evaluation criteria for the Outside Area are defined below.

- ***Protectiveness:*** Overall protectiveness of human health and the environment, including the degree to which existing risks are reduced, time required to reduce risk at the facility and attain cleanup standards, on-site and offsite risks resulting from implementing the alternative, and improvement of the overall environmental quality.
- ***Permanence:*** The degree to which the alternative permanently reduces the toxicity, mobility, or volume of hazardous substances, including the adequacy of the alternative in destroying the hazardous substances, the reduction or elimination of hazardous substance releases and sources of releases, the degree of irreversibility of waste treatment process, and the characteristics and quantity of treatment residuals generated.
- ***Relative Cost:*** The relative costs to implement the alternative, including the cost of construction, the net present value of any long-term costs, and agency oversight costs that are cost-recoverable. Long-term costs include operation and maintenance costs, monitoring costs, equipment replacement costs, and the cost of maintaining institutional controls. The alternatives with the lowest relative cost when compared to the other alternatives will be ranked higher.
- ***Long Term Effectiveness:*** Includes the degree of certainty that the alternative will be successful, the reliability of the alternative during the period of time hazardous substances are expected to remain on site at concentrations that exceed cleanup levels, the magnitude of residual risk with the alternative in place, and the effectiveness of controls required to manage treatment residues or remaining wastes. The following types of cleanup action components may be used as a guide, in descending order, when assessing

the relative degree of long-term effectiveness: reuse or recycling; destruction or detoxification; immobilization or solidification; on-site or off-site disposal in an engineered, lined and monitored facility; on-site isolation or containment with attendant engineering controls; and institutional controls and monitoring. Alternatives that actively degrade or destroy 1,4-dioxane would be ranked higher for this criterion than alternatives that utilize slower methods.

- ***Management of Short Term Risks:*** The risk to human health and the environment associated with the alternative during construction and implementation, and the effectiveness of measures that will be taken to manage such risks.

- ***Technical and Administrative Implementability:*** Ability of the alternative to be implemented, including consideration of whether the alternative is technically possible, availability of necessary off-site facilities, services and materials, administrative and regulatory requirements, scheduling, size, complexity, monitoring requirements, access for construction operations and monitoring, and integration with existing facility operations and other current or potential remedial actions. Factors considered for evaluation of this criterion include:

  - the size and complexity of the remedial alternative;
  - the degree to which the remedial alternative can be integrated with existing operations and activities within affected areas;
  - regulatory requirements, including permitting; and
  - present and future land use for the area above and adjacent to the project area, including any specific constraints land use may have on the alternative.

- ***Consideration of Public Concerns:*** Whether the community has concerns regarding the alternative and, if so, the extent to which the alternative addresses those concerns. This process includes concerns from individuals, community groups, local governments, tribes, federal and state agencies, or any other organization that may have an interest in or knowledge of the site. Remedial alternatives likely to be readily accepted by the public would rank higher than alternatives that may create issues that must be addressed. Potential public concerns include factors such as increased truck traffic, adverse traffic impacts, noise, dust, odors, release of vapors, use of hazardous materials, safety, and effects on property values. The heavy industrial, commercial, and residential land uses in an urban environment create significant potential for public concern related to site remediation.

The remedial alternatives considered in this technical memorandum were designed to attain the remediation objectives outlined above to the extent practicable. Table 3 summarizes the alternatives, the screening criteria, and the alternative evaluation for the site. Alternative descriptions are provided below.

6.2 REMEDIAL ALTERNATIVES CONSIDERED

All alternatives discussed in this section rely on in situ processes to achieve the objectives outlined in Section 3. Each of the remedial alternatives are designed to reduce the restoration time frame for 1,4-dioxane in the shallow and intermediate groundwater zones, by reducing 1,4-dioxane mass in the areas with concentrations over 400 µg/L in the Outside Area. Common problems shared by all alternatives outlined below are:

- subsurface heterogeneities, preferential flow paths, and poor mixing in the subsurface may result in incomplete treatment;
- difficulty in targeting lower permeability zones that may be acting like secondary sources; and
- the resulting uncertainty in cleanup time frames.

For the purpose of conceptual alternative design, the high concentration plume area is the triangular area approximately bounded by a line drawn between CG-122, CG-128, and CG-127. In general, target zones include the shallow groundwater zone located approximately between 35 and 45 feet bgs and the intermediate zone located approximately between 65 and 75 bgs.

All alternatives will require a long term monitoring plan to evaluate the effectiveness of the alternative and to ensure that the objectives outlined above are met. The monitoring wells will be used to monitor the important parameters for each alternative such as oxidant distribution (oxygen reduction potential), substrate distribution (total organic carbon), and other parameters in the shallow and intermediate groundwater intervals. Degradation of 1,4-dioxane and consumption of the oxidant or substrate would also be monitored in or adjacent to injection and recovery wells. The monitoring plan will be developed as part of the remedial design work plan for the selected alternative.

The three alternatives considered for the remediation of the Outside Area employ a targeted approach for ISCO, ISB, and a combination of the two. Plume-wide application of ISCO was rejected from inclusion as part of a remedial alternative because it is unlikely to be effective at treating 1,4-dioxane in lower permeability units and it would not be cost effective in locations with lower concentrations. The majority of the oxidant injected into the aquifer would not address 1,4-dioxane but rather the oxidant demand of the soil and other constituents in the groundwater. A targeted approach for ISCO application will allow for immediate mass removal to occur in areas with the highest concentrations (over 400 µg/L) of 1,4-dioxane. Plume wide application of ISB was rejected from inclusion as part of a remedial alternative because injections of substrate and microorganisms will be most cost effective injected into the upgradient edge or center of the plume. This targeted approach will allow for the injected substrate and microorganisms to spread throughout the plume via dispersion and diffusion from the up gradient extents of the plume.

6.2.1 Alternative 1: In Situ Chemical Oxidation Targeted Approach

Alternative 1 incorporates the use of a push probe injection network that addresses areas with 1,4-dioxane concentrations over 400 µg/L throughout the public right of way. Injections would consist of persulfate with an activator. ISCO would be conducted in an effort to reduce mass in the hottest areas of the plume. Alternative 1 would include the following elements:

- Injection of persulfate and activator adjacent to CG-122, CG-161, and CG-127;
- Follow up injection of persulfate and activator to address secondary sources;
- ISCO performance monitoring program; and
- Long term MNA.

The components of Alternative 1 would be implemented in phases. Phase I would involve the injection of persulfate and an activator adjacent to the wells in the public right of way. A follow-up injection approximately 30 days after the initial injections. Approximately 35 injection points would be required to effectively distribute the oxidant in the targeted treatment zones described previously for 1,4-dioxane.

The advantages of Alternative 1 are:

- Chemical oxidation is a proven technology for addressing 1,4-dioxane, and is particularly cost effective in source areas.
- The alternative should result in a reduced restoration time frame to meet remediation levels in the shallow and intermediate zones.
- The alternative would provide more time for MNA to reach cleanup levels in the Outside Area.

The disadvantages of this alternative are:

- The geochemistry within the shallow and intermediate zones in the Outside Area is complex, and iron and manganese concentrations are very high. These metals. as well as organic carbon and soil oxidant demand could consume a considerable amount of chemical oxidant.
- The alternative may not address interbedded silt layers, which may be contaminated.
- It is doubtful whether cleanup levels in any of the aquifer zones would be met by this alternative, due to recontamination that would be expected to occur from the secondary source(s).
- The alternative would only address sections of the plume with the hottest concentrations of 1,4-dioxane within the public right of way.

- The restoration timeframe will be reduced, but the amount of reduction is difficult to predict.

6.2.2 Alternative 2: In Situ Biological Degradation Targeted Approach

Alternative 2 incorporates enhanced bioremediation and bioaugmentation with the use of a push probe injection network. Diffusion and dispersion will be utilized and injection areas will be located in the public right of way in order to transport the substrate and microorganisms throughout the plume. ISB would be conducted in an effort to reduce mass throughout the plume. Alternative 2 would include the following elements:

- Rice University bench-scale studies for substrate selection and bioaugmentation requirements.
- Injection of substrate and microorganisms as required adjacent to CG-122 (upgradient of plume area) and adjacent to CG-161 in the middle of the plume area; and
- an ISB performance monitoring program.

Upon receipt of recommendations from Rice for ISB, the injection of substrate and target microorganisms would be conducted in the public right of way adjacent to CG-122 and CG-161. A large number of injection points would be required to effectively distribute the substrate and microorganisms in the targeted treatment zones.

The advantages of implementing Alternative 2 are:

- Targeted ISB will likely spread out throughout the plume area and bacteria will be better able to provide long-lasting treatment for 1,4-dioxane in the interbedded silt layers.
- The alternative should result in a reduced time frame to meet cleanup levels in the shallow and intermediate zones.
- Less costly than Alternative 1.

The disadvantages of this alternative are:

- Implementing this alternative would take longer than other alternatives and would require bench-scale testing for ISB.
- There is uncertainty as to whether indigenous biota may outcompete targeted biota or planted microorganisms for selected substrate.
- The alternative may not fully address interbedded silt layers that may be contaminated.
- The restoration timeframe will be reduced, but the amount of reduction is difficult to predict.

6.2.3 Alternative 3: In Situ Chemical Oxidation and In Situ Biological Degradation Targeted Approach

Alternative 3 incorporates the use of a targeted mass removal approach in the plume areas with 1,4 -dioxane concentrations over 400 µg/L, followed by targeted ISB to address the more diffuse concentrations of 1,4-dioxane in the plume. Alternative 3 relies on a push probe injection network to initially reduce mass in the plume areas with 1,4-dioxane concentrations over 400 µg/L followed by a push probe injection network to implement ISB that relies on diffusion and dispersion to transport the substrate and injected microrganism throughout the plume. Target injection areas would need to be located in the public right of way. Using ISCO and ISB in tandem would provide initial mass removal of 1,4-dioxane from the highest concentration areas and would serve as a mechanism to speed up biodegradation and reduce remedial time frames. Alternative 3 would include the following elements:

- Rice University bench-scale studies for substrate selection and bioaugmentation requirements.
- Injection of persulfate and activator adjacent to wells CG-122, CG-161, and CG-127 (Figure 4);
- A follow up injection of persulfate and activator approximately 30 days after initial injections;
- An ISCO performance monitoring program;
- Injection of substrate and microorganisms (as determined by the bench study) adjacent to CG-122 (upgradient of plume area) and adjacent to CG-161 in the middle of the plume area (Figure 5);
- An ISB performance monitoring program; and
- Long-term MNA for diffuse concentration locations.

The components of Alternative 3 would be implemented in two phases. Phase I would involve the injection of persulfate and an activator adjacent to the wells in the public right of way. Based on recommendations for the application of persulfate and an activator for the Outside Area target areas, one follow-up injection would be performed. Approximately 35 injection points would be required to effectively distribute the oxidant in the targeted treatment zones (Figure 4). Upon recommendations from Rice, Phase II would include the injection of substrate and microorganisms (if required) in the public right of way adjacent to CG-122 and CG-161. Approximately 36 injection points would be required to effectively distribute the substrate and microorganisms in the targeted treatment zones (Figure 5). MNA will be implemented for other diffuse areas outside of the main plume area using the monitoring well network currently in place (Figure 2).

The advantages of implementing Alternative 3 are:

- Chemical oxidation is a proven technology for addressing 1,4-dioxane; it is particularly cost effective in source areas.
- Targeted ISB may spread throughout the plume area and bacteria would be better able to provide long-lasting treatment for 1,4-dioxane in the interbedded silt layers.
- The alternative should attain cleanup levels in the shallow and intermediate zones in a reduced time frame.
- The alternative uses both ISCO and ISB in ways that play to each technology's strengths, providing a better chance at both an initial quick mass removal action in the highest concentration areas while providing a remedial measure to accelerate biodegradation rates in the long term.

The disadvantages of this alternative are:

- The geochemistry within the shallow and intermediate zones in the Outside Area is complex, and iron and manganese concentrations are very high. These metals as well as other organic carbon and soil oxidant demand could consume a considerable amount of chemical oxidant.
- Implementing this alternative would take longer than ISCO alone and would require bench scale testing for ISB.
- There is uncertainty as to whether indigenous biota may outcompete targeted biota or planted microorganisms for selected substrate.
- The alternative may not fully address interbedded silt layers that may be contaminated.
- The restoration timeframe will be reduced, but the amount of reduction is difficult to predict.

6.3 PREFERRED ALTERNATIVE

Alternative 3 is the preferred alternative to implement as a contingent remedy in place of the existing groundwater extraction contingent remedy presented in the CAP. The assumed risk for exposure to 1,4-dioxane for ecological or human receptors is negligible, so the primary objectives for the selected alternative is to aggressively remove some mass and try to enhance degradation of the 1,4-dioxane plume to expedite cleanup of the Outside Area. Alternative 3 addresses these objectives with a good performance rating for the ISCO and potential to expedite cleanup throughout the plume with ISB.

Alternative 3 will address the 1,4-dioxane contamination through the implementation of two phases. All necessary permits to implement each phase will be in hand prior to implementing either phase of the selected remedy (see Table 1, Push Probe Injections).

Prior to the implementation of Phase I, groundwater samples will be collected from the leading edge of the plume adjacent to CG-127, in the middle of the plume near CG-161, and upgradient of the plume adjacent to CG-122, and shipped to Rice University. Soil samples will be collected during the implementation of Phase I at both shallow and intermediate depth intervals and shipped to Rice University. Rice University will perform treatability studies on the samples by evaluating:

- Microorgansims currently present in groundwater/soil with the ability to degrade 1,4-dioxane either through assimilation into biomass or as an energy source;
- Nutrient limitations and substrate evaluation;
- Potential for bioaugmentation; and
- Substrate requirements for bioaugmentation to be successful.

Phase I will target high concentration target areas in the intermediate and shallow zones near the leading edge of the plume and well CG-122 near the back of the plume to shrink the plume’s mass aggressively with ISCO. Activated persulfate, such as the proprietary product by Regenesis; PersulfOx®, will be used to oxidize the 1,4-dioxane. Figure 4 shows the approximate injection locations with the potential radius of influence of 5 feet for each injection point, which is estimated based on information from Regenesis for geologic units such as those encountered during monitoring well installations in the area planned for injection (primarily silty sands). PersulfOx® or an equivalent activated persulfate technology will be injected in the locations shown on Figure 4, although injection locations may change slightly to avoid conflicting utilities or surface structures. Regenesis recommends a second round of injections approximately one month later in the same locations. It is assumed that approximately 35 injection locations will be sufficient to target the highest concentration locations.

Upon approval of this technical memorandum, a remedial design work plan will be submitted to Ecology outlining the design details for the injection of PersulfOx® or the equivalent.

Phase II will involve ISB. Upon receiving a recommendation from Rice for the best solution for ISB to be effective for the Outside Area, a supplemental memorandum to the remedial design work plan will be submitted to Ecology with injection details and designs to begin Phase II. Figure 5 shows the preliminary locations for injection of substrate and microorganisms as required. The location near CG-122 is selected because this area is most likely to be effective for dispersion and diffusion transporting microorganisms and substrate throughout the downgradient plume area. The location near CG-161 is more likely to provide quicker distribution throughout the plume area. A monitoring plan will be developed and presented in the remediation design work plan. The monitoring network will be used to track 1,4-dioxane degradation rates and to project the cleanup time frame during annual reporting to Ecology.

7.0 SCHEDULE

This memorandum acts as an alternatives evaluation for the Outside Area to address 1,4-dioxane and a conceptual design to implement Alternative 3. Upon approval of the 1,4-dioxane remediation approach outlined in this document by Ecology, a remedial design work plan will be prepared, as an attachment to the Agreed Order. Since the Agreed Order acknowledges PSC may produce plans for approval by Ecology after the Engineering Design Report is approved, the remedial design work plan would fall under that description. The work plan will outline the design for the ISCO injection system and describe the ISB program in as much detail as is feasible to include prior to completion of the Rice University study. Assuming that Ecology wishes to consider this a “substantial change to the work to be performed” as defined under Section VIII of the Agreed Order, the work plan would go through public comment prior to approval and implementation. Assuming this process takes approximately 6 months, Phase I will begin in the third quarter of 2015. The Rice University study will begin in the beginning of 2015. Upon receipt of recommendations from Rice University for ISB, a supplemental memorandum to the remedial design work plan will be prepared for Ecology summarizing the results of the treatability study and the design for injection of substrate and microorganisms. ISB application will likely begin by the beginning of 2017. Phases I and II will be completed by the middle of 2017 and long term monitoring will be completed as will be defined in the remediation design work plan. Progress reports would be provided as part of the currently prepared quarterly progress reports and summarized as part of the final implementation report for the cleanup east of 4th Avenue. The preliminary schedule for the implementation of Alternative 3 is shown in Figure 6.

This page intentionally left blank.

8.0 REFERENCES

Aitchison, Eric W, Sara L Kelley, Pedro JJ Alvarez, and Jerald L Schnoor, 2000, Phytoremediation of 1,4-dioxane by Hybrid Poplar Trees, *Water Environment Research*, May/June.

Dalton, Olmsted & Fuglevand, Inc. (DOF), 2013, Evaluation of 1,4-Dioxane in Groundwater, PSC Georgetown Facility, Seattle, Washington, June.

Ecology – see Washington State Department of Ecology

Li, Menryan, Stephanie Fiorenza, James R Chatham, Shaily Mahendra, and Pedro J.J. Alvarez, 2010, 1,4-dioxane biodegradation at low temperatures in Arctic groundwater samples, *ScienceDirect*, February.

Li, Menryan, Jacques Mathieu, Yu Yang, Stephanie Fiorenza, Ye Deng, Zhili He, Jizhong Zhou, and Pedro J.J. Alvarez, 2013, Widespread Distribution of Soluble Di-Iron Monooxygenase (SDIMO) Genes in Arctic Groundwater Impacted by 1,4-dioxane, *Environmental Science and Technology*, ACS Publications, August 2.

Mahendra, Shaily and Lisa Alvarez-Cohen, 2006, Kinetics of 1,4-Dioxane Biodegredation by Monooxygenase-Expressing Bacteria, *Environ. Sci. Technol*. 40: 5435-5442 .

Regenesis Remediation Technologies (Regenesis), no date, Project Profile, 1,4-dioxane and 1,1 DCE in Fractured Bedrock Treated with ISCO.

Regenesis, no date, PersulfOx Catalyzed Persulfate Contaminant Oxidation Data, PersulfOx Technical Bulletin2.0.

U.S. Environmental Protection Agency (EPA), 1994, RCRA Corrective Action Plan (Final), Office of Waste Programs Enforcement/Office of Solid Waste, OSWER Directive 9902.3-2A, May.

Washington State Department of Ecology (Ecology), 2010, Draft Cleanup Action Plan, PSC Georgetown Facility, Seattle, Washington, February 2.

Ecology, 2014, 1,4-dioxane in site groundwater; dispute resolution, PSC-Georgetown Facility, Ecology/EPA # WAD 00081 2909, June 19 letter to William Beck, PSC Environmental Services.

This page intentionally left blank.

TABLES

TABLE 1

SUMMARY OF PERMIT REQUIREMENTS FOR POTENTIAL REMEDIAL ACTION ALTERNATIVES

PSC Georgetown Facility
Seattle, Washington

Potential Alternative Description	Work Location	Permanent Equipment (minimum 1–2 years)	DPD Permits Required	DPD Time	SDOT Permits Required[2]	SDOT Time	KC Permits Required	KC Time	Ecology Permits Required	Ecology Time	Maximum Potential Permitting Time (weeks)
Contingent Remedy Groundwater Extraction[1]	Public Right of Way	- Extraction well vault - Trenching for piping to sewer - Electrical connection to system - Treatment system temporary bldg	Over-the-counter electrical and side sewer permits	1 day	51A- Well Installation Permit "Utility Major Permit" requiring an annual permit	10–20 weeks	Discharge Authorization	4–6 weeks	Well Start Card	1 day	27
Contingent Remedy Groundwater Extraction[2]	Private Property	- Extraction well vault - Trenching for piping to sewer - Electrical connection to system - Treatment system temporary bldg	Over-the-counter electrical and side sewer permits and a full permit review	3–4 months	51A- Well Installation Permit "Utility Major Permit" requiring an annual permit	10–20 weeks	Discharge Authorization	4–6 weeks	Well Start Card	1 day	43
Recirculation Wells[1]	Public Right of Way	- Extraction and injection well vault - Electrical connection to system - Treatment system temporary bldg	Over-the-counter electrical permits	1 day	51A- Well Installation Permit "Utility Major Permit" requiring an annual permit	10–20 weeks	None	None	Well Start Card UIC permit	2 weeks	23
Recirculation Wells[2]	Private Property	- Extraction and injection well vault - Electrical connection to system - Treatment system temporary bldg	Over-the-counter electrical permit and a full permit review	3–4 months	51A- Well Installation Permit "Utility Major Permit" requiring an annual permit	10–20 weeks	None	None	Well Start Card UIC permit	2 weeks	38
Push Probe Injections	Public Right of Way	Temporary injection points	None	None	51A- Well installation permit Utility Major Permit	8–12 weeks	None	None	Well Start Card UIC permit	2 weeks	14
Push Probe Injections[2]	Private Property	Temporary injection points	Full permit review	3–4 months	51A- Well installation permit Utility Major Permit	8–12 weeks	None	None	Well Start Card UIC permit	2 weeks	30

Notes:

1. Alternative does not include time to negotiate terms for long-term storage of hazardous chemicals and/or an indemnity agreement for long-term equipment in SDOT right of way. SDOT said they could not provide time until application was submitted.
2. Alternative does not include time for negotiations with individual property owners. Time and associated costs may be prohibitive.

Abbreviations:

DPD = Department of Planning and Development
Ecology = Washington State Department of Ecology
KC = King County
OTC= Over the Counter
SDOT = Seattle Department of Transportation
UIC = Underground Injection Control

TABLE 2

REMEDIATION TECHNOLOGY SCREENING FOR OUTSIDE AREA GROUNDWATER
PSC Georgetown Facility
Seattle, Washington

General Response Actions	Remediation Technologies	Technology Description	Technology Characteristics			Rationale for Retention or Rejection	Screening Result
			Technology Development Status	General Performance Record	Site-Specific Issues Affecting Technology or Implementation		
In Situ Biological Treatment	Enhanced Bioremediation	Injection of substrate to promote in situ biological degradation. Injection of limiting nutrients for the indigenous or planted microorganisms to allow for the target species to out-compete other indigenous microbes in the groundwater.	Pilot-Scale	Has been effective for biodegradation of 1,4-dioxane on small-scale studies. Requires application of specific substrate such as fuels (i.e., propane and THF) or alcohols such as 1-butanol.	Target organisms may not compete successfully with indigenous organisms. 1,4-Dioxane appears to be currently degrading at the site, based on historic trend data. Most cost-effective if injected on the upgradient edge or the middle of the plume, allowing groundwater flow to distribute across a large area.	Enhanced biodegradation is retained as a potential technology to supplement and speed up existing biodegradation or to use in conjunction with bioaugmentation.	Retain
	Bioaugmentation	Injection of specialty, (may be non-indigenous or currently present) microbes to enhance biodegradation. Microorganisms are commercially available for degradation of 1,4-dioxane.	Pilot-Scale	Has been effective for biodegradation of 1,4-dioxane on small-scale studies. Requires application of specific microorganisms. May require repeated application.	Non-indigenous organisms may not compete successfully with indigenous organisms. 1,4-Dioxane appears to be currently degrading at the site, based on historic trend data. May be especially cost-effective on upgradient edge or the middle of the plume. Best chance to add a long-lasting treatment that would continue to degrade 1,4-dioxane releases from low permeability lenses.	Bioaugmentation is retained as a potential technology to supplement and speed up existing biodegradation. In addition, it is the most likely to provide long lasting treatment for 1,4-dioxane from low permeability lenses.	Retain
	Natural Attenuation	Intrinsic attenuation of groundwater constituents via the natural processes of biodegradation (aerobic and/or anaerobic), adsorption, and dilution. This passive technology relies on natural conditions within impacted groundwater.	Full-Scale	Traditionally believed to be primarily based on dilution, biodegradation has been shown to occur in situ at sites with appropriate conditions.	Natural biodegradation of 1,4-dioxane is likely active in area groundwater, resulting in declining trends in most monitoring wells. Technology has potentially longer remediation times than more active technologies.	This technology would result in longer restoration time frames for 1,4-dioxane but may be feasible for lower concentrations given that monitoring data indicate no threat to surface waters.	Retain
	Phytoremediation	Phytoremediation works by absorption into the roots of the plant. 1,4-Dioxane is typically absorbed into the plant's biomass or transpired. Poplars have shown the ability to remediate 1,4-dioxane in groundwater and soil.	Small-Scale	Has been proven in mostly small-scale applications.	The extent of contamination for 1,4-dioxane is primarily in the intermediate and shallow aquifer; too deep to target with phytoremediation. In addition, remediation would need to take place in dense urban locations, making it difficult to plant appropriate plants. A large number of plants would be required and likely a lot of maintenance would be required to maintain plants.	The depth of contamination prohibits the use of this treatment technology.	Reject
In Situ Chemical Treatment	In Situ Chemical Oxidation	An oxidizing chemical (persulfate, hydrogen peroxide, Fenton's Reagent) is added to the groundwater to chemically oxidize 1,4-dioxane. Usually applied through injection wells or via direct push technology.	Full-Scale	Usually applied to source areas or higher concentration areas. Mixed performance record. Some applications have been effective, while others have been unsuccessful in attaining cleanup objectives. Technology depends on contact with 1,4-dioxane and oxidant demand of the soil, organic carbon and inorganics in the subsurface.	High iron concentrations at the site will exert a large oxidant demand, reducing efficiency of treatment and reducing the longevity of treatment in situ. Variability in oxidant demand from other sources such as soil oxidant demand, total organic carbon, and other organics and inorganics may result in very high oxidant demands to have sufficient contact with 1,4-dioxane to fully oxidize it. Penetration of low permeability lenses is unlikely, even with many injections. Technology not cost-effective for treatment of diffuse groundwater concentrations. May be combined with enhanced biodegradation or bioaugmentation if planned correctly. Requires handling of hazardous chemicals.	High oxidant demand and diffuse groundwater concentrations make treatment of the entire area costly. This technology is retained for areas in which it will be most cost-effective for mass removal spotsareas with 1,4-dioxane concentrations over 400 µg/L and leading edge of plume).	Retain

TABLE 2

REMEDIATION TECHNOLOGY SCREENING FOR OUTSIDE AREA GROUNDWATER

PSC Georgetown Facility
Seattle, Washington

General Response Actions	Remediation Technologies	Technology Description	Technology Characteristics			Rationale for Retention or Rejection	Screening Result
			Technology Development Status	General Performance Record	Site-Specific Issues Affecting Technology or Implementation		
Groundwater Extraction and Treatment (Pump and Treat)	Mass Reduction	Groundwater extraction wells are installed to remove contaminated groundwater, thereby reducing contaminant mass. Extracted water is then treated and discharged.	Full-Scale	Has been used to remove contaminants in source areas. Requires ongoing operation and maintenance. Is a long-duration technology. Not effective to expeditiously attain cleanup levels or to treat diffuse plumes.	Limited ability to target highest 1,4-dioxane concentrations. Not cost-effective for diffuse plumes. Pumping from the 1,4-dioxane plume will pull primarily from the most permeable zones, while the majority of the 1,4-dioxane mass could likely be trapped in less permeable geology. 1,4-dioxane could likely continue to slowly back diffuse from the less permeable silt and clay layers. Long-term pumping would be required to attain cleanup levels. Long-term O&M facilities would trigger additional permitting requirements, delaying implementation and adding cost. Long-term property access would be needed to install, operate, and maintain the extraction and treatment components. Volume of discharge water would be limited by King County publicly owned treatment works, or National Pollutant Discharge Elimination System permitting would be necessary. Would require substantial permitting time prior to implementation.	Implementation of a multi-well extraction and treatment system across many different properties is logistically complex, and would not likely attain cleanup levels in an expedient time frame. Ancillary treatment technologies for 1,4-dioxane could likely result in long-term storage of hazardous contaminants in the public right of way. Permitting would delay response action significantly and be costly. With a longer remedial time frame, uncertainty in effective mass removal, and the highest costs, this technology is rejected.	Reject
	Biological Reactors	This technology is used in conjunction with pump and treat systems. Extracted groundwater is passed into a bioreactor where substrate is added to assist in the bioremediation of 1,4-dioxane. Initial microorganisms would be required in the bioreactor and likely a fuel such as propane or THF would need to be added.	Full-Scale	Has been used to remove contaminants in source areas. Requires ongoing operation and maintenance. Requires fuels that may be considered hazardous chemicals to be stored on site.	Long-term property access would be needed to install, operate, and maintain the extraction and treatment components in areas not owned by PSC. Significant long-term O&M costs make active in situ technologies preferable. Would require substantial permitting time prior to implementation. Technology would result in significant waste generation and would require long-term storage of hazardous chemicals in the public right-of-way. Biological reactors are sensitive to environmental changes (temperature, system shutdown.)	Rejected in conjunction with rejection of pump and treat technology.	Reject
	Adsorption	This technology is used in conjunction with pump and treat systems. Extracted groundwater is passed through vessels containing adsorptive media that preferentially absorbs 1,4-dioxane and certain volatile organic compounds. The media is reclaimed by using a steam method to strip and concentrate the 1,4-dioxane into a waste stream for disposal.	Full-Scale	Has been effectively used to remove 1,4-dioxane and chlorinated volatile organic compounds from the aqueous phase at several sites on the east coast. Pre-packaged treatment and media regeneration systems are now available for sale.	Long-term property access would be needed to install, operate, and maintain the extraction and treatment components in areas not owned by PSC. Significant long-term O&M costs make active in situ technologies preferable. Would require substantial permitting time prior to implementation. Technology would result in significant waste generation (media and condensate of 1,4-dioxane/volatile organic compounds, in addition to sanitary sewer discharge).	Rejected in conjunction with rejection of pump and treat technology.	Reject
	Advanced Oxidation	This technology is used to support pump and treat remediation. Extracted groundwater is passed through a specially designed advanced oxidation unit. Advanced oxidation processes typically use ultraviolet light, hydrogen peroxide and ozone, or other aggressive advanced oxidation technologies to aggressively oxidize organics. Treatment products are typically carbon dioxide, water, and hydrochloric acid (if chlorinated compounds are present).	Full-Scale	Has been effectively used to treat groundwater, including 1,4-dioxane. Requires ongoing operation and maintenance. Requires hazardous chemicals to be stored on site.	Long-term property access would be needed to install, operate, and maintain the extraction and treatment components in areas not owned by PSC. Significant long-term O&M costs make active in situ technologies preferable. Would require substantial permitting time prior to implementation. Technology would result in significant waste generation and would require long-term storage of hazardous chemicals in the public right of way. High concentrations of inorganics such as iron will add to cost of O&M.	Rejected in conjunction with rejection of pump and treat technology.	Reject

TABLE 2

REMEDIATION TECHNOLOGY SCREENING FOR OUTSIDE AREA GROUNDWATER

PSC Georgetown Facility
Seattle, Washington

General Response Actions	Remediation Technologies	Technology Description	Technology Characteristics			Rationale for Retention or Rejection	Screening Result
			Technology Development Status	General Performance Record	Site-Specific Issues Affecting Technology or Implementation		
Subsurface Injection Technologies	Push Probes	This technology is commonly used for temporary well installation for subsurface investigation and chemical treatment of the subsurface. A drill rig pushes steel rod into the ground. Minimal waste is created.	Full-Scale	Good for sandy and silty soils, unable to reach deeper units in formations with gravel or cobbles. Spacing is determined by porosity and permeability of site soils.	A higher number of injection points ensure better distribution than recirculation wells. No permanent equipment or subsurface installations are left behind.	Retained for use with in situ bioremediation or in situ chemical oxidation technologies.	Retain
	Recirculation Wells	Recirculation wells are permanent wells typically installed by hollow stem auger drill rigs. A drill rig augers soil out of the ground and a permanent well casing is installed. A more significant amount of drill cuttings are created, heavily dependent on the size of boring.	Full-Scale	Best for projects where repeat injections are likely for the long term and where site soils are uniform.	Recirculation wells require either permanent or portable equipment, electrical, and pumping systems. Not ideal for heterogeneous soils due to the likelihood of short circuiting. Most cost effective when many rounds of repeat injections are necessary.	Rejected due to poor control of where in situ bioremediation or in situ chemical oxidation would go in the subsurface.	Reject
	Hydraulic Fracturing	A high-pressure injection technique that is useful for injections into low permeability material.	Full-Scale	Most useful for injecting into bedrock or other very low permeability geologic units.	Chemicals may daylight for shallower injections. Adds cost and health and safety concerns (high pressure) with minimal benefit to distribution. May create flow channels that transport injected chemicals outside of treatment area.	Rejected, not appropriate for site geology.	Reject

Abbreviations:

µg/L = micrograms per liter
O&M = operation and maintenance
PSC = PSC Environmental Services, LLC
THF = tetrahydrofuran

TABLE 3

1,4-DIOXANE TREATMENT ALTERNATIVES EVALUATION

PSC Georgetown Facility
Seattle, Washington

Alternative [1]	Implementation Method	Protectiveness	Permanence	Relative Cost
Alternative 1: In Situ Chemical Oxidation Targeted Approach	Upon Ecology approval, inject persulfate by push probe in three areas with 1,4-dioxane concentrations over 400 µg/L: 1) along the east side of 6th Avenue South, between Orcas and Findley Streets (near CG-127) in the shallow and intermediate zones; 2) at the northwest corner of Lucile and Maynard Streets (near CG-122-60) in the intermediate zone; and 3) along the southern side of Findlay Street between 6th Avenue South and Maynard Street (adjacent to CG-161) in both the shallow and intermediate zones. Follow up injection in same locations per recommendations from manufacturer.	- Should immediately reduce concentrations of 1,4-dioxane in target areas. - Should reduce remedial time frame.	- Permanently destroys 1,4-dioxane under conditions similar to those in groundwater on site. - Minimal wastes created. - Some chance for mobilization of metals and other contaminants.	- Moderate cost for permitting and oxidant. - Several weeks would be required to do initial injection and follow-up injection.
Alternative 2: In Situ Biological Degradation Targeted Approach	Upon completion of Rice Study; inject seed microorganisms and substrate at three locations. Inject persulfate by push probe in three areas with 1,4-dioxane concentrations over 400 µg/L: 1) Along the East side of 6th Ave S, between Orcas and Findley street (near CG-127) in the shallow and intermediate zones. 2) At the NW corner of Lucile and Maynard (near CG-122-60) in the intermediate zone. Along the southern side of Findlay street between 6th and Maynard (adjacent to CG-161) in both the shallow and intermediate zones.	- Should increase degradation rate of 1,4-dioxne in target areas. - Should reduce remedial time frame. - Will likely distribute to entire plume area over time. - Microorganisms may penetrate low permeability lenses. - Could provide a long-lasting treatment for back diffusion of 1,4-dioxane from low permeability units.	- Permanently destroys 1,4-dioxane under conditions similar to those in groundwater on site. - Minimal wastes created.	- Initial study to determine if bioaugmentation is possible on site adds a significant cost. - Moderate cost for permitting, substrate, and microorganisms. - Several weeks would be required to do initial injection.
Preferred Alternative Alternative 3: In Situ Chemical Oxidation and In Situ Bioremediation Targeted Approach	Use a combination of ISCO and ISB delivered by push probe to target different areas of the plume. The highest concentrations would be targeted with ISCO following Ecology approval, followed approximately a year later by injection of microorganisms and substrate in the center of the plume and along the upgradient edge of the plume. Persulfate would be injected in three areas with 1,4-dioxane concentrations over 400 µg/L: 1) along the east side of 6th Avenue South, between Orcas and Findley Streets (near CG-127) in the shallow and intermediate zones; 2) at the northwest corner of Lucile and Maynard Streets (near CG-122-60) in the intermediate zone; and 3) along the southern side of Findlay Street between 6th Avenue South and Maynard Street (adjacent to CG-161) in both the shallow and intermediate zones. Follow up injection in same locations per recommendations from manufacturer. Microorganisms and substrate would be injected in two locations: 1) along the west side of Maynard Street, starting at the northwest corner of Lucile and Maynard Streets (near CG-122-60) in the intermediate zone and extending south across the intersection half way down Maynard Street toward Findlay Street; and 2) along the south side of Findlay Street between 6th Avenue South and Maynard Street (adjacent to CG-161) in both the shallow and intermediate zones.	- Should immediately reduce concentrations of 1,4-dioxane in target areas. - Should increase degradation rate of 1,4-dioxane in target areas. - Should reduce remedial time frame. - Will likely spread to entire plume area over time. - Microorganisms may penetrate low permeability lenses. - Could provide a long-lasting treatment for back diffusion of 1,4-dioxane from low permeability units.	- Permanently destroys 1,4-dioxane under conditions similar to those in groundwater on site. - Minimal wastes created. - Some chance for mobilization of metals and other contaminants, though less than the ISCO only alternative.	- Initial study to determine if bioaugmentation is possible on site adds a significant cost. - Moderate cost for permitting, oxidant, and for substrate and microorganisms. - Several weeks would be required to perform injections.

TABLE 3

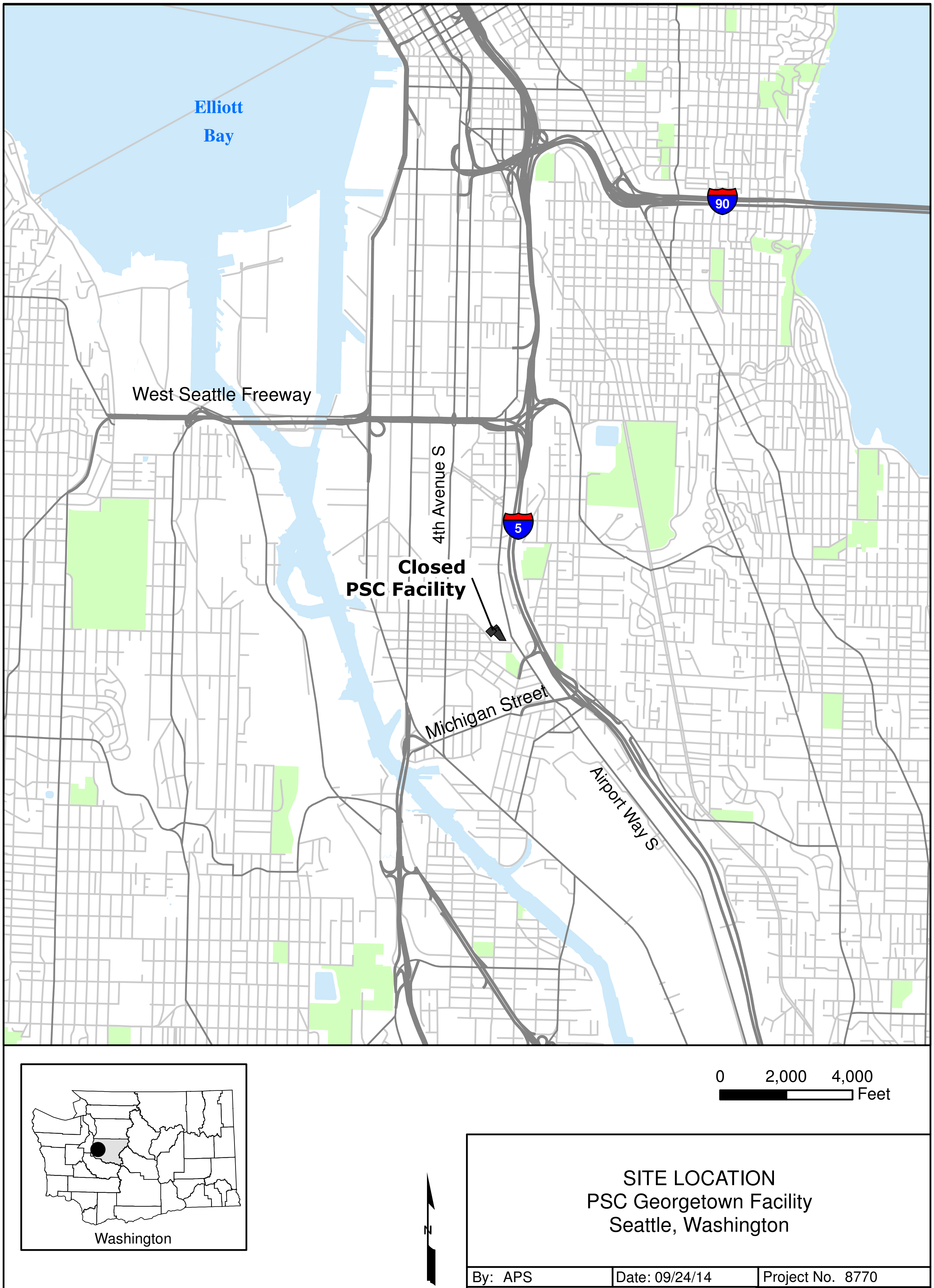
1,4-DIOXANE TREATMENT ALTERNATIVES EVALUATION
PSC Georgetown Facility
Seattle, Washington

Long Term Effectiveness	Management of Short Term Risks	Technical and Administrative Implementability	Consideration of Public Concerns
- ISCO will destroy any 1,4-dioxane that it comes into direct contact with. - ISCO is unlikely to penetrate deeply into silt and clay layers, so 1,4-dioxane could possibly continue to be released through back diffusion from the silts. - Persulfate will be scavenged by total organic carbon and inorganic chemicals in soil in groundwater.	- Short-term risk to human health during injection (from construction equipment and potential chemical exposure). All workers will wear appropriate PPE. Chemical handling and injection will be performed a safe distance from members of the public, who will be barred from entry into the work zone. - Small risk from daylighting of chemicals during injection, which can be mitigated using engineering controls. - Small risk to underground utilities. All utility companies with nearby buried lines will be consulted prior to injection of chemicals and a utility locate will be performed prior to subsurface disturbance.	- Oxidant should remove a significant amount of 1,4-dioxane mass in the areas injected. - The injection locations are on side streets and in the right of way, where significant room is available, thus limiting disturbance to traffic and pedestrians. - Locations where injections could be completed would not cover the entire plume and some residual concentrations would remain in impermeable zones. - Minimal permitting required as all work would be completed in the City of Seattle right of way.	- A traffic control plan will be set up to ensure minimal disruption to vehicle and pedestrian traffic. - The injection locations are on side streets and in the right of way, where significant room is available, thus limiting disturbance to traffic and pedestrians. - Surface streets and pavement with residual chemicals will be pressure washed and waste water will be managed appropriately. - Work can be completed during normal business hours and equipment will be muffled if necessary.
- ISB effectiveness depends on ability of injected microorganisms to out-compete local organisms. - ISB has shown effectiveness at 1,4-dioxane degradation at other sites through co-metabolic processes. - Has the best chance for long-lasting remediation of 1,4-dioxane back diffusing from less permeable units.	- Short-term risk to human health during injection (from construction equipment and potential chemical exposure). All workers will wear appropriate PPE. Chemical handling and injection will be performed a safe distance from members of the public, who will be barred from entry into the work zone. - Substrate used for ISB is likely to be less dangerous than ISCO chemicals. - Small risk from daylighting of chemicals during injection, which can be mitigated using engineering controls. - Small risk to underground utilities. All utility companies with nearby buried lines will be consulted prior to injection of chemicals and a utility locate will be performed prior to subsurface disturbance.	- In order to distribute oxidant, substrate, and microorganisms throughout the targeted plume, a large number of injection points would be required. However, injection points could be located on side streets to minimize traffic impacts. - Locations where injections could be completed would not cover the entire plume and some residual concentrations would remain in impermeable zones. - Precipitation of iron in ISCO area may make follow-up injections difficult due to increasing injection pressures required. - Minimal permitting required as all work would be completed in the City of Seattle right of way.	- A traffic control plan will be set up to ensure minimal disruption to vehicle and pedestrian traffic. - The injection locations are on side streets and in the right of way, where significant room is available, thus limiting disturbance to traffic and pedestrians. - Surface streets and pavement with residual chemicals will be pressure washed and waste water will be managed appropriately. - Work can be completed during normal business hours and equipment will be muffled if necessary.
- ISCO will destroy any 1,4-dioxane that it comes into direct contact with. - ISB effectiveness depends on ability of injected microorganisms to out-compete local organisms. - ISB has shown effectiveness at 1,4-dioxane degradation at other sites through co-metabolic processes. - ISB has the best chance for long-lasting remediation of 1,4-dioxane back diffusing from less permeable units.	- Short-term risk to human health during injection (from construction equipment and potential chemical exposure). All workers will wear appropriate PPE. Chemical handling and injection will be performed a safe distance from members of the public, who will be barred from entry into the work zone. - Small risk from daylighting of chemicals during injection, which can be mitigated using engineering controls. - Since use of ISCO is replaced by the likely less dangerous ISB substrates, less risk than ISCO use alone. - Small risk to underground utilities. All utility companies with nearby buried lines will be consulted prior to injection of chemicals and a utility locate will be performed prior to subsurface disturbance.	- In order to distribute oxidant, substrate, and microorganisms throughout the targeted plume, a large number of injection points would be required. However, injection points could be located on side streets to minimize traffic impacts. - Locations where injections could be completed would not cover the entire plume and some residual concentrations would remain in impermeable zones. - Precipitation of iron in ISCO area may make follow-up injections difficult due to increasing injection pressures required. - Minimal permitting required as all work would be completed in the City of Seattle right of way.	- A traffic control plan will be set up to ensure minimal disruption to vehicle and pedestrian traffic. - The injection locations are on side streets and in the right of way, where significant room is available, thus limiting disturbance to traffic and pedestrians. - Surface streets and pavement with residual chemicals will be pressure washed and waste water will be managed appropriately. - Work can be completed during normal business hours and equipment will be muffled if necessary.

Note:
1. All alternatives assumes all work will take place in the public right of way to reduce cost and time for permitting.

Abbreviations:
µg/L = micrograms per liter
Ecology = Washington State Department of Ecology
ISB - in situ bioremediation
ISCO = in situ chemical oxidation
PPE = personal protective equipment

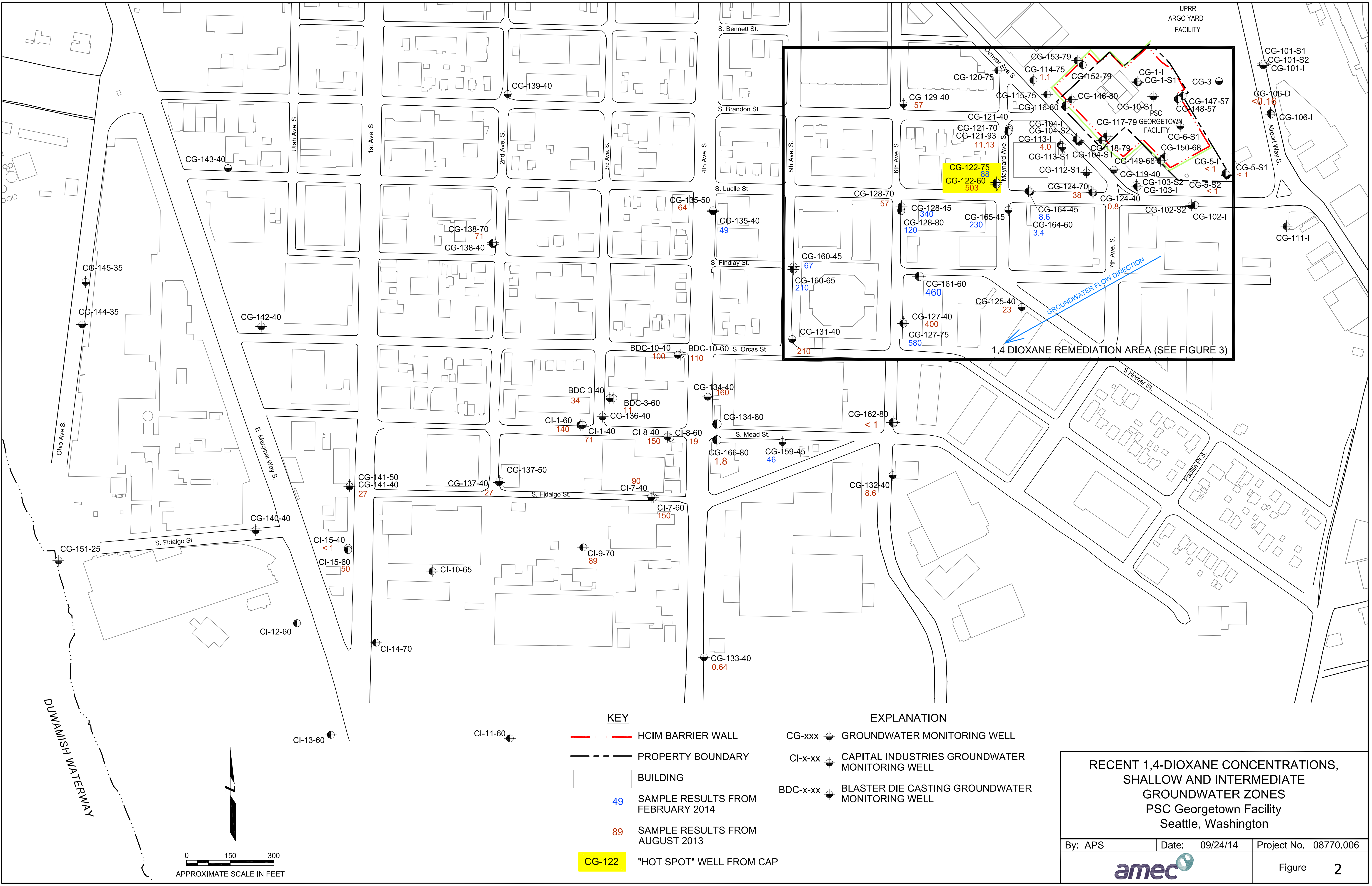
FIGURES



SITE LOCATION
PSC Georgetown Facility
Seattle, Washington

By: APS	Date: 09/24/14	Project No. 8770
		Figure 1

S:\8770_2006\045_14Dioxane-Plume\GIS\SiteLocation_090814.mxd



KEY

HCIM BARRIER WALL
PROPERTY BOUNDARY
BUILDING
49 SAMPLE RESULTS FROM FEBRUARY 2014
89 SAMPLE RESULTS FROM AUGUST 2013
CG-122 "HOT SPOT" WELL FROM CAP

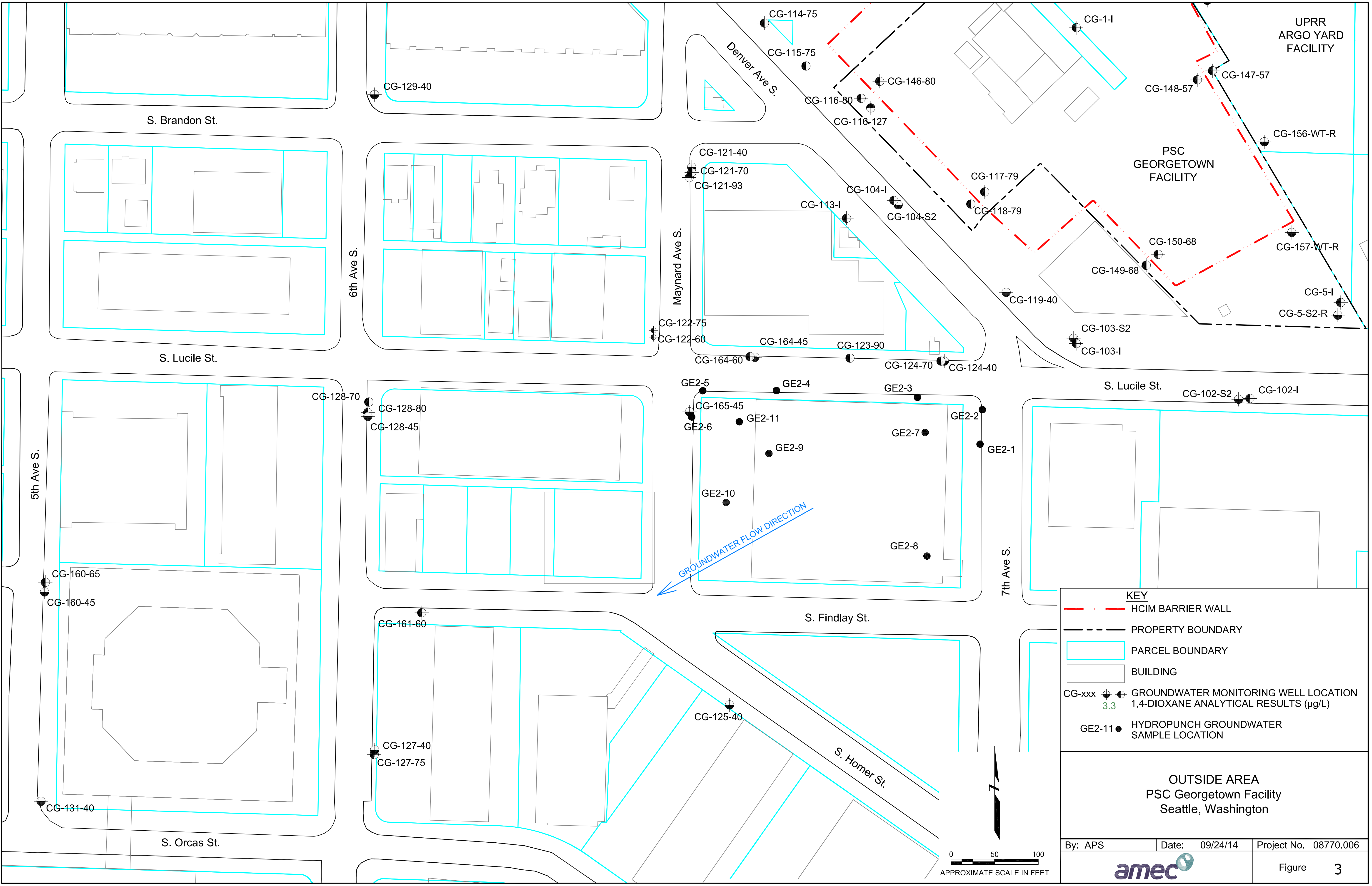
EXPLANATION

CG-xxx GROUNDWATER MONITORING WELL
CI-x-xx CAPITAL INDUSTRIES GROUNDWATER MONITORING WELL
BDC-x-xx BLASTER DIE CASTING GROUNDWATER MONITORING WELL

RECENT 1,4-DIOXANE CONCENTRATIONS,
SHALLOW AND INTERMEDIATE
GROUNDWATER ZONES
PSC Georgetown Facility
Seattle, Washington

By: APS	Date: 09/24/14	Project No. 08770.006
amec		Figure 2

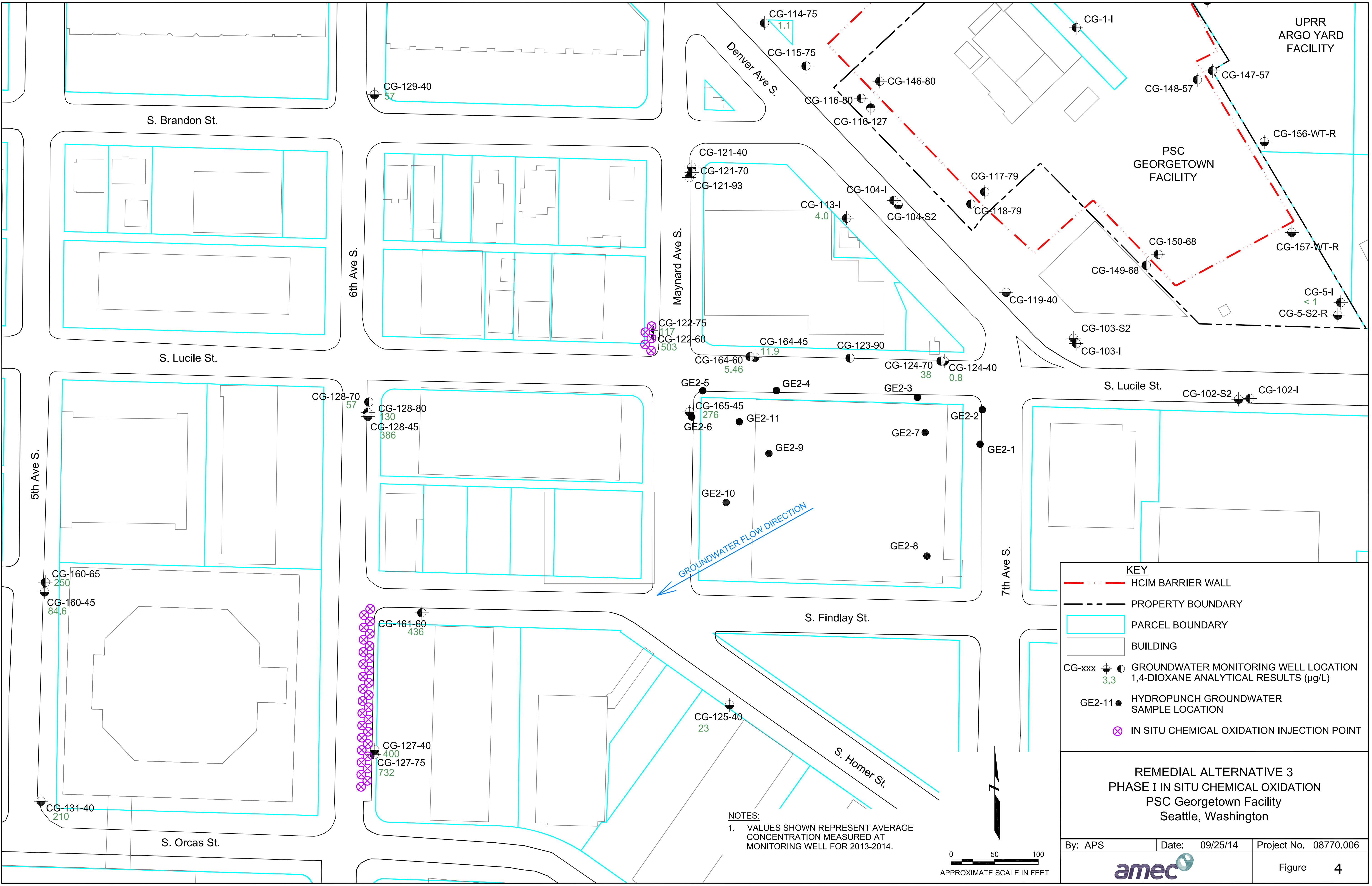
Plot Date: 09/24/14 - 3:44pm, Plotted by: adam.stenberg
Drawing Path: S:\8770_2006\045_14Dioxane-Plume\, Drawing Name: PSC-GT_MW-GW-SampLoc-090214.dwg



OUTSIDE AREA
PSC Georgetown Facility
Seattle, Washington

By: APS	Date: 09/24/14	Project No. 08770.006
amec		Figure 3

Plot Date: 09/24/14 - 3:52pm, Plotted by: adam.stenberg
Drawing Path: S:\8770_2006\045_14Dioxane-Plume\, Drawing Name: PSC-GT_14DioxConcAltPhase1-090514.dwg



KEY

🟥	HCIM BARRIER WALL
— — —	PROPERTY BOUNDARY
🟦	PARCEL BOUNDARY
▭	BUILDING
CG-xxx ⊕ 3.3	GROUNDWATER MONITORING WELL LOCATION 1,4-DIOXANE ANALYTICAL RESULTS (µg/L)
GE2-11 ●	HYDROPUNCH GROUNDWATER SAMPLE LOCATION
⊗	IN SITU CHEMICAL OXIDATION INJECTION POINT

NOTES:
1. VALUES SHOWN REPRESENT AVERAGE CONCENTRATION MEASURED AT MONITORING WELL FOR 2013-2014.

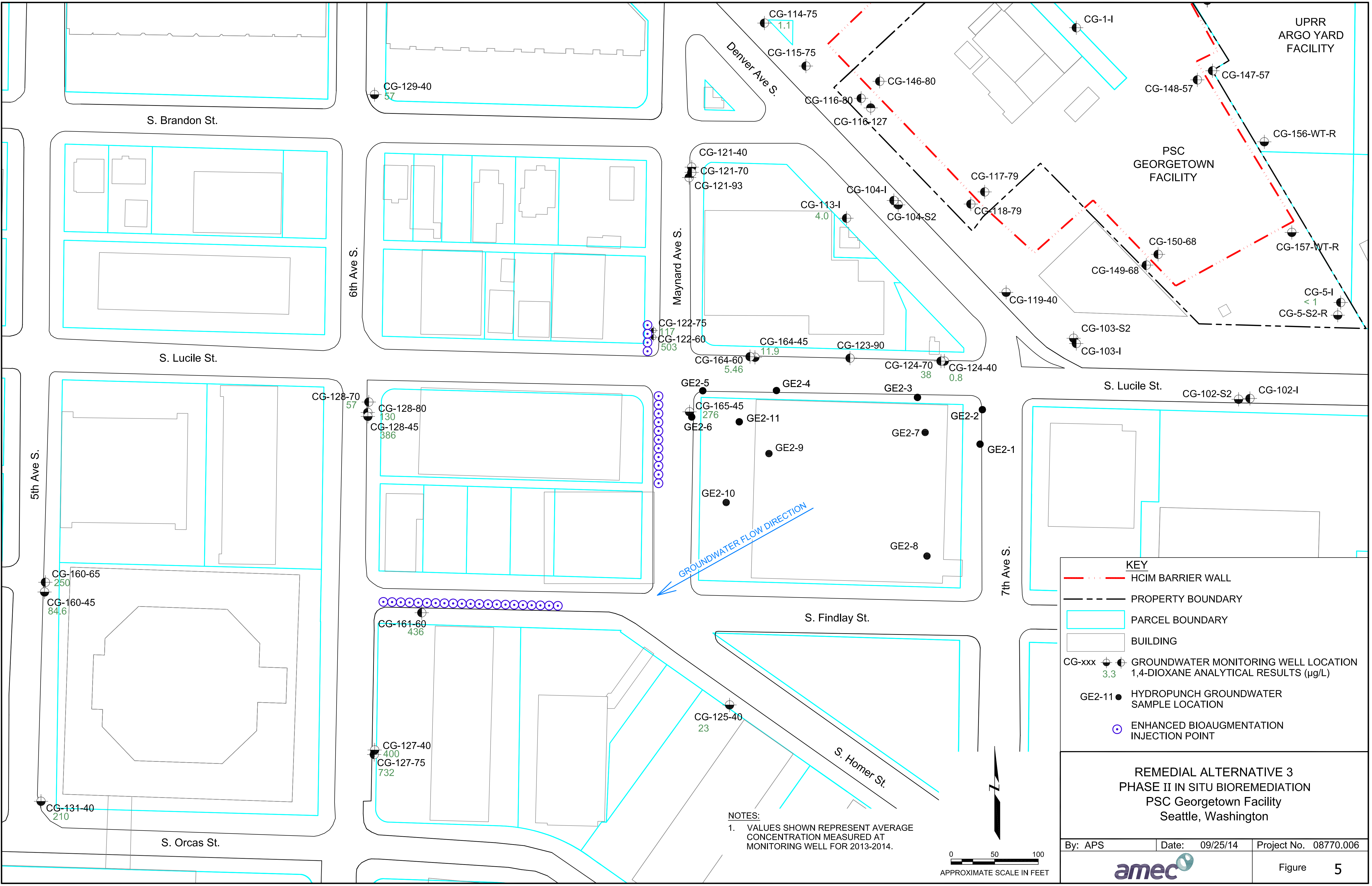
REMEDIAL ALTERNATIVE 3
PHASE I IN SITU CHEMICAL OXIDATION
PSC Georgetown Facility
Seattle, Washington

By: APS | Date: 09/25/14 | Project No. 08770.006

amec

Figure 4

Plot Date: 09/25/14 - 9:51am, Plotted by: adam.stenberg
Drawing Path: S:\8770_2006\045_14Dioxane-Plume\, Drawing Name: PSC-GT_14DioxConcAltPhase1-090514.dwg



KEY

🟥	HCIM BARRIER WALL
— —	PROPERTY BOUNDARY
🟦	PARCEL BOUNDARY
☐	BUILDING
CG-xxx ◐ ◐ 3.3	GROUNDWATER MONITORING WELL LOCATION 1,4-DIOXANE ANALYTICAL RESULTS (µg/L)
GE2-11 ●	HYDROPUNCH GROUNDWATER SAMPLE LOCATION
⊙	ENHANCED BIOAUGMENTATION INJECTION POINT

NOTES:

1. VALUES SHOWN REPRESENT AVERAGE CONCENTRATION MEASURED AT MONITORING WELL FOR 2013-2014.

REMEDIAL ALTERNATIVE 3
PHASE II IN SITU BIOREMEDIATION
PSC Georgetown Facility
Seattle, Washington

By: APS
Date: 09/25/14
Project No. 08770.006

amec

Figure 5

Plot Date: 09/25/14 - 9:51am, Plotted by: adam.stenberg
Drawing Path: S:\8770_2006\045_14Dioxane-Plume\, Drawing Name: PSC-GT_14DioxConcAllPhase1-090514.dwg

1,4-Dioxane Remediation Approach Proposed Schedule

PSC Georgetown
Seattle, WA

ID	Task Name	Duration	Start	Finish
1	**1,4-Dioxane Remediation Approach**	**198 days**	**Wed 10/1/14**	**Fri 7/3/15**
2	1,4-Dioxane Remediation Approch Technical Memorandum Submitted	1 day	Wed 10/1/14	Wed 10/1/14
3	90 day Comment & Response Period	65 days	Thu 10/2/14	Wed 12/31/14
4	1,4-Dioxane Remediation Approch Technical Memorandum Approval	1 day	Thu 1/1/15	Thu 1/1/15
5	CAP and Agreed Order Modification Period (ISCO Work Plan)	131 days	Fri 1/2/15	Fri 7/3/15
6	**Phase 1 : In Situ Chemical Oxidation**	**464 days**	**Mon 7/6/15**	**Thu 4/13/17**
7	Begin Permitting Process with Seattle DOT	71 days	Mon 7/6/15	Mon 10/12/15
8	In Situ Chemical Oxidation Injections	25 days	Tue 10/13/15	Mon 11/16/15
9	Additional 1,4-Dioxane Monitoring	368 days	Tue 11/17/15	Thu 4/13/17
10	**Phase 2 : In Situ Bio Augmentation**	**1117 days**	**Fri 1/2/15**	**Mon 4/15/19**
11	First Sample Collection for Rice University Study	15 days	Mon 2/2/15	Fri 2/20/15
12	Rice University 1,4-Dioxane Study	477 days	Fri 1/2/15	Mon 10/31/16
13	Bio Augmentation Study Memorandum	25 days	Tue 11/1/16	Mon 12/5/16
14	Begin Permitting Process with Seattle DOT	71 days	Tue 12/6/16	Tue 3/14/17
15	Enhanced Bioaugmentation Injections	22 days	Wed 3/15/17	Thu 4/13/17
16	1,4-Dioxane Monitoring	522 days	Fri 4/14/17	Mon 4/15/19

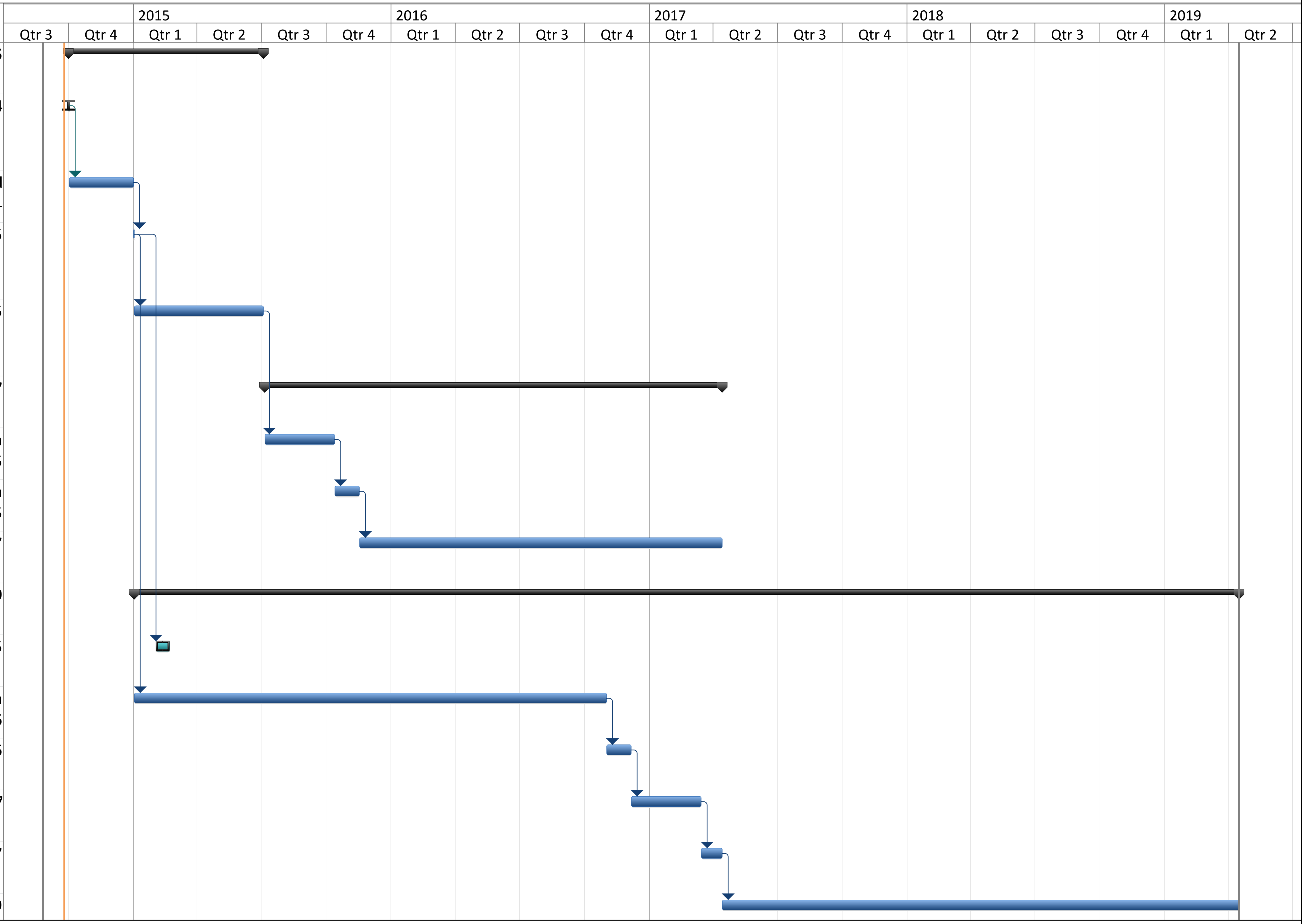


Figure 6
Project: 1,4-Dioxane Remediation
Date: Thu 9/25/14

Task	▬	Project Summary	▬	Inactive Milestone	◇	Manual Summary Rollup	▬	Deadline	⬇
Split	┈┈┈	External Tasks	▬	Inactive Summary	▭	Manual Summary	▬	Progress	▬
Milestone	◆	External Milestone	◆	Manual Task	▬	Start-only	[		
Summary	▬	Inactive Task	▭	Duration-only	▬	Finish-only	]		