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30 August, 2010

Mr. Chuck Curtis
Supervising Water Resource Control Engineer
Manager, Cleanup and Enforcement Division
California Regional Water Quality Control Board, Lahontan Region
2501 Lake Tahoe Boulevard
South Lake Tahoe, California 96150

Subject: Feasibility Study
Pacific Gas and Electric Company (PG&E) Hinkley Compressor Station
Hinkley, California

Dear Mr. Curtis:

Please find enclosed the Feasibility Study and Resolution 92-49 Evaluation (Feasibility Study) for the chromium remediation project at the Hinkley Compressor Station site in Hinkley, California. This Feasibility Study was prepared to develop a final remedy for chromium in groundwater, in accordance with the requirements of Cleanup and Abatement Order (CAO) No. R6V-2008-0002 and guidance provided by the California Regional Water Quality Control Board, Lahontan Region.

Based on more than 20 years of assessment, pilot testing, and interim remedial measures, which collectively provided a comprehensive basis for this evaluation and final remedy selection, this Feasibility Study recommends Alternative 4 (Core In-Situ Treatment and Beneficial Agricultural Use) as the groundwater remedy.

The primary components of this recommended approach include:

¾ Aggressive in-situ treatment of the plume core/source area using in-situ reduction zone chromium treatment;

¾ Hydraulic containment of the chromium plume via groundwater extraction and injection; and

¾ Treatment of a portion of the extracted groundwater in agricultural fields.

The primary beneficial attributes of this alternative include:

¾ Re-establishment of the aquifer beneficial use criterion, by achieving the maximum contaminant level (MCL) for chromium in less than 10 years (based on plume modeling estimates) following full scale startup;

¾ Robust containment of the chromium plume, with enhanced flexibility to respond to future outside hydraulic influences;

¾ Productive use of extracted groundwater through the production of agricultural feed crops; and

¾ Reduction of nitrate impacts from non-PG&E sources in groundwater near the Desert View Dairy.

We look forward to your review and assistance with putting the regulatory structure in place to implement the components of this final remedy in a timely manner. Please call me at (530) 520-2959 if you have any questions.

Sincerely,

Eric Johnson
Hinkley Remediation Project Manager

Enclosure

cc: Lisa Dernbach / RWQCB Lahontan Region, South Lake Tahoe
Mike Plaziak / RWQCB Lahontan Region, Victorville

FEASIBILITY STUDY
PACIFIC GAS AND ELECTRIC COMPANY
HINKLEY COMPRESSOR STATION
HINKLEY, CALIFORNIA

Prepared for

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30 August 2010

This report incorporates Site conditions observed and described by others as reported in records available to Haley & Aldrich as of the date of report preparation. Haley & Aldrich relied on such data collected by others in the development of interpretations about environmental conditions at the Site. The accuracy, precision, or representative nature of data, figures, and appendices originally generated by others was not independently verified by Haley & Aldrich and would be beyond the scope of this project.

HALEY & ALDRICH

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LIST OF ACRONYMS

AUs	Agricultural Units
bgs	Below Ground Surface
Basin Plan	Water Quality Control Plan for the Lahontan Region
BMPs	Best Management Practices
CAO	Cleanup and Abatement Order No. R6V-2008-02
Cr(III)	Trivalent Chromium
Cr(T)	Total Chromium
Cr(VI)	Hexavalent Chromium
DPT	Direct-Push Technology
DVD	Desert View Dairy
EVO	Emulsified Vegetable Oil
FS	Feasibility Study
FS/92-49	Feasibility Study and Resolution 92-49
General Permit	General Site-Wide Groundwater Remediation Project (General Permit), Board Order No. R6V-2008-0014
gpm	Gallons per Minute
IRZ	In-Situ Reactive Zone
LTU	Land Treatment Unit
LRWQCB	Lahontan Regional Water Quality Control Board
MBfR	Membrane Biofilm Reactors
MCL	State of California Maximum Contaminant Level
mg/kg	Milligrams per Kilogram
mg/L	Milligrams per Liter
MNA	Monitored Natural Attenuation
MUN	Municipal and Domestic Supply
MWA	Mojave Water Agency
NPV	Net Present Value
OEHHA	California Office of Environmental Health Hazard Assessment
PG&E	Pacific Gas and Electric Company
PHG	Public Health Goal
plume	The Chromium Plume

Resolution 68-16	State Water Resources Control Board Resolution 68-16
Resolution 88-63	State Water Resources Control Board Resolution 88-63
Resolution 92-49	State Water Resources Control Board Resolution 92-49
ROs	Remedial Objectives
SBA	Strong Based Anion
SCRIA	South Central Reinjection Area
Site	PG&E Compressor Station in Hinkley, California
SWRCB	State Water Resources Control Board
TDS	Total Dissolved Solids
TOC	Total Organic Carbon
μg/L	Micrograms per Liter
UTLs	Upper Tolerance Limits
WBA	Weak Based Anion
WDRs	Waste Discharge Requirements
WQOs	Water Quality Objectives

1. FEASIBILITY STUDY OVERVIEW

Pacific Gas and Electric Company (PG&E) prepared this feasibility study (FS) to select a final groundwater remedy for the chromium impacts related to historical operations at the PG&E Compressor Station in Hinkley, California (Site). In accordance with the Cleanup and Abatement Order (CAO) issued by the Lahontan Regional Water Quality Control Board (LRWQCB), this FS identifies and evaluates technologies capable of remediating hexavalent chromium (Cr(VI)) in groundwater to achieve the following two regulatory water quality objectives (WQOs):

- Site-specific background conditions as required under State Water Resources Control Board (SWRCB) Resolution 92-49 (Resolution 92-49); and
- The State of California Maximum Contaminant Level (MCL) of 50 micrograms per liter (μg/L), which provides the basis for the most restrictive beneficial use for groundwater (total chromium (Cr(T) and Cr(VI)).

Extensive site assessment and remediation efforts conducted at the Site have delineated the chromium impacts, characterized the complex hydrogeological setting, and determined the Site-specific background chromium conditions. Findings from this work underscore the significant challenges in selecting and implementing a groundwater remedy that not only meets these WQOs but also supports the most appropriate groundwater beneficial use. These challenges include significant historical agricultural impacts to groundwater that are unrelated to PG&E's activities, primarily total dissolved solids (TDS) and nitrate; non-PG&E agricultural pumping outside of the chromium plume (the plume) that influences plume migration; very low Site-specific background concentrations of chromium; and complex hydrogeology that makes assessment and treatment difficult on the large scale that is required.

PG&E has already implemented an extensive number of groundwater treatment measures and studies in an effort to determine the most effective methods to control and remediate the chromium plume, while addressing these difficult Site conditions. These efforts included containment pumping, in-situ treatment, agricultural application treatment, aboveground physical/biological treatment, subsurface treatment, as well as natural attenuation evaluations. Through all of this work, significant progress has been made toward containing the plume and reducing the size of the plume that exceeds the MCL. This work has further highlighted the challenges of achieving the very low background chromium levels at the scale that is required to address the entire chromium-impacted area. This extensive amount of treatment testing, experience, and learning provided a solid foundation upon which this FS and Resolution 92-49 (FS/92-49) analysis was performed.

The primary goal of this FS/92-49 analysis was to evaluate and propose a final groundwater remedy for attaining the two regulatory WQOs, or the lowest chromium concentrations that are technically and economically achievable in a reasonable time frame. As required by the CAO, PG&E evaluated the possibility of remediating to average background chromium values and concluded that there is no regulatory basis or precedent for using average background as a cleanup level and cleaning to average background would be technically and economically infeasible. Site maximum background chromium values are the most reasonable background criteria to be used for this evaluation. Because of the historical agricultural operations and their associated TDS and nitrate impacts to groundwater, the most productive current use of a large portion of groundwater at the Site is for agricultural livestock crop production. PG&E is committed to being a responsible and long-term partner in the Hinkley community. As such, the proposed final groundwater remedy will restore the aquifer beneficial use designation, facilitate the productive agricultural use of groundwater during remediation efforts, and attempt to overcome the challenges listed above to achieve background chromium concentrations.

The results of this FS/92-49 analysis, along with past Site remediation experience, indicate that the most reasonable plan to achieve these goals includes containment pumping, agricultural application of the extracted water, and in-situ treatment of the plume core (the area where Cr(VI) concentrations are greater than 50 μg/L). This plan has significant benefits - including the use of an already marginal resource (TDS/nitrate-impacted groundwater not related to PG&E's actions) for livestock crop production, removal of nitrate from groundwater, minimizing secondary environmental impacts (e.g., drawdown, TDS, secondary byproducts), increasing local agricultural production, and potentially reducing the import of potable water for agriculture. The following sections of this FS detail the Site background information and the identification, evaluation, and selection of the preferred final groundwater remedy.

2. BACKGROUND

This section provides background information on the regulatory chronology, framework, and historical land use of the Site used to develop the final remedy for this FS document. Figure 2-1 illustrates the location of the Site.

2.1 Regulatory Chronology of Remedial Activities

Investigation and cleanup activities conducted under the oversight of the LRWQCB at the Site began with PG&E's discovery of elevated Cr(VI) concentrations in wells north of the evaporation ponds at the Site in late November 1987, as part of an ongoing environmental assessment of PG&E facilities. The LRWQCB issued a CAO on 29 December 1987 that directed PG&E to undertake specified site investigation activities.

2.1.1 Land Treatment Operations at Hinkley

Following initial groundwater and soil investigations at the Site, PG&E submitted a Report of Waste Discharge on 6 June 1991 to treat Cr(VI) in groundwater by application of that water to agricultural fields, in a process whereby the Cr(VI) would be converted to trivalent chromium (Cr(III))and removed from the groundwater. On 12 September 1991 the LRWQCB adopted waste discharge requirements (WDRs) for the application of extracted groundwater to a 40-acre parcel termed the East Landfarm. Those WDRs were amended 12 August 1993 to allow application of extracted groundwater to an adjacent 0.91-acre parcel.

The LRWQCBdirected that additional site characterization and evaluation be conducted, and a full-scale groundwater extraction system be designed and implemented, through an amendment to the CAO issued 3 June 1994.

On 30 April 1997 PG&E submitted a revised Report of Waste Discharge to expand the extraction and land application to a second land treatment unit (LTU), utilizing the same treatment technology as the East Landfarm, located at the Highway 58 Ranch and termed the Ranch Landfarm. The LRWQCB adopted WDRs for the 95-acre Ranch Landfarm on 17 July 1997.

The LRWQCB directed that computer modeling of the cleanup process be conducted and also directed that annual reports regarding the corrective actions measures be submitted in a further amendment of the CAO issued 3 August 1998.

On 29 June 2001 the LRWQCB issued a new CAO which directed PG&E to take immediate action to abate the creation of a threatened nuisance by eliminating any airborne discharges of Cr(VI) originating from operation of the East and Ranch Landfarms which applied water to crops using spray nozzles. In response to this CAO, PG&E discontinued use of the East and Ranch Landfarms immediately.

Through documents submitted on 4 August2003, 13 January 2004, and 5 March 2004, PG&E submitted a Report of Waste Discharge to implement a plume containment and groundwater treatment facility at the Desert View Dairy (DVD), near the northernmost extent of the chromium groundwater plume. On 27 July 2004 the LRWQCB adopted WDRs for the 80-acre DVD LTU, which applies extracted groundwater to grass crops irrigated by subsurface drip lines, rather than through spray irrigation. Cr(VI) is removed from groundwater by conversion to insoluble Cr(III) that occurs within the root zone of the irrigated crops. Groundwater is extracted at an annual average rate not to exceed 345 gallons per minute (gpm) from wells located on the DVD property.

On 25 July 2007 PG&E submitted a Report of Waste Discharge to optimize hydraulic containment of the chromium plume (thereby positioning the LTU pumping to better respond to external hydraulic influences) by extending the location of extraction for the DVD LTU to include wells located off the DVD property. The LRWQCB adopted amended WDRs on 28 November 2007 that provide for extraction from up to six groundwater wells located off the DVD property, while retaining the existing limit of 345 gpm on an annual average basis.

In March 2010, PG&E proposed further optimization of the DVD LTU to provide additional hydraulic control for the northeastern portion of the leading edge of the chromium plume. On 14 July 2010 the LRWQCB adopted WDRs that provide for the addition of extracted water to the LTU from parcels located north and east of the DVD, together with a 50 percent increase in the allowable combined extraction rate (to a new annual average of up to 520 gpm).

2.1.2 In-Situ Treatment Operations

Through documents dated 4 August 2003 and 13 September 2003, PG&E submitted a Report of Waste Discharge to operate an in-situ pilot test at two test cell areas: one area located on the former compressor station property, and one area located at the former East Landfarm location. On 13 October 2004 the LRWQCB issued WDRs for the pilot test which involved the injection of two food-grade organic substrates (emulsified vegetable oil (EVO) and sodium lactate) into plume groundwater to create conditions in which Cr(VI) is removed from groundwater by its conversion to Cr(III).

Based on the success of the pilot test, PG&E submitted a Report of Waste Discharge, through documents submitted on 6 January 2006 and 1 March 2006, to conduct an in-situ pilot test across an area perpendicular to plume flow in the central area of the plume, near the intersection of Frontier and Fairview Roads. On 14 June 2006 the LRWQCB adopted Waste Discharge Requirements for the Central Area In-Situ Remediation Pilot Study Project located in an area approximately 1800 feet wide (cross-gradient) and 1000 feet long. Wells across the width of the project site were used to deliver a food-grade organic reductant (initially, sodium lactate solution) to groundwater, stimulating the growth of indigenous bacteria which, in turn, create chemically reducing conditions. Cr(VI) in groundwater was reduced to the insoluble Cr(III) under these conditions.

By documents submitted 2 June 2006 and 4 August 2006, PG&E filed a Report of Waste Discharge to construct a full-scale in-situ treatment system at, and immediately north of, the area within the compressor station where chromium-containing waste water was originally discharged to land. The LRWQCB approved this system, termed the In-Situ Source Area Remediation Project, on 9 November 2006. The project involved injection of food-grade organic reductant and downgradient extraction to induce flow of reductant amended groundwater over a project area approximately 2400 feet long and 1400 feet wide.

PG&E submitted a Report of Waste Discharge through documents submitted on 15 June 2007 and 28 June 2007 to modify the In-Situ Central Area Remediation Project. On 28 November 2007 the LRWQCB issued revised WDRs for the project, specifying ethanol as an additional permitted reductant, adding permitted tracer compounds, approving an expansion of the project area and the stepping-out of monitoring well locations, and specifying revised concentrations for monitoring of chromium.

2.1.3 Actions under a General Permit

PG&E submitted a Report of Waste Discharge, through documents submitted on 27 August 2007 and 19 September 2007, to implement various remediation projects both inside and outside the chromium plume. On 9 April 2008 the LRWQCB issued general WDRs for the General Site-Wide Groundwater Remediation Project (General Permit). The General Permit establishes a streamlined process for implementing certain plume containment and groundwater treatment measures, including (1) discharges to groundwater of specified biological or chemical reduction compounds, well rehabilitation compounds, tracers, process chemicals, and nutrients; (2) reinjection of treated or untreated extracted groundwater within the plume boundary; and (3) reinjection of untreated extracted groundwater that is not affected by Cr(VI) to areas outside of the plume to create a hydraulic barrier for plume control.

PG&E has received authorization to implement a number of measures under the provisions of the General Permit, including (1) the injection of treated groundwater extracted within the northwest portions of the plume at a central reinjection area in the southern portion of the plume and (2) injection of fresh water outside the western plume boundary to create a hydraulic barrier.

2.2 Regulatory Framework

The following regulatory framework was used to identify and evaluate remedial technologies and options to select the final groundwater remedy:

2.2.1 Cleanup and Abatement Order

A CAO was issued to PG&E on 6 August 2008 (LRWQCB 2008) and requires PG&E to clean up and abate the effects of waste discharges and threatened discharges containing Cr(VI) and Cr(T) to waters of the State. The key requirements of the CAO are:

- **Chromium Plume Containment** – PG&E is required to contain the chromium plume. The CAO defines containment as no further migration or expansion of the chromium plume to locations where Cr(VI) is below 4 μg/L and Cr(T) is below 50 μg/L. On a case by case basis, and under specific conditions, the CAO does allow for plume expansion for a specific area and in a defined period of time.

- **Interim Chromium Remediation** – PG&E is required to continue the full-scale in-situ corrective actions in the Central Area (i.e., the Central in-situ reactive zone [IRZ]) and the Source Area (i.e., Source Area IRZ).
- **Final Cleanup Actions** – PG&E is required to submit a FS report by 1 September 2010, to assess remediation strategies and propose a groundwater remediation alternative to achieve compliance with Resolution 92-49.

The CAO has been amended twice since it was issued in August 2008.

- Amendment R6V-2008-0002A1 establishes background levels for Cr(VI) and Cr(T) in groundwater for the purpose of the Final Cleanup Actions, including this FS. These background levels are based on the "Groundwater Background Chromium Study Report, Hinkley Compressor Station" (CH2MHILL 2007), and are as follows:
  - Maximum background Cr(VI) = 3.1 μg/L
  - Maximum background Cr(T) = 3.2 μg/L
  - Average background Cr(VI) = 1.2 μg/L
  - Average background Cr(T) = 1.5 μg/L

  The amended CAO requires that the FS include an evaluation of each remedial alternative's ability to achieve background water quality within the Remedial Area; it also requires that discrete samples within the Remedial Area do not exceed the maximum background levels. These requirements result in three key definitions:

  <u>Remedial Area</u> - The maximum background values for Cr(VI) and Cr(T) (3.1 μg/L and 3.2 μg/L, respectively) define the boundaries of the Remedial Area subject to remedy evaluation in this FS (Figure 2-2). The final definition of this boundary is ongoing; however, for the purpose of this FS, these boundaries were determined based on samples collected in February 2010, and as directed by LRWQCB staff during a meeting in South Lake Tahoe on 16 March 2010. Going forward in this FS, the "Remedial Area" refers to the area of groundwater shown on Figure 2-2, where the maximum background values are known to be exceeded. This area is also referred to as "the plume" in the remainder of the document. Appendix A contains a more detailed summary of the Background Chromium Study.

  <u>Background Water Quality</u> – As required by the CAO, PG&E evaluated the possibility of remediating groundwater to average background chromium concentrations (see Section 5.1). PG&E concluded that there is no regulatory basis and precedent for remediating to average background levels and achieving average background values would not be technically or economically feasible. Therefore, for the purpose of this FS, containment for the Remedial Area is evaluated using the maximum background chromium concentration as defined above for each alternative.

- Amendment R6V-2008-0002A2 allows for lateral migration of the 4 μg/L Cr(VI) plume east of the existing plume boundary, which may occur as a result of the reinjection of pumped groundwater (amended with carbon) into the South Central Reinjection Area (SCRIA). The amendment was issued consistent with the provisions provided for in the

CAO for plume containment, and requires the area of potential plume expansion to return to pre-SCRIA conditions within 10 years after completing the SCRIA project. The SCRIA project is being conducted in accordance with the Notice of Applicability issued to PG&E on 9 April 2009 pursuant to the General Waste Discharge Requirements for the General Site-wide Groundwater Remediation Project (General Permit), Board Order No. R6V-2008-0014.

2.2.2 Water Quality Control Plan for the Lahontan Region

The Water Quality Control Plan for the Lahontan Region (Basin Plan) details the LRWQCB policies to protect water quality in the region. Key functions of the Basin Plan relative to this FS are:

- The Basin Plan establishes beneficial uses for ground and surface waters; and
- The Basin Plan incorporates State-wide and Region-specific policies to protect the prescribed beneficial uses. State-wide policies incorporated into the Basin Plan include SWRCB Resolutions 68-16, 88-63, and 92-49. These three policies are discussed below.

The plume is located in the Middle Mojave River Valley Groundwater Basin. The beneficial uses for this basin's groundwater - as defined in the Basin Plan - are municipal and domestic supply (MUN), agriculture, industrial, freshwater replenishment, and aquaculture. Narrative and numerical water quality standards established for protection of these uses are applicable to this FS. For example, while the current MCL for Cr(T) of 50 μg/L must be considered, there is no current standard specifically established for Cr(VI) in groundwater for the prescribed beneficial uses. Under current water quality standards, cleanup of Cr(T) and Cr(VI) to levels below 50 μg/L will achieve beneficial use as defined by the Basin Plan.

2.2.3 SWRCB Resolution 68-16

SWRCB Resolution 68-16 (Resolution 68-16) is commonly referred to as the Anti-Degradation Policy or Policy for Maintaining High Quality Water. In summary, with respect to cleanup and abatement actions, the Water Boards have interpreted Resolution 68-16 to require dischargers to consider remediation of impacted groundwater to levels consistent with background conditions. Cleanup plans that propose remediation to levels above background conditions must be *"consistent with the maximum benefit to the people of the State, not unreasonably affect present and anticipated beneficial use of such water, and not result in water quality less than prescribed in the policies."* For the purpose of this FS, LRWQCB has interpreted Resolution 68-16 to require consideration of cleanup to the background levels specified in the amended CAO, and any proposed cleanup level that is higher than these levels must include the appropriate justification. Resolution 92-49, discussed below, references Resolution 68-16 as the basis for groundwater cleanup level evaluations.

2.2.4 SWRCB Resolution 88-63

SWRCB Resolution 88-63 (Resolution 88-63) is commonly referred to as the Sources of Drinking Water Policy and defines minimum standards that allow groundwater resources to be considered under this policy. This policy states that California surface and ground waters are considered to be suitable, or potentially suitable, for municipal or domestic water supply with the following exceptions:

- An average well yield of 200 gallons per day or less;
- A man-made or naturally occurring impact (other than the plume) that cannot reasonably be treated using best management practices (BMPs) or economically achievable treatment; and/or
- A naturally occurring salinity of 3,000 milligrams per liter (mg/L) or higher (measured as TDS).

For the purpose of this FS, certain portions of the aquifer have impacts from historical agricultural practices, unrelated to PG&E's activities, which resulted in TDS and nitrate levels exceeding standards appropriate for some beneficial uses. Figures 2-3 and 2-4 illustrate a summary of the nitrate and TDS groundwater data in the area of the Site.

2.2.5 SWRCB Resolution 92-49

SWRCB Resolution 92-49 (Resolution 92-49) is commonly referred to the Policy and Procedures for Investigation and Cleanup and Abatement of Discharges under Water Code Section 13304. Key elements of Resolution 92-49 with respect to this FS are:

- **Cleanup Levels** – PG&E must clean up and abate the effects of discharges in a manner that either attains background water quality or promotes the most reasonable water quality, if background water quality levels cannot be restored.
  - In approving any alternative cleanup levels less stringent than background, the cleanup levels must be consistent with Resolution 68-16; and
  - The LRWQCB must prescribe cleanup levels consistent with appropriate levels set by the SWRCB for analogous discharges that involve similar wastes, site characteristics, and water quality considerations.

  As detailed above, background water quality is defined in terms of both the maximum and average values as specified in the amended CAO. As to what is "reasonable," achieving average background values with no single point exceeding the maximum values would require that some residual chromium concentrations be considerably lower than the average values specified in the amended CAO; that is, single detections exceeding the average but less than the maximum values must be "offset" when calculating the statistical average by values lower than those average values. Accomplishing average background concentrations plume-wide would require remediation of groundwater in some areas to concentrations below average background. For the reasons cited in Section 2.2.1 above, maximum background is the remediation criterion that defines the Remedial Area, is the value to be used for this FS/92-49 analysis, and is herein referred to as "background." Incorporation of background values in the ROs for the FS/92-49 analysis is included in Section 5.

- **Cleanup Methods** – PG&E must consider the effectiveness, feasibility, and relative costs of applicable alternative methods for cleanup and abatement. Such comparison may rely on previous analysis of analogous sites, and include supporting rationale for the selected methods.
- **Containment Zone** - the LRWQCB must consider the designation of a containment zone when it is unreasonable to remediate to the level that achieves WQOs. The lowest established numerical WQO is 50 μg/L for Cr(T). The LRWQCB shall determine whether WQOs can be reasonably achieved within a reasonable period by considering what is technologically and economically feasible.
  - Technological feasibility is determined by assessing available technologies, including bench-scale or Site-specific field-scale pilot tests.
  - Economic feasibility objectively balances the incremental benefit of attaining further reductions in the concentrations of constituents of concern as compared with the incremental cost of achieving those reductions. The economic feasibility evaluation will include consideration of current, planned, or future land use and social and economic impacts to the surrounding community, including property owners other than PG&E.
  - The LRWQCB may make technological or economic infeasibility determinations after PG&E either implements a cleanup program that cannot reasonably attain cleanup objectives or demonstrates that it is unreasonable to clean up to WQOs. PG&E may determine that WQOs cannot be achieved on the basis of projection, modeling, or other analysis of Site-specific data without necessarily first constructing and operating remedial measures.

In summary, Resolution 92-49 requires that PG&E:

- Develop a cleanup plan that evaluates multiple remedies and weighs them against numerous factors such as:
  - ability to achieve background levels;
  - time frame to achieve; and
  - potentially significant impacts such as:
    - byproducts from in-situ remediation (i.e., dissolved manganese, iron, or arsenic);
    - excessive drawdown of the aquifer associated with remedial pumping;
    - an increase in salinity or other compounds associated with land application, or the potential movement of higher salinity groundwater; and
    - potential for the area of groundwater affected by Cr(T) to expand.
- PG&E must propose a cleanup plan that either targets cleanup of groundwater to background levels or provides the appropriate justification for a higher standard. PG&E must also consider what is reasonable when evaluating a cleanup goal, taking into account the technical and economic feasibility of attaining background conditions,

the projected time frame to achieve background conditions, and the maximum beneficial use of the resource being protected.

- If PG&E determines that the 50 μg/L WQO for Cr(T) cannot be achieved in a reasonable time frame, the FS may propose the establishment of a containment zone as part of the FS process or in future documents after a period of time following the initial implementation of a chosen remedy. A containment zone evaluation would also include an analysis of the impact if the MCL for Cr(T) and/or Cr(VI) is decreased to below 50 μg/L after implementing the final remedy. A containment zone is a regulatory tool to temporarily suspend a beneficial use, e.g., when a numerical WQO cannot be achieved in a reasonable time frame. In such a case, the LRWQCB would still maintain the long-term goal of achieving the WQO at some time in the future.

2.3 Historical Land Use

The following is a discussion of historical land use.

2.3.1 Agricultural Land Use

Based on a review of historical aerial photographs, most of the land that overlies the current plume was used for agriculture up to as recently as the mid-1980s. The agricultural types have varied, but consisted primarily of dairy farming and fodder crops such as alfalfa and barley. Some parcels appear to have included orchard crops, but these crops are no longer present in the area. The number of parcels under active crop cultivation has declined over the last two decades. The current land use shown on Figure 2-2, illustrates that some of the land overlying the plume is no longer used agriculturally, and can be classified as undeveloped. Agriculture continues to play a major role in land use management for the Hinkley area and is an important economic element for its residents.

2.3.2 Mixed Residential, Commercial, and Industrial Land Use

This section discusses historical residential, commercial, and industrial land use (Figure 2).

- Residential land use overlying and in the immediate vicinity of the plume has been historically limited to single family houses on large agricultural acreage lots, and single family homes on smaller lots (primarily west and northwest of the plume). There is no historical or existing high density residential land use overlying or near the plume.
- Commercial land use has been historically limited to the small mercantile/gas station and Hinkley School, both located northwest of the plume.
- Industrial land use has been limited to the PG&E compressor station.

The regulatory framework presented above provides the criteria for developing the remedial objectives (ROs) and performing the remedial alternative evaluations. The historical Site conditions presented above establish the baseline groundwater conditions that resulted from historical land use other than the compressor station operation; these conditions must be taken into account in the evaluation and selection of a final groundwater remedy.

3. SITE BACKGROUND AND CURRENT CONDITIONS

3.1 Summary of Work Completed

PG&E has conducted extensive investigations to define the limits of chromium in groundwater, and implemented remediation to remove chromium from groundwater. The following summarizes these efforts:

- Groundwater Investigations – PG&E has conducted extensive investigations to define the lateral and vertical limits of chromium in groundwater. Investigation has been completed primarily through the installation and sampling of monitoring wells. The majority of monitoring wells have been installed as "nests," with multiple wells at each location to allow for discrete sampling of groundwater at various depths within the Upper Aquifer. Approximately 160 groundwater monitoring wells have been installed in the Upper Aquifer and are sampled periodically, not including in-situ remedial monitoring wells which are discussed below. Results from these wells are reported quarterly (CH2MHill 2010a; CH2MHill 2010b). Additionally, PG&E has installed and continues to sample 9 monitoring wells in the Lower Aquifer to demonstrate that chromium is not migrating vertically through the blue clay aquitard.
- Groundwater Remediation – As discussed in detail in Section 4, groundwater remediation is currently in progress through pumping and land application for crop production, and through in-situ treatment methods. PG&E has pumped groundwater and applied the water for crop production under permit from the LRWQCB. On an annual average, approximately one-half million gallons of groundwater per day are currently pumped and treated using these methods (approximately 180 million gallons per year). PG&E also operates three in-situ remedial systems; groundwater in these areas is dosed with reducing agents, primarily ethanol, to reduce chromium in-situ from hexavalent to the trivalent state. The three remedial systems consist of 34 remedial wells used for injection/recirculation of reductant. Approximately 180 groundwater monitoring wells have been installed and sampled by PG&E for the primary purpose of evaluating the effects of these in-situ remedial systems on groundwater quality. Results of these systems are reported semi-annually (CH2MHill 2010a).

3.2 Groundwater Overview

Groundwater in the Hinkley area has long been a resource for beneficial use, primarily for agriculture. As discussed in Section 2, at one time much of the Hinkley area was under active cultivation. Long-term historical pumping resulted in declining groundwater levels and use of this water for agricultural purposes such as fodder crop production and dairy farming resulted in water quality impacts other than chromium (i.e., TDS and nitrate).

In the 1990s, the Mojave Water Agency (MWA) was legally appointed as Water Master for surface and groundwater in the Mojave River basins, including the Hinkley area. After several years of studies and discussions among the MWA and local water users, a Stipulated Agreement was reached that established water rights based on historical usage and required participating water users to either decrease pumping compared to prior baseline levels, or attain additional water rights and/or pay a fee to the MWA for the additional water use. The MWA also manages the recharge of the California State Water Project water into the watershed, including a spreading basin located along the Mojave River upstream of the Site. As a result of these management activities, groundwater levels in the Hinkley area have generally stabilized or risen in recent years.

3.2.1 Groundwater Occurrence

Groundwater occurs in the Hinkley area and at the Site as an unconfined Upper Aquifer, and a confined Lower Aquifer. The following sections discuss these two aquifers.

3.2.1.1 Upper Aquifer

The lithology of the shallow and deep layers is highly variable due to the layers being deposited in a fluvial environment. Grain size can vary from course to fine over short distances laterally and vertically. These geological conditions complicate the transport and distribution of chromium in groundwater.

The Upper Aquifer groundwater flows in a northerly direction in unconsolidated coarse-grained (primarily medium to coarse-grained sand) and fine-grained (primarily silt) sediments. Figure 3-1 presents the groundwater contours for the Upper Aquifer. The coarse-grained sediments contain varying degrees of fine sand, silt, and clay, with minor amounts of gravel in some locations. The fine-grained sediments contain varying amounts of fine sand and clay, which results in heterogeneous and locally complex hydrogeologic conditions. The origin of the sediments is generally fluvial in nature (DWR 1983); some geologic facies exhibit lateral connectivity, while others are highly discontinuous over short distances.

Depth to groundwater in the Upper Aquifer at the Site currently ranges from about 75 to 90 feet below ground surface (bgs) with some degree of variability directly adjacent to remedial activities such as pumping or injection. Groundwater velocity in the Upper Aquifer is variable, depending upon the type(s) of sediments encountered and the local gradients. In general, modeling, tracer, and remedial system performance confirm that groundwater velocities range from 1 to 4 feet per day.

The groundwater recharge for the area primarily originates from the Mojave River, located immediately south and southeast. The thickness of the Upper Aquifer is variable, a function of depth to the underlying basal units (blue clay or bedrock). The aquifer thickness generally ranges from about 20 feet (where blue clay is absent and bedrock is shallow) to 90 feet thick (where the blue clay is present and deep, see Figure 3-2).

The base of the Upper Aquifer is defined across much of the Site by a blue clay aquitard; the origin of these sediments is likely a shallow playa lake (DWR 1983). Where present, the depth to the aquitard is variable across the Site, generally ranging from about 140 feet bgs at the shallowest locations to the west, to 170 feet bgs at the deepest locations to the east. The blue clay unit thins to the west and is absent (i.e., pinches out) in the far western areas of the Site.

Where the blue clay is absent, granitic bedrock provides the base of the Upper Aquifer. The bedrock unit outcrops in the area of the DVD. Where the blue clay is absent beneath the plume, depth to bedrock ranges from about 100 to 130 feet bgs.

For the purpose of recent monitoring well construction by PG&E, the Upper Aquifer has been separated into a shallow and deep layer; however, there is no defining aquitard that separates these two layers. The shallow layer is typically described as being from the water table surface to about 110 feet bgs; the deep layer is typically described as 110 feet bgs to the top of the underlying blue clay aquitard (or bedrock). Well screens are typically 20 feet in length and target the most transmissive (i.e., most course-grained) sediments present in the shallow and deep layers. The relatively short screens of groundwater monitoring wells, rather than the long screens of irrigation and domestic supply wells, provide comprehensive data regarding the lateral and vertical distribution of the very low Cr(VI) and Cr(T) concentrations.

3.2.1.2 Lower Aquifer

The Lower Aquifer consists of sediments between the base of the blue clay and the top of the consolidated bedrock. In borings where the Lower Aquifer was encountered by PG&E, the sediments appear to be composed of weathered bedrock and colluvium (i.e., eroded and re-deposited bedrock detritus). The thickness of the weathered rock is variable, generally ranging from a few feet to upwards of 20 feet.

3.3 Groundwater Quality

The following summarizes groundwater impacts in the Site area.

3.3.1 Background Chromium Study for the Site

Background levels for Cr(VI) and Cr(T) were proposed to the LRWQCB by PG&E in the "Groundwater Background Chromium Study Report, Hinkley Compressor Station," (CH2MHILL 2007). The proposed background levels were developed based on a comprehensive Site-specific study that included groundwater samples collected during four rounds of sampling in 2006, and from up to 48 wells located outside the plume. All sampled wells were long-screen wells previously used for extracting groundwater for beneficial use. The long-screened wells were used to collect groundwater samples which had the effect of averaging the detected Cr(VI) and Cr(T) concentrations vertically throughout the formation. The Site wells used for groundwater monitoring and remediation have much shorter screens that detect variations in concentrations due to geologic and hydraulic variations in the formation with depth. Therefore, concentrations detected in the long-screened wells may not be comparable to concentrations detected in the shorter screened Site wells. The report documents statistical data evaluation, including:

- The 95th percent upper tolerance limits (UTLs) for Cr(VI) and Cr(T) were 3.1 μg/L and 3.2 μg/L, respectively; and
- The arithmetic mean concentrations for Cr(VI) and Cr(T) were 1.2 μg/L and 1.5 μg/L, respectively.

As discussed in Section 2, the CAO was subsequently amended to establish the following Site-wide background values for Cr(VI) and Cr(T):

- Maximum background Cr(VI) = 3.1 μg/L;
- Maximum background Cr(T) = 3.2 μg/L;
- Average background Cr(VI) = 1.2 μg/L; and
- Average background Cr(T) = 1.5 μg/L.

A more detailed discussion of the background study and an electronic copy of the above-referenced report are included in Appendix A.

3.3.2 Nature and Extent of Chromium Groundwater Impacts

As required in the amended CAO and specified in Section 2, the maximum background values are used in this report to define the lateral boundaries of chromium in groundwater subject to the FS evaluations (Remedial Area; Figure 3-3). The Remedial Area for the purposes of this FS/92-49 analysis was developed based on samples collected in February 2010, as directed by LRWQCB staff during a meeting in South Lake Tahoe on 16 March 2010. This data set was used because it provided a current, comprehensive Site-wide representation of chromium concentrations to complete the analysis of remedial alternatives. In general, the Remedial Area extends from the Compressor Station in the south to the area immediately north of the DVD, a distance of about 2.75 miles. The width of the Remedial Area is variable and generally ranges from about 0.75 miles to the south to 1.25 miles at the widest extent near Highway 58. Chromium impacts are primarily present in the Upper Aquifer. Recent detections of chromium above background levels in well MW-23C (south of the Santa Fe Railroad) indicate that some impacts have also occurred in the Lower Aquifer; assessment of this area is currently ongoing.

Since February 2010, additional data has been collected from existing and new monitoring wells. Figure 3-4 provides the updated chromium data at the Site. Recent data from wells that existed in February 2010 has remained mostly unchanged; the overall configuration of the Remedial Area remains unaffected. However, chromium data from new monitoring wells to the north and northeast of the Remedial Area indicate concentrations above background levels. PG&E is currently evaluating these data. While it is possible the results indicate the Remedial Area may be larger than currently depicted, it is also possible these relatively low levels of chromium are indicative of higher background levels than have been previously documented. PG&E and the LRWQCB will be working collaboratively to evaluate the appropriate representation and use of these data. Regardless, these data do not suggest a deviation from the analysis presented in this document or the selection of the final remedy.

3.3.3 Nature and Extent of Agricultural Groundwater Impacts

Historical agricultural use, unrelated to PG&E's activities, has resulted in impacts to groundwater quality typical of such activity. The primary impacts to groundwater have been from TDS and nitrate. Figure 3-5 illustrates nitrate and TDS groundwater quality in the area of groundwater affected by chromium. The following summarizes the key conclusions of these data:

- Groundwater in the southern portions of the plume (i.e., closest to the Mojave River) is generally of good quality. South of Community Boulevard, TDS levels are typically less than the secondary MCL standard of 1,000 mg/L, and in some cases below 500 mg/L (note: there is no primary MCL for TDS; the secondary standard of 1,000 mg/L is based on taste and odor). In most cases, nitrate as nitrogen levels are below the primary MCL of 10 mg/L and in several cases are non-detectable.
- Moving north (i.e., downgradient), TDS and nitrate levels increase. North of Highway 58, TDS and nitrate levels are typically higher than the above-referenced MCLs. Between Highway 58 to the south and the Santa Fe railroad line to the north, nitrate levels typically range from 10 to 20 mg/L; TDS levels typically range from 1,000 to 1,500 mg/L. Groundwater of this quality is appropriate for irrigation of fodder crops grown in the Hinkley area, such as alfalfa and barley. Although the groundwater does not meet MCLs, it is suitable for agriculture.
- North of the Santa Fe railroad tracks, groundwater quality further declines with regard to TDS and nitrate. Between the Santa Fe railroad tracks to the south and Thompson Road to the north, TDS levels are typically above 1,500 mg/L; north of Alcudia Road, TDS levels are commonly greater than 3,000 mg/L. Nitrate exhibits similar conditions, with levels commonly exceeding 40 mg/L in the general area of Alcudia Road and Thompson Road. Groundwater in this area is acceptable for most kinds of agriculture. TDS levels in some locations are elevated to levels that may result in challenges for some types of crops.
- The Lower Aquifer does not appear to be affected by historical agricultural use, and continues to provide a source of water suitable for domestic and agricultural use.

In summary, approximately 50 percent of the groundwater area affected by chromium (above background) meets MCLs for chromium, but does not meet MCLs for TDS and/or nitrate. For the most part, the current Upper Aquifer conditions support agriculture as the most reasonable long-term beneficial use. The water quality of the Lower Aquifer is higher, and the Lower Aquifer is presently the most suitable drinking water supply.

Much of the area that meets MCLs for chromium (i.e., northern diffuse plume with chromium levels less than 50μg/L) does not support the drinking water beneficial use for TDS and/or nitrate. These baseline groundwater quality conditions need to be taken into account by PG&E in remedial planning, technology evaluations, and final remedy design and implementation.

3.4 Conceptual Site Model

Groundwater generally flows from south to north in the Upper Aquifer, with depth to groundwater typically ranging from 75 to 90 feet bgs. The Upper Aquifer geology is a complex heterogeneous mixture of fine-grained (silt and clay) and course-grained (fine to coarse sand) sediments. The underlying blue clay aquitard provides an effective hydraulic barrier between the Upper and Lower Aquifers, which has prevented the downward migration of chromium. The Upper Aquifer ranges from about 20 to 80 feet in saturated thickness, depending upon depth to the underlying blue clay or bedrock (where blue clay is absent).

The Remedial Area is generally separated into two categories: a higher concentration area (generally south of Highway 58) where chromium concentrations exceed the 50 μg/L chromium MCL, and a northern diffuse area where chromium concentrations are less than the 50 μg/L MCL. The majority of groundwater affected by chromium exceeding the current 50 μg/L MCL in the higher concentration area is located south of Highway 58.

Groundwater quality at the Site is affected by TDS and nitrate associated with historical agricultural activities. In general, groundwater quality in the southern higher concentration area is suitable for drinking water and agriculture with regard to TDS and nitrate. In contrast, groundwater in much of the northern diffuse plume area does not meet drinking water standards, but may be suitable for agriculture.

Current groundwater production in the vicinity of the plume is generally limited to remedial pumping by PG&E, agricultural pumping for farming, and individual private wells associated with rural residential land use. Groundwater extraction by others, primarily for agriculture, has the greatest potential to influence groundwater flow and chromium movement.

There are several unique challenges to defining the area of the plume, providing plume boundary control, and conducting long-term remedial activities. These challenges include:

- Very low background concentrations for Cr(VI) and Cr(T);
- Large lateral distribution of the relatively low chromium concentrations in the northern diffuse plume;
- Complex, heterogeneous geology;
- Groundwater quality affected by TDS and nitrates associated with historical agricultural activities, unrelated to PG&E activities; and
- Variable groundwater hydraulic gradients caused by non-PG&E agricultural pumping.

These current Site conditions, combined with the regulatory framework and the remedial work performed to date (discussed in the following section) were taken into account when developing the ROs and evaluating final remedial alternatives.

4. ONGOING AND COMPLETED SITE REMEDIATION ACTIVITIES

PG&E has implemented several phases of remedial action, and completed extensive field pilot testing of several remedial technologies, to address the plume beneath the Site since remedy evaluation and implementation began in 1987. PG&E has also compiled and synthesized performance data from the implementation of each of these technologies, resulting in a robust performance database and Site conceptual model. This knowledge was used to identify and evaluate the remedial technologies included in this FS.

The components of the existing remediation system include:

- Hydraulic containment through groundwater extraction and, more recently, injection of groundwater sourced from outside of the plume;
- DVD LTU to treat extracted groundwater for Cr(VI); and
- IRZ systems to treat extracted groundwater and create a reducing zone to treat Cr(VI)-impacted groundwater in-situ.

The components of the existing remediation system are shown on Figure 4-1. Through these historical and current remediation efforts, including several pilot studies performed for the FS, PG&E developed a solid understanding of the feasibility of applying various technologies to address the plume in both the plume core, where Cr(VI) concentrations remain above 50 µg/L (generally south of Highway 58), and in the downgradient diffuse portions of the plume (generally north of Highway 58), where Cr(VI) concentrations are between 50 µg/L and background. Performance data collected over the past several years has facilitated a critical evaluation of the potential limitations associated with each remedial technology in achieving background water quality within a reasonable and somewhat predictable time frame. PG&E has also defined tradeoffs associated with application of the remedial technologies being considered; this FS reflects consideration and weighing of those tradeoffs.

This section provides a summary of the technologies that have been applied and pilot tested at the Site, and the key concepts learned through their application. Remedial technologies are presented in the following categories:

- Plume containment approaches and technologies are described in Section 4.1;
- Land application for treatment of extracted groundwater is described in Section 4.2;
- In-situ treatment technologies are described in Section 4.3; and
- Additional technologies are described in Section 4.4.

4.1 Plume Containment

One of the requirements of the CAO is plume containment. PG&E has used two technology approaches to achieve this objective: 1) the strategic extraction of groundwater to induce drawdown and direct flow of the plume toward extraction points and 2) groundwater injection (using groundwater sourced from outside of the plume) to create a hydraulic barrier that prevents the flow of the plume toward potential sensitive receptors. Each approach is discussed below.

4.1.1 Hydraulic Containment through Groundwater Extraction

Former East and Ranch Land Treatment Unit Extraction and Treatment Systems

PG&E began a groundwater extraction remedy in 1992. This initial system included extraction from 32 wells completed in the shallow aquifer. Groundwater from 24 of these wells was routed to the East LTU, a 29-acre plot with a single central pivot irrigation system used to irrigate alfalfa. Groundwater from the remaining 8 extraction wells was routed to the Ranch LTU, a 52-acre facility with two central-pivot irrigation systems also used to irrigate alfalfa. The locations of the former East and Ranch LTUs are shown on Figure 4-1.

Groundwater extracted from the plume and applied to the East and Ranch LTUs was treated by reducing the Cr(VI) to Cr(III) as the water percolated through the biologically active plant root zone. The land application technology, and PG&E's experience with this technology, are presented in Section 4.2.

The performance of the East and Ranch LTU extraction systems was monitored in compliance with requirements set forth in LRWQCB Order 6-97-81 and Monitoring and Reporting Program 97-81. This program included monitoring of extracted groundwater, vadose zone soil moisture, and soil and plant tissue analysis. Results of these monitoring activities were reported in semi-annual reports to the LRWQCB. PG&E discontinued the groundwater extraction systems at the East and Ranch LTUs in June 2001, in response to requirements from the LRWQCB. The East and Ranch LTU systems removed approximately 1,500 lbs of Cr(VI) from groundwater.

Plume Boundary Control through Extraction-Desert View Dairy and SCRIA

The current groundwater extraction system is composed of a network of nine groundwater extraction wells (EX-1 through EX-4, EX-15, EX-16, EX-21, and EX-22; Figure 4-1), pumping at a combined extraction rate of approximately 580 gpm. The primary objective for operating this system is to minimize the potential for further downgradient (north/northeast) plume migration.

Groundwater flow modeling was used to simulate hydraulic capture associated with groundwater extraction and to help determine the locations for these wells. Groundwater extracted from wells EX-1 through EX-4 is routed to the DVD LTU (Section 4.2); groundwater extracted from new extraction wells EX-23 and EX-24 will also be routed to the DVD LTU. Groundwater extracted from wells EX-15, EX-16, and EX-20 through EX-22 is routed to the SCRIA (Section 4.3).

The performance of these extraction wells in achieving hydraulic plume containment is assessed through measuring groundwater elevations and plotting the resulting potentiometric surface. These data show that groundwater extraction from this well network is largely effective in achieving hydraulic capture of the northern portion of the Remedial Area plume, thus containing it. However, because of agricultural pumping influences on the plume, additional extraction may be needed to enhance plume control.

Hydraulic plume containment through groundwater extraction is a proven successful technology at the Site. However, due to the large size and asymmetric shape of the plume, achieving hydraulic capture of the leading portion of the plume requires the extraction of large volumes of groundwater and applies stress to the groundwater system that can affect surrounding groundwater supplies.

4.1.2 Plume Boundary Control through Groundwater Injection

In addition to the groundwater extraction systems described above, PG&E is using groundwater injection as another means to contain the plume and prevent it from migrating toward potentially sensitive receptors. The northwest interim remediation measure takes unimpacted groundwater (i.e., groundwater extracted upgradient of the plume) and injects it into four injection wells located west of the Cr(VI) plume (Figure 4-1). This injection creates a hydraulic barrier in the groundwater, preventing migration of the plume in that direction.

The northwest injection system began operation in March 2010. Groundwater is extracted from a supply well (PGE-14) upgradient of the plume, conveyed north through an underground conveyance pipeline, and injected into four injection wells (IN-01, IN-02, IN-03, and IN-04). Preliminary monitoring data collected from observation wells surrounding the injection well field indicate that the injection system is operating as designed, and is expected to be effective at providing a hydraulic barrier between the plume and potential receptors to the west. Injection flow rates are optimized as further monitoring data become available. Water is currently filtered through an ion exchange system to remove naturally-occurring arsenic present at concentrations that exceed its MCL for drinking water.

4.2 Agricultural Water Treatment

As described above, PG&E has historically used the agricultural land application technology extensively at the Site to treat extracted plume groundwater, while providing the additional beneficial use of supplying irrigation water to the local farming economy. This agricultural land application was and is currently being conducted within conventional subsurface drip-irrigated farming plots.

This section provides an overview of the land application technology, PG&E's experience with this technology, and the implications for its expanded use.

4.2.1 Description

Extracted plume groundwater is used to irrigate fodder crops for cows. The groundwater is treated as it passes through the soil and root zone, via the following mechanisms:

- Reduction of Cr(VI) to Cr(III) through interaction with electron donors in soil and organic matter;
- Uptake and reduction by plant roots;
- Adsorption onto colloids and organic matter in the root zone, and subsequent microbially-induced reduction to Cr(III); and
- Complexation with organic functional groups involved in the reduction.

As described below, Site performance monitoring demonstrates that these mechanisms have consistently achieved reduction of the Cr(VI) concentrations in groundwater applied to the LTU. Treated water passing below the root zone can then recharge and replenish the underlying groundwater resource. Performance is monitored using a series of 5- and 20-foot deep lysimeters.

4.2.2 Land Application Technology at the Desert View Dairy

The DVD LTU is approximately 72 acres of agricultural fields used to cultivate fodder crops (primarily Bermuda grass and alfalfa) which are then used as animal feed for the adjacent DVD operation. The 72-acre farm is divided into eight irrigation fields (W1, S1 through S6, and SE1) shown on Figure 4-2. Field irrigation is supplied by groundwater extracted as part of the hydraulic containment system described in Section 4.1, and applied using a sub-surface drip irrigation system.

DVD Monitoring Program

The DVD LTU has been extensively studied and monitored, including evaluation of applied irrigation water, pore water, soil, plant tissue, and groundwater monitoring. Monitoring components for the DVD LTU are shown on Figure 4-2. In compliance with the requirements set forth in the waste discharge requirements (WDRs), PG&E installed and is implementing a monitoring and reporting program that includes:

- Collection and analysis of pore water for Cr(T) and Cr(VI) from sixteen 5-foot pore water samplers (LW-01 through LW-16) on a quarterly basis;
- Collection and analysis of pore water for TDS and nitrate from sixteen 20-foot pore water samplers (LS-1 through LS-16) on a quarterly basis;
- Collection and analysis of plant tissue samples for Cr(VI) and Cr(T) on a semi-annual basis;
- Collection and analysis of groundwater samples for Cr(T), Cr(VI), and TDS from 10 monitoring wells on a quarterly basis;
- Collection and analysis of 8 soil samples for Cr(T) and Cr(VI) on a quarterly basis; and
- Daily inspection and reporting of the LTU.

The WDR specifies the maximum volume of water applied to the LTU, until recently set at an annual average of 345 gpm. The LRWQCB recently revised the permit to increase the application rate to 520 gpm (annual average) to facilitate increased groundwater extraction for enhanced plume boundary control in the northern portion of the Site. This request was based in part on the results of a pilot study conducted on the LTU which demonstrated that a 50 percent increase in the irrigation rate would not significantly affect performance, and would not result in exceedances of the WDR limitations (CH2MHILL 2010c [Appendix C]).

Performance of the DVD LTU

Five years of performance monitoring has demonstrated the DVD LTU to be highly successful at treating Cr(VI) in extracted groundwater, with Cr(VI) and Cr(T) concentrations in soil and pore water remaining well below the limits set forth in the WDR. These data confirm the results from the Ranch and East LTU operations, and demonstrate the effectiveness of this technology.

A summary of findings from performance monitoring of the DVD LTU includes:

- Cr(VI) and Cr(T) concentrations have remained well below the permit-specified limits; the 95 percent UTL of the median Cr(VI) concentrations detected in the 5-foot lysimeters over the past 11 quarters has ranged from 0.9 μg/L to 7.7 μg/L, well below the WDR criterion of 21 μg/L.
- Similarly, the 95 percent UTL of the median Cr(T) concentrations detected in the 5-foot lysimeters have ranged from 1.6 to 7.7 μg/L over the past 11 quarters, well below the permit criterion of 50 μg/L.
- Cr(T) and Cr(VI) concentrations in soil have remained well below permit limitations; results of the most recent soil sampling event (February 2010) show that the Cr(T) concentrations (average of 5.6 milligrams per kilogram [mg/kg]) are lower than the pre-DVD condition (average of 7.6 mg/kg). These data indicate that the DVD operation has not resulted in accumulation of chromium in soils.
- Cr(VI) and Cr(T) concentrations in groundwater beneath the DVD have generally decreased since the startup of the DVD LTU and are, therefore, not negatively impacted with Cr(VI) or Cr(T) by the LTU operation.
- Cr(T) and Cr(VI) concentrations in plant tissue samples have been consistently below the WDR permit requirements.

Similar to the performance data collected from the East LTU, comparison of the Cr(VI) concentrations in the applied irrigation water with the Cr(VI) concentrations in the pore water collected from 5 feet bgs indicates Cr(VI) removal rates generally greater than 95 percent across the majority of the DVD LTU. Data from a few of the irrigation fields (e.g., W1, S1, and SE1) exhibit slightly lower removal efficiencies. Soil data for these fields indicate the presence of a more sandy soil type, which exhibits a slightly lower treatment capacity for chromium.

These and other performance data are consistent with findings from operating the Ranch and East LTUs, and confirm that agricultural land application is a consistently effective technology for treatment of the groundwater that is extracted from the plume.

TDS and Nitrate in Groundwater in the DVD LTU Area

In addition to the Cr(VI) treatment discussed above, the LTU operation also results in the beneficial removal of nitrate present in Site groundwater. The historical operation of the DVD area as a dairy has resulted in the presence of elevated concentrations of TDS and nitrate in groundwater beneath and north of the DVD. Such increases in TDS and nitrate in groundwater underlying dairy operations are common throughout much of arid California.

Elevated TDS and nitrate concentrations from non-PG&E dairy operations adjacent to the LTU have impacted local domestic water supply wells, and led to the issuance of a CAO from the LRWQCB to the current and former operators of the DVD. However, as described below, PG&E's LTU and SCRIA operations (Section 4.3.3) resulted in a significant treatment (removal) of nitrate from groundwater in the vicinity of the DVD.

Nitrate Removal

Nitrate is an important crop nutrient and the application of nitrate-rich groundwater on the DVD results in removal of that nitrate (treatment), primarily through plant uptake. PG&E has been monitoring nitrate concentrations in groundwater applied to the DVD LTU and in pore water beneath the LTU. PG&E also conducted baseline sampling of soil at the DVD prior to startup of the DVD LTU operation.

Leaching tests of soil collected from beneath the DVD LTU prior to startup indicated the presence of elevated nitrate concentrations. The average leachate concentration from soil samples collected beneath the DVD LTU was 13.8 mg/L. These soil leachate tests were later confirmed with the results of lysimeter sampling, which revealed nitrate in pore water at concentrations of over 100 mg/L in several of the sixteen 20-foot lysimeters that were installed at the DVD prior to startup (March 2004). The presence of elevated nitrate concentrations in soils beneath the DVD is consistent with locally elevated nitrate in surrounding groundwater. Prior to/at startup of the DVD, the nitrate concentrations in groundwater in the vicinity of the DVD ranged from 7 to 18.5 mg/L, with an average of 11.3 mg/L.

Subsequent data collected from these same lysimeters show that the nitrate concentrations in pore water have generally decreased to below detection limits. With one exception (1.1 mg/L in lysimeter LS#3) nitrate has not been detected in the 20-foot lysimeters since 2008.

Nitrate is present in groundwater applied to the LTU at concentrations ranging over the years from just over 9 mg/L to 15.1 mg/L. Data from the 20-foot lysimeters described above revealed that this nitrate is being effectively treated by the LTU process; the resulting pore water that percolates through the soil beneath the DVD is generally below detection limits for nitrate.

Decreased nitrate concentrations were shown for many of the lysimeters by 2006, indicating that treated groundwater from the DVD had reached the 20-foot depth in approximately 2 years. The agricultural land application at the DVD LTU has successfully removed over 40 tons of nitrate from the applied groundwater as of December 2009. It is expected that the recharge of nitrate-free treated water from the DVD LTU will continue to have a beneficial impact on the underlying groundwater quality into the future.

Impact of LTU Operations on TDS

Similar to nitrate, elevated TDS concentrations were present in soil and groundwater prior to startup of the DVD LTU. For example, TDS were detected in the leachate from soil samples collected from the LTU at an average concentration of 4,392 mg/L. This elevated TDS concentration was confirmed in pre-startup lysimeter data, which indicated TDS concentrations at the 20-foot depth of 3,257 mg/L (average of first samples collected from 20-foot lysimeters).

As with any farming practice involving irrigation in an arid climate, the DVD LTU operation is expected to result in a net increase in TDS in groundwater. As groundwater is applied to the LTU for fodder crop production, the TDS in that groundwater can be concentrated in the root zone through evaporation and evapotranspiration. Water quality data collected from the 20-foot lysimeters beneath the DVD LTU indicate that operation of the LTU resulted in an increase in TDS; the average TDS concentration detected in all 20-foot lysimeters increased from 3,257 (2005 data) to 4,400 mg/L.

It is expected that TDS impacts observed at the DVD LTU will decrease in the future as higher water volumes are applied. The application of increased water volumes is expected to prevent TDS buildup in the root zone, by the movement of applied water not needed for plant uptake.

It is important to note that the potential increases in TDS that can result from irrigated agricultural fields in the DVD area are not expected to affect the primary beneficial use of groundwater in the area, which is agricultural supply. Past agricultural practices in the DVD area have resulted in TDS concentrations in excess of applicable water quality standards (1000 mg/L is the secondary MCL). Given this historical condition, beneficial use of groundwater in the area is limited to the irrigation of more salt-tolerant crops; the DVD LTU operation is consistent with that use.

4.2.3 Alternative Method of Irrigation Water Application

As described in Section 4.1, PG&E discontinued the groundwater extraction systems at the East and Ranch LTUs in June 2001, in response to requirements from the LRWQCB related to potential air quality concerns. The current subsurface drip system at the DVD was implemented in part to address those potential concerns.

The subsurface drip system has successfully distributed irrigation water to the fodder crops, and minimized the potential for contact of plume groundwater with the surrounding environment. However, all subsurface drip systems are complex, labor intensive, expensive to maintain, and are highly vulnerable to leaks caused by gophers and connection failure, as well as clogging caused by salt encrustation and root intrusion.

To address these operational challenges, PG&E completed a drag-drip irrigation demonstration in early December 2005 at the Ranch LTU, using a center-pivot irrigation machine. The first span of drag-drip lines extended 180 feet from the center pivot, with risers spaced at 5-foot intervals along the top of the span. The risers were tied to drop tubes spaced 30 inches apart. Each drop tube was equipped with a 10-pound-per-square-inch pressure regulator. Flexible drip tubes were attached to the drop tubes.

During the demonstration, the drag-drip irrigation system successfully applied adequate water to the ground surface without causing surface misting or ponding. The high rate of center pivot movement applied water to the ground surface in "pulses," allowing the water to fully infiltrate the soil before the next pass of the machine. The water application rate for all of the tested emitters was lower than the soil infiltration rate which resulted in no surface ponding or surface flow.

Demonstration results show that this irrigation method represents a practical, cost effective method of applying plume groundwater to agricultural land, while minimizing the potential for Cr(VI) contact with the surrounding environment, as well as having fewer maintenance issues than subsurface drip irrigation. Based on these conclusions, and as part of ongoing system adjustments and improvements, PG&E is converting the two Gorman agricultural pivots (located at the northern edge of the plume) to drag-drip configuration in 2010.

4.2.4 Summary of Experience with LTUs

In summary, PG&E has extensive experience in the design and operation of agricultural land application at the Site. Monitoring data collected for these systems over the past several years support the following conclusion:

- Agricultural land application technology has been highly effective at consistently treating plume groundwater at the Ranch, East, and DVD LTUs;
- Performance of the DVD LTU in treating Cr(VI) has exhibited some variability across the LTU; however, chromium reduction efficiencies consistently average over 82 percent;
- Agricultural land application is effective at treating nitrate in groundwater from past (non-PG&E) agricultural practices, as nitrate is taken up by crops as an essential nutrient;
- TDS impacts from LTU operations are consistent with any other irrigated agricultural practice, are not expected to reduce or change the productive use of groundwater in the area, and are outweighed by the benefits of Cr(VI) and nitrate removal; and
- The drag-drip irrigation method represents a practical and cost effective means to deliver irrigation water while minimizing the potential for contact of the plume groundwater with the surrounding environment.

4.3 Plume Core In-Situ Reduction Treatment

IRZs remove Cr(VI) mass from groundwater within the plume by converting Cr(VI) to relatively insoluble Cr(III), a necessary human nutrient. IRZs are established by injection of an organic carbon source such as ethanol or lactate to stimulate the growth of naturally occurring microbes in the subsurface. In turn, the Cr(VI) to Cr(III) conversion occurs through direct microbial reduction and/or indirect chemical reduction by reduced iron and sulfide. Cr(III) is removed from groundwater through precipitation of relatively insoluble chromium hydroxides and iron-chromium hydroxides. The IRZs established through groundwater recirculation and carbon amendment have proven to be an effective treatment option at the Site. To date, three pilot and three full-scale IRZs have been implemented. Each full-scale system was implemented with a different treatment objective and design. The operation results for these systems demonstrate that:

- Injection of organic carbon substrates is an effective technology for removing Cr(VI) from groundwater. Several organic carbon substrates (including ethanol, lactate, and EVO) were shown to be effective reagents on the pilot-scale and/or full-scale IRZs at the Site.
- Recirculation systems are an effective means of distributing amendment (i.e., organic carbon substrates), establishing IRZs, treating Cr(VI), and generating a clean water front with Cr(VI) concentrations that are less than background at some locations.
- The aerial coverage of amendment distribution and Cr(VI) treatment varies across the Site, due to geologic heterogeneities and spatial variations in groundwater flux. This causes non-uniform distribution of the amendment, leaving areas of the formation where IRZs are not established and Cr(VI) concentrations are not reduced to less than background. However, amendment is effectively distributed to higher permeability zones, where the majority of Cr(VI) transport and flux occurs. An adaptive operational approach is required to optimize treatment and to minimize the areas of the formation where Cr(VI) concentrations are not reduced to background. These modifications may include adjustments to injection and extraction rates or well locations in order to accommodate varying conditions.
- Secondary byproducts including dissolved manganese, iron, and arsenic are generated within IRZs, and are usually found to attenuate to background conditions downgradient of the IRZs. The operation of IRZ systems must manage the tradeoff between maximizing the Cr(VI) treatment area and the Cr(VI)-reducing storage capacity (i.e., creation, through total organic carbon (TOC) loading, of aquifer soil minerals reactive toward dissolved Cr(VI) over the long term) and minimizing the generation of secondary byproducts and the associated impacts to water quality.

4.3.1 Central Area IRZ

System Purpose and Design

The Central Area IRZ was constructed across a portion of the plume core along Highway 58 (Figure 4-3) to serve as a treatment barrier, removing Cr(VI) from groundwater as it migrated through the IRZ. The IRZ system consists of 12 remediation wells (CA-RW-01 through CA-RW-12) screened in the shallow layer of the Upper Aquifer (located approximately 80 to 115 feet bgs) and spaced approximately 150 feet apart in a line perpendicular to the direction of groundwater flow. The system initially operated in a dipole configuration, with recirculation completed by extracting groundwater from the even-numbered well in each pair, and injecting the groundwater into the odd-numbered well in each pair (Figure 4-3). Coverage and treatment were incomplete in a few locations, allowing a continued downgradient flux of Cr(VI). The system was reconfigured in September 2009, resumed operating in November 2009, and continues to date.

The Central Area remediation wells are screened in the shallow layer of the Upper Aquifer; in the deep layer of the Upper Aquifer, some Cr(VI) in groundwater has been treated due to the downward migration of treated water from the remediation wells, as presented in Figure 4-4. The extent of treatment in the deep layer varies with depth and location. To further address the deep layer of the Upper Aquifer, injections began into the SCRIA injection wells screened across the deep layer of the Upper Aquifer, upgradient of the Central Area IRZ, in November 2009.

Continuous groundwater recirculation and daily addition of sodium lactate amendment began in the six dipole well pairs in December 2007 and January 2008. The amendment was switched from sodium lactate to ethanol in October 2008, because of the cost of sodium lactate and the ability to move ethanol further into the formation. The system was reconfigured in September 2009, and resumed operating in November 2009.

Cr(VI) Treatment Results and Optimization

Results from the Central Area IRZ monitoring network demonstrate effective treatment of Cr(VI) in the shallow layer of the Upper Aquifer, as groundwater passes through the IRZ. Figure 4-3 shows a comparison of Cr(VI) isoconcentration contours in the shallow aquifer layer in November 2007 (prior to IRZ startup) to contours following two years of operation. Treatment performance statistics for this system include the following:

- Cr(VI) treatment was observed in 70 percent of the wells within the area of influence of the system;
- Treatment to background was achieved in approximately 50 percent of the treated wells;
- Treated groundwater migrated at least 800 feet downgradient of the IRZ line;
- Treated water propagation downgradient is non-uniform, resulting in closely-spaced treatment/non-treatment zones or "stripes;"
- The ability to distribute carbon into the formation using the dipole injection/extraction design is variable, and is dependent on local lithologic conditions and the degree of "biological fouling" of the aquifer matrix; and
- Byproducts (iron and manganese) were produced at over threshold concentrations in approximately 30 percent of the wells.

A complete statistical analysis of the effectiveness of the IRZ system for the plume core is included in Appendix B.

Based upon experience with this methodology and data collected to date, it would be extremely difficult to fully treat Cr(VI) to background in all areas of the plume, due to variations in groundwater flux and heterogeneities in the formation (Figure 4-3).

4.3.2 Source Area IRZ

System Purpose and Design

The Source Area IRZ was designed to treat source concentrations of Cr(VI) in groundwater. A recirculation system parallel to groundwater flow was used to distribute organic carbon and treat Cr(VI) throughout the area. The system was planned in phases; the first phase consisted of four downgradient extraction wells (SA-RW-01 through SA-RW-04) and 12 upgradient injection wells (SA-RW-05 through SA-RW-16) screened across both the shallow and deep layers of the Upper Aquifer. Phase 1 of the Source Area IRZ system operation began in April 2008 using sodium lactate as the organic carbon amendment. Ethanol was substituted for lactate in August 2008.

<u>Cr(VI) Treatment Results and Optimization</u>

Results from the Source Area IRZ monitoring network demonstrate the effective treatment of Cr(VI), for the shallow and deep layers of the Upper Aquifer, as shown in Figures 4-5 and 4-6. Treatment performance statistics for the Source Area IRZ include the following:

- Treatment of Cr(VI) across the majority of the Phase I area within the first year of operation;
- Cr(VI) treatment was observed in 75 percent of the wells within the area of influence of the system;
- Treatment to background was achieved in approximately 60 percent of the treated wells;
- Treated water and organic carbon propagated in excess of 300 to 400 feet from the treatment wells in a non-uniform manner, which resulted in treatment variability similar to the Central Area IRZ; and
- Byproducts (iron and manganese) were produced at over threshold concentrations in approximately 60 percent of the wells.

A statistical analysis of the effectiveness of the IRZ system operation for the plume core is included in Appendix B.

4.3.3 South Central Reinjection Area IRZ

<u>System Purpose, Design, and Performance</u>

The SCRIA IRZ was designed to: 1) treat groundwater that is extracted from the northern diffuse end of the plume for hydraulic control and 2) treat Cr(VI) in the aquifer within the SCRIA. Twelve widely-spaced injection wells screened in both the shallow and deep layers of the Upper Aquifer were installed in the first phase of construction in two transects across the area (SC-IW-21 through SC-IW-26 and SC-IW-32 through SC-IW-37; Figure 4-7). The system design is flexible and allows for installation of additional injection wells within existing transects or additional transects, if needed. Operation of the SCRIA IRZ was planned in stages using alternating injection wells to treat Cr(VI) in the aquifer, while allowing groundwater flux through the transect. Startup of the first stage of operation began in October 2009, with groundwater injection into 6 of the 12 injection wells; continuous operation was initiated in November 2009 (Figure 4-7).

Results to date demonstrate that some Cr(VI) treatment has been observed in the vicinity of operating injection wells in the first three months of operation, as shown in Figure 4-7.

Operations are planned to continue and injection rates and locations will be modified as needed to optimize treatment throughout the SCRIA.

4.3.4 In-Situ Byproduct Analyses

The generation of anaerobic IRZs for Cr(VI) treatment also results in the formation of in-situ byproducts including dissolved manganese, iron, and arsenic. Experience gained from operation of the three IRZ systems provides a comprehensive basis for byproduct management. The main factors controlling byproduct generation and attenuation are summarized below and are discussed in more detail in the In-Situ Byproducts Analysis Memo included in Appendix C:

- In-situ byproducts dissolve into groundwater within the reducing (low redox potential) footprint of the IRZ, Their concentrations are dependent upon the type of carbon amendment that is applied, the rate of TOC loading, and the location within the Site (i.e., Source Area versus Central Area and SCRIA).
- The generation of byproducts can be somewhat controlled through TOC loading. As a result, the applied TOC loading can be adjusted to lower byproduct formation. However, there is a tradeoff between maximizing the area of treatment and the storage of Cr(VI)-reducing capacity (i.e., creation, through TOC loading, of aquifer soil minerals that are reactive with dissolved Cr(VI) over the long term) and minimizing the generation of byproducts.
- Byproducts dissipate within the IRZ when amendment injections end. The time for recovery to baseline conditions varies, likely on the order of months to years, within the affected zone.
- Byproducts attenuate with distance downgradient of the IRZ. Given adequate distance, a clean water front arrives downgradient without Cr(VI) or byproducts above background.

Byproduct management is a necessary component of in-situ treatment. The extensive Site-specific experience detailed above shows that byproduct management is effective at the Site. Under the current regulatory framework, byproducts are managed through an extensive monitoring program that includes several lines of closely-spaced sentry and contingency wells, pre-defined carbon amendment modifications under the contingency plan, and complex regulatory reporting requirements. When in-situ systems were first implemented at the Site on a large scale, these rigorous requirements provided a high level of control and communication of results appropriate for that stage of the project. Given the experience with byproduct management gained over the first few years of operating large-scale IRZ systems at the Site, as described above, a less rigorous monitoring and reporting plan that allows for more efficient management of the IRZ systems is now appropriate.

In summary, in-situ treatment is an effective method of converting Cr(IV) to Cr(III), but its effectiveness is not consistently absolute. Additionally, it is not a logical strategy to treat groundwater containing acceptable drinking water levels of Cr(VI), in exchange for the creation of non-drinking water levels of dissolved metals. The generation of unwanted byproducts restricts the applicability of this treatment method to areas with non-drinking water levels of Cr(IV), and sufficient downstream buffer to allow for byproduct attenuation.

4.4 Additional Technologies Evaluated

In addition to land application for treatment of extracted groundwater, and recirculation systems to establish IRZs for Cr(VI) treatment in the aquifer and in extracted groundwater, several technologies have been pilot tested or researched for application at the Site. These technologies include direct-push injection of reducing agents, infiltration galleries for in-situ Cr(VI) reduction in the vadose zone, ex-situ treatment using ion exchange units, ex-situ treatment using membrane biofilm reactors (MBfRs), and monitored natural attenuation. An assessment of each technology is detailed in Appendix C. The findings of the evaluations are summarized below.

4.4.1 Direct-Push Injections

An injection tracer study using direct-push technology (DPT) was conducted to assess the efficacy of delivering carbon amendment for in-situ Cr(VI) treatment in groundwater. The DPT pilot test is described in the report titled, "Direct Push Injection Pilot Study" prepared by ARCADIS on 3 June 2010 (ARCADIS 2010a) and is included in Appendix C). The primary objectives of the DPT pilot test were to:

- Determine whether DPT can be used at depths up to 130 to 150 feet bgs at the Site;
- Assess the delivery effectiveness of amendment injection via DPT;
- Determine design parameters (e.g., injection rates, amendment concentration, and quantity requirements) for use in full-scale cost estimates; and
- Evaluate treatment effectiveness and longevity of treatment with EVO.

Three DPT injection points were installed on 20-foot centers up to 120 feet bgs and approximately 10 feet upgradient of a multi-level observation well. Injections were performed at various depths in each of the DPT injection points, through a 1-foot-long screen. Injection rates varied from 0.5 to 8.6 gpm. Higher injection rates were realized in the coarser sandy lithologies. A total of 7,836 gallons of EVO (selected for its known persistence in the subsurface, a required characteristic of one-time injection in-situ treatment) and fluorescein dye were injected through the three points. The EVO and fluorescein were never detected in the multi-level observation well.

The study confirmed that DPT can be used to inject treatment amendments at depth at the Site. However, the distribution of injected amendment throughout target areas was demonstrated to be somewhat unpredictable and would likely require very close injection spacing, thus limiting the applicability of this technology on a full-scale. The application of this technology may be appropriate on a smaller, more focused scale, depending on local site conditions and/or constraints. Further evaluation and testing at other locations would be appropriate prior to implementation.

4.4.2 Infiltration Gallery

A subsurface infiltration gallery was constructed to evaluate the effectiveness of infiltrating carbon-amended extracted groundwater at treating Cr(VI). The pilot test was also performed to evaluate whether the infiltration gallery would cause any secondary effects on groundwater quality. Details of the infiltration pilot study are described in the report titled, "Infiltration Pilot Test Results," prepared by ARCADIS on 3 June 2010 (ARCADIS 2010b) and included in Appendix C.

The pilot study (which is located within the SCRIA and treated between 0.8 and 5 gpm) consists of five perforated lateral distribution pipes placed within a bed of gravel at approximately 4 feet bgs within a 20-foot by 30-foot area. Lysimeters were installed at 14.5, 29.5, and 45 feet bgs to monitor treatment effectiveness. Impacted groundwater was diverted from the SCRIA to the infiltration gallery, and amended with ethanol and the tracer dye eosine. Through 20 May 2010, a total of 224,100 gallons of groundwater were discharged to the infiltration gallery. The study is ongoing.

Results indicate that the Cr(VI) was successfully treated before reaching the first lysimeter at 14.5 feet bgs, without increasing TDS concentrations in the vadose zone and underlying groundwater. Dissolved metals (iron, manganese, and arsenic) were generated in the reducing zone but were attenuated before reaching the deep lysimeter (45 feet bgs). The results also indicate that approximately 60 gpm of extracted groundwater could be treated for each acre of land. Infiltration galleries are a promising technology for potential future use at the Site for the treatment of large volumes of low-concentration chromium-impacted groundwater. Potential benefits include lower TDS impacts to groundwater when compared to agricultural units (AUs) and smaller land area needed per gallon of water treated. Infiltration galleries would also help with plume boundary control similar to AUs if they are located outside or downgradient of the plume. Potential drawbacks of infiltration galleries are that they do not beneficially use groundwater (e.g, for crop production) and have the potential for generating byproducts such as iron, manganese, and arsenic (similar to IRZ operations). Full-scale infiltration galleries have not been tested or proven at the Site.

4.4.3 Membrane Biofilm Reactors

A bench-scale test of MBfRs, a membrane-based biological treatment to reduce Cr(VI) and nitrate in extracted groundwater, was performed on groundwater samples collected from the Site. The MBfR process uses hydrogen as the electron donor to develop a biofilm of indigenous bacteria on hollow filter membranes in an ex-situ reactor. As groundwater is moved through the reactor, the Cr(VI) and nitrate that come in contact with the biofilm serve as electron acceptors and are reduced. The results of the MBfR bench-scale test are described in the technical memorandum titled, "Findings and Recommendations: Membrane Biofilm Reactor Bench-Scale Test," prepared by CH2MHill on 28 December 2009 (CH2MHill 2009a) and included in Appendix C.

Two bench-scale tests were performed. The first was performed on relatively low Cr(VI) concentration (53 μg/L) groundwater collected from the northern diffuse portion of the plume. The second test was performed on higher Cr(VI) concentration groundwater (5,400 μg/L) representative of the plume core. The technology was successful at reducing the Cr(VI) and nitrate concentrations in the first test, but was unsuccessful in the second test.

Bench-scale test results indicate that MBfR technology appears to be effective at treating Cr(VI) and nitrate in groundwater at the relatively low concentrations encountered in the diffuse portion of the plume (53 μg/L chromium and 13 mg/L nitrate as nitrogen were reduced to 0.42 μg/L and <1.0 mg/L, respectively). However, results also indicate that for groundwater with the higher concentrations encountered in the plume core, this technology is ineffective. This technology is not considered a primary water treatment technology candidate for the Site.

4.4.4 Monitored Natural Attenuation

An evaluation of monitored natural attenuation (MNA) was performed to consider whether low levels of Cr(VI) in groundwater could be remediated through naturally-occurring mechanisms. The study focused on the capacity of the aquifer to reduce Cr(VI) to Cr(III) under the geochemical conditions that exist in groundwater in the northern diffuse portion of the plume. The MNA evaluation is described in the technical memorandum titled, "Evaluation of Monitored Natural Attenuation for Hexavalent Chromium in Groundwater, Hinkley Compressor Station, Hinkley, California," prepared by CH2MHill on 1 June 2010 (CH2MHill 2010d) and included in Appendix C.

Seven core samples were collected for testing: five from the Upper Aquifer and two from the blue clay that separates the Upper and Lower Aquifers. The cores were sampled for TOC and ferrous iron. Pore water in the cores was also analyzed for Cr(VI). Core samples were mixed with Site groundwater (50 grams of soil per 1.5 liters of Site groundwater), and allowed to react for 8 weeks.

Results of the study indicate that portions of the Upper Aquifer have some reductive capacity, which can reduce low levels of Cr(VI) in groundwater. However, the magnitude of this reductive capacity did not appear sufficient for use as a primary component of a plume-wide remedy. The blue clay appeared to have significant reductive capacity wherever the unit was sufficiently thick. This undoubtedly helps to prevent the vertical migration of Cr(VI) to the Lower Aquifer.

4.4.5 Ion Exchange

The current state of the art of treating Cr(VI) in extracted groundwater using ion exchange technology was evaluated through case study reviews and discussions with vendors. Case studies of the use of strong-based anion (SBA) and weak-based anion (WBA) resins at Lawrence Livermore National Laboratory and the City of Glendale were reviewed. The evaluation of the ion exchange technology is described in the memorandum titled, "PG&E Hinkley – Ion Exchange Technology Update," prepared by CH2MHill on 12 October 2009 (CH2MHill 2009b) and included in Appendix C.

SBA resins are not expected to be successful at the Site because of the high concentrations of sulfate present in the groundwater. The SBA resin has a high affinity for sulfate which would decrease the removal effectiveness of Cr(VI). WBA resins exhibit a higher affinity and removal rate for Cr(VI) than SBA resins, and removal capacities increase at lower pH (in the 6.0 to 6.8 range). However, they would likely only be viable in the northern diffuse portion of the plume where lower Cr(VI) concentrations are found. In addition, ion exchange may require frequent regeneration and/or resin disposal, and performance is strongly influenced by the presence of other species in the water. Finally, under some operational conditions, synthetic resins have been found to leach N-Nitrosodimethylamine, which exhibits a high toxicity. A bench-scale study would be needed to further evaluate the applicability of this technology on Site conditions. Regardless of the findings of such a study, the cost of resin filtration is cost prohibitive compared to other technologies such as in-situ and infiltration galleries.

5. REMEDIAL OBJECTIVES

The ROs are the guiding principles to identify potential treatment technologies, screen those technologies for their site-specific applicability, and select a final groundwater remedy for the Site. In accordance with the State of California resolutions outlined in Section 2, the ROs must consider a broad range of criteria to maximize the beneficial use of the groundwater resource.

Considering this broad range of criteria, the primary RO for groundwater at the Site, in accordance with the CAO and state requirements, is to achieve background chromium concentrations. In the course of implementing the final remedy to achieve background conditions, other objectives that were given consideration include restoration of aquifer beneficial use, plume containment, and maintaining a productive use of groundwater during cleanup. The proposed ROs are discussed in greater detail below.

5.1 Achieve Background Conditions for Chromium

Within the context of Resolutions 68-16 and 92-49, PG&E is evaluating cleanup options to reduce plume-wide Cr(VI) and Cr(T) concentrations to background conditions. The amended CAO directs PG&E to evaluate cleanup to both maximum and average background values identified in the CAO. The statistical maximum background values identified in the CAO are 3.1 μg/L Cr(VI) and 3.2 μg/L Cr(T); average background values are 1.2 μg/L Cr(VI) and 1.5 μg/L Cr(T). These values were taken from the background study conducted by PG&E at the Site. As required by the CAO, PG&E has evaluated cleanup to both maximum and average background concentrations as outlined in the CAO and has concluded that there is no regulatory basis for an average background cleanup level and that cleaning up to average background would be technically and economically infeasible:

- Resolution 92-49 requires cleanup to background water quality and refers to 23 CCR section 2550.4 to define background. As outlined by the State Water Resources Control Board Office of Chief Counsel, "Section 2550.4 refers to Section 2550.7(e) which provides the methodology for determining background levels for ground water." (Q&A SWRCB Resolution 92-49, Feb. 16, 1995). Section 2550.7(e) makes it very clear that when a background study is performed that produces a UTL (as PG&E did at this site) that monitoring data are to be compared to the UTL (and not to some other value such as average background). "[T]he value for each constituent of concern or monitoring parameter at each monitoring point is compared to the upper tolerance or prediction limit." (23 CCR section 2550.7 (e) (8) (C)). Thus, there is no regulatory or statutory basis to rely on PG&E's background study which produced a UTL for background Cr(VI) and required cleanup to another level such as average background.

- Remediation of groundwater to average background concentrations is technically and economically unreasonable because it would require the treatment and removal of naturally-occuring chromium from groundwater. That is, PG&E would have to remove naturally-occuring chromium from groundwater to "offset" areas where residual concentrations are above the average but less than the maximum. This is contrary to the specific language of Resolution 92-49: "[U]nder no circumstances shall these provisions be interpreted to require cleanup and abatement which achieves water quality conditions that are better than background conditions." (Resolution 92-49 III.F.1.).

- A search of available information reveals no sites in California that use this approach, nor any precedent that requires cleanup to an average background concentration. For the purpose of setting ROs, the statistical maximum background concentration (95 percent upper tolerance or confidence level) is used when a background study is based on a UTL.

- The average concentrations for Cr(VI) and Cr(T) presented in PG&E's background study provided nothing more than an overall median concentration of the chromium concentrations naturally present in groundwater over an area comprised of several square miles. It is inappropriate to compare the results from an individual well located within the plume to such widespread average concentrations.

- The background study determined statistically defensible upper tolerance concentrations of Cr(VI) and Cr(T) that could be present in groundwater throughout the Hinkley valley groundwater basin. The 95 percent UTL (95 UTL) concentrations proposed in the background study, including the acceptable method derived analytical uncertainty, provided a technically defensible upper limit of what could be detected in any given well sampled throughout the Hinkley valley. PG&E's background study recommended including the chromium testing method acceptable uncertainty in the upper tolerance or maximum background level. In other words, when a laboratory test method allows a laboratory to produce "valid" data that can be up to 25% off of the actual value, PG&E recommended that this level of uncertainty be added to the upper tolerance background concentration. If this laboratory uncertainty were included in the upper tolerance levels, the concentrations would be 3.55 μg/L for Cr(VI) and 4.04 μg/L for Cr(T). PG&E believes that laboratory uncertainty should be factored into the background level cleanup goal.

- As the plume remediation progresses, different portions of the aquifer may be cleaned up at different rates. Cleanup rates will be a function of several factors, including proximity to locations where remediation activities such as groundwater pumping and in-situ treatment are being conducted. If average background were the required cleanup level, PG&E would be required to continue remediation even when all wells were below the UTL or maximum background level.

Since there is no regulatory basis or precedent and it would be technically and economically infeasible to clean up to average chromium background concentrations, the proper background cleanup level for this site is the statistical upper tolerance level or maximum background levels established by PG&E's background study. PG&E believes that these numbers should include permitted laboratory variation or uncertainty. If those levels are used, the background cleanup goal would be: 3.55 μg/L for Cr(VI) and 4.04 μg/L for Cr(T). If laboratory uncertainty is excluded from the background calculation, then the background cleanup goal would be: 3.1 μg/L Cr(VI) and 3.2 μg/L Cr(T). This analysis uses the maximum background chromium values established and required by the CAO as the WQO for the Remedial Area. Nevertheless, PG&E believes that the background cleanup values should include the laboratory uncertainty as outlined above.

Given the very low background values for the Site, combined with the large plume size and natural variability of the aquifer, it is anticipated that this objective will take considerable time to achieve, regardless of the remedy selected. Two important balancing factors that offset the estimated time to achieve the background WQO include:

- Achievement of the drinking water MCL within 10 years; and
- Provide immediate productive/agricultural use of the extracted groundwater.

A program will be developed to monitor and verify progress toward meeting the WQO. Part of the program should include a critical progress review cycle on the order of every 5 years. This program should be jointly developed with the LRWQCB as part of the remedy implementation.

5.2 Restore Beneficial Use

The aquifer at and in the vicinity of the Site currently has multiple beneficial use designations. These designations exist even though historical agricultural impacts not associated with chromium (TDS and nitrate) largely limit their use in the area to agriculture.

Current State Water Code regulations stipulate that beneficial use aquifers must meet the MCL for chromium, which is currently 50 μg/L as Cr(T). No specific Cr(VI) MCL currently exists. In 2009, the California Office of Environmental Health Hazard Assessment (OEHHA) published a draft public health goal (PHG) for Cr(VI) for public comment. OEHHA received significant comments on the draft PHG and set no timeline regarding revisions to the draft. Further, PHGs once officially adopted are advisory values, which are not enforceable. The California Department of Public Health will use the final PHG to formulate a new MCL while taking into account the technical and economic feasibility of regulating at a specific concentration. For the purposes of completeness regarding this RO, the draft Cr(VI) PHG was reviewed as a part of this FS for its possible application to the Site. Because the draft Cr(VI) PHG is lower than the Site specific background concentrations, implementation of this goal at the Site would not be applicable. Until a new PHG and a new chromium MCL are officially adopted, the current chromium MCL of 50 μg/L will remain the criterion for re-establishing aquifer beneficial use. As such, re-establishment of the beneficial use designation relative to chromium impacts will be based on achievement of the current chromium MCL.

At present, more than half of the plume already meets this objective, from years of operating remedial measures discussed in Section 4. Most of the plume area north of Highway 58 exhibits chromium concentrations less than 50 μg/L (as shown on Figure 2-2). Implementation of the final groundwater remedy in an attempt to achieve background conditions will focus on reducing plume-wide chromium concentrations and, in particular, reducing concentrations in the plume core where concentrations exceed the MCL. Based on the chromium reduction progress made to date, achievement of this objective is anticipated to be accomplished within approximately 10 years of implementation of the final remedy.

5.3 Chromium Plume Containment

Plume containment is a requirement of the CAO; in a meeting on 16 March 2010 the LRWQCB directed PG&E that the Resolution 92-49 analysis for selection of the final groundwater remedy would be performed on the Remedial Area defined by the 3.1 μg/L Cr(VI) contour. While the Remedial Area may be refined in the future based on new groundwater monitoring data, Figure 2-2 presents the plume configuration that was used for this analysis. In accordance with this requirement, plume containment is a key objective when considering selection of a final groundwater remedy.

Within the context of Resolution 92-49, plume containment will maintain the limits of the Remedial Area within the Project Area. PG&E proposes that the Project Area be defined as the Remedial Area, plus a buffer zone that takes into account local chromium data variability, data density, groundwater flow directions, and plume edge vacillation. This proposed Project Area has been defined to allow the plume edge to reasonably vacillate as the various natural and remediation stresses are at work, while at the same time maintaining containment and regulatory compliance. Consistent with the other ROs, specifics of the Project Area and development of a reasonable monitoring plan will be jointly developed with the LRWQCB and included in the final remedy implementation plan.

Critical factors that have, and continue to influence plume containment include:

- The plume size and shape;
- Aquifer complexity;
- The influence of non-PG&E nearby agricultural pumping on plume migration; and
- The ability to pump and manage sufficient groundwater without impacting other users (e.g., via drawdown).

These factors have played a significant role in the ability to comply with the containment portion of the CAO to date. Achieving the RO of plume containment in the future will require the development of engineering measures that include a hydraulic evaluation of pumping rates and plume capture analysis balanced against local/regional groundwater level drawdown. Hydraulic control of the chromium plume will likely require pumping substantially more groundwater than is presently being pumped. Since local aquifer drawdown is a potential issue, attention will be focused on attempting to develop an approach that balances the benefits of robust hydraulic capture against the drawbacks of localized drawdown.

5.4 Productive Use of Groundwater Resource

Because the groundwater remediation process to achieve the chromium MCL is anticipated to take about a decade after startup of the final remedy, an additional RO is to maintain the productive use of groundwater during this treatment period, given the combined chromium and historical agricultural impacts (e.g., TDS and nitrate).

The breakdown of the past and current uses of groundwater in the Barstow groundwater basin (DWR 2009) and the approximate volumetric percentages are:

- Agriculture (~55 percent);
- Industrial (~5 percent); and
- Municipal (~40 percent).

Within the immediate area around the Site, groundwater use is more focused on agriculture with the approximate volumetric percentages:

- Agriculture (including dairy) (~85 percent);
- Industrial (~5 percent); and
- Municipal (~10 percent).

On a volumetric basis, groundwater in the immediate vicinity of the Site is predominantly used for agriculture. Section 2 illustrated the historical significance of groundwater use for agriculture in the basin, supporting many different crop types and providing a significant economic base and benefit to the community. However, this lengthy history of agricultural and dairy activities has also resulted in TDS and nitrate groundwater impacts that exceed California and Federal primary and secondary drinking water quality standards. Additionally, unsustainable drawdown of the aquifer occurred as a result of these historical agricultural activities. The combination of declining water tables and elevated nitrate/TDS levels resulted in an area-wide reduction in agricultural production over recent years.

The chromium groundwater impacts at the Site are co-mingled with these non-PG&E related historical agricultural impacts. Even after chromium has been reduced below the MCL to meet the beneficial use criterion, the historical agricultural impacts over much of the plume will limit the beneficial use of groundwater to agricultural or industrial use for a considerable time.

Given PG&E's long-term commitment to the Hinkley community and to sustainable/green business practices, PG&E feels strongly that the groundwater remedy should make the most productive use of this currently marginal resource. Based on the groundwater use statistics above and the combined chromium and historical agricultural impacts, the best current use of groundwater remains agricultural. The selected remedies must include features that potentially make the most productive use of groundwater in this manner, such as:

- Use of agricultural application to reduce chromium concentrations in extracted groundwater;
- Use of impacted water (chromium/TDS/nitrate) for fodder and livestock crops, instead of importing fresh water or using the higher-quality water from the Lower Aquifer;
- Use of crops that tolerate irrigation using the impacted water; and
- Groundwater basin recharge.

Potential additional benefits that may be derived from such an approach include:

- Reduction of nitrate through agricultural application; and
- Potential reduction of fresh water imports for crop production, by using Site water for crop production.

Each potential technology and assembled remedy was evaluated for the most productive reasonable use of the groundwater resource during the remediation period. This RO is being partially met at the current time through ongoing operation of the DVD; further achievement of this RO should be realized shortly after the final remedy is implemented.

5.5 Remedial Objectives Summary

In summary, the four ROs for addressing chromium impacts to groundwater at the Site are:

- Achieve background conditions;
- Restore groundwater beneficial use;
- Achieve plume containment; and
- Restore productive use of the groundwater resource.

These ROs were considered the "effectiveness" criteria for evaluation of the alternatives in this FS. The treatment technologies and assembled remedial alternatives were evaluated against their ability to reasonably achieve these ROs, taking into consideration all of the technical, logistical, and regulatory complexities of the Site.

6. DEVELOPMENT AND ANALYSIS OF SELECTED REMEDIAL ALTERNATIVES

The development and analysis of selected remedial alternatives was based on their ability to meet the four ROs outlined in Section 5. The analysis considered the effectiveness, implementability (feasibility), and relative cost of each alternative to meet the requirements of Part III.C of Resolution 92-49.

Effectiveness measures the alternative's ability to meet the four ROs; 1) Achieve Background Conditions for Chromium; 2) Restore Beneficial Use; 3) Chromium Plume Containment; and 4) Productive Use of Groundwater Resource. Implementability measures the technical and administrative feasibility of the alternative. Cost measures the net present value (NPV) cost carried over the life cycle of the alternative.

The remedial technologies identified in Section 6.1 were screened for their ability to satisfy the ROs based on effectiveness, implementability, and cost. A set of promising technologies that were retained following the screening process were combined to form comprehensive alternatives that represent a range of approaches, with varying performance and cost. These alternatives and their key advantages and disadvantages are described in detail in Section 6.2.

To evaluate the cleanup duration of each of the alternatives, predictive fate and transport modeling was conducted. The predictive modeling output included duration estimates for two of the primary ROs identified in Section 5, as well as an interim goal. These include:

- Plume-wide achievement of the 50 μg/L Cr(T) MCL;
- Plume-wide achievement of background; and
- Removal of 80 percent of the estimated Cr(VI) mass (interim goal).

The interim threshold of 80 percent Cr(VI) mass removal is not specifically identified as a remedial goal in Section 5, but was selected to highlight remedial alternatives that focus on and achieve more accelerated Cr(VI) mass removal. Output of the predictive modeling is included as Appendix E.

A comparative analysis describing the supporting rationale for each selected remedial action alternative is provided in Section 6.3. Each alternative was measured against the ROs using effectiveness, implementability, and cost as criteria.

This analysis was supported by years of data collection, on-Site pilot tests, and full-scale remediation experience as discussed in Section 4. These experiences were invaluable while screening technologies most readily applicable to the Site and combining those technologies into comprehensive remedial alternatives for further analysis as described below.

6.1 Remedial Action Technology Screening

Thirty-six remedial technologies and process options were identified (as shown in Table 6-1) and screened for further evaluation, based on Cr(VI)'s attributes, affected media, Site characteristics, and the significant amount of existing Site-specific data and knowledge gathered over the years. Prior information gathered from bench-scale tests, pilot tests, and full-scale interim actions performed at the Site were also used to further evaluate and screen the technology and treatment process options. Many of these pilot tests are discussed in Section 4, or are included in Appendix C. Remedial technology types and associated process options typical of an FS technology screening process are listed in Table 6-1. The technologies listed in this table include a diverse list common to remediating a broad spectrum of contaminant types (including non-metals). As such, the purpose of the initial screening was to eliminate inappropriate technologies and focus attention and further evaluation on those technologies potentially applicable to Cr(VI) in Site groundwater, when applied either individually as a stand-alone alternative or as a component for use in combination with other appropriate technologies.

To streamline the process and factor in special consideration for the large size of the Site's plume, the technology screening summarized in Table 6-1 involved two steps. Step 1 screened technologies for general applicability to reduce Cr(VI) (the left half of Table 6-1); Step 2 further screened those technologies retained from Step 1, based on more Site-specific considerations including relative effectiveness (achieve background conditions for chromium, restore beneficial use, contain chromium plume, and productively use groundwater resource), implementability, and cost (the right half of Table 6-1). Each technology was evaluated against these criteria, and if it could not effectively meet them it was eliminated from further consideration.

The matrix in Table 6-2 lists the retained technologies from the screening process (as summarized in Table 6-1), and presents combinations of those retained technologies in five remedial alternatives. The alternatives were subject to a more detailed comparative evaluation of their ability to meet the ROs. The remedial alternatives cover a range of options from no action (which was included as a basis for comparison to the other active remedies) to plume-wide in-situ treatment and plume-wide pump and ex-situ treatment. The details associated with each alternative presented in Table 6-2 are also described below.

6.2 Description of Alternatives

The assembled alternatives from Table 6-2 combine proven technologies used at this or other sites for Cr(VI) treatment in groundwater and incorporate years of experience gained in pilot testing and operating numerous remedial alternatives at the Site. Further, the assembled alternatives are presented based on their perceived ability to comply with the project regulatory requirements outlined in Section 2 (in particular the CAO and Resolution 92-49) and their ability to meet the ROs detailed in Section 5. With the exception of Alternative 1, all of the alternatives employ robust containment of the plume. The five assembled alternatives are described below.

6.2.1 No Further Action (Alternative 1)

<u>Conceptual Approach</u>

The No Further Action Alternative (Alternative 1) was included as a basis for comparison to the other active remedies. Figure 6-1 illustrates the general configuration of Alternative 1. This alternative was included in this FS per requirements established in the Environmental Protection Agency Directive No. 9355.3-01FS2 titled "The Feasibility Study, Development and Screening of Remedial Action Alternatives."

Implementation Details

As shown on Figure 6-1, this alternative assumes no future pumping or groundwater treatment; thus, current containment pumping, agricultural water treatment, and in-situ chromium treatment operations would be discontinued.

Estimated Time Frame and Cost to Reach Background

Alternative 1 is projected to achieve the 50 μg/L chromium MCL RO in over 1000 years. Because Site background concentrations are so low and no plume core/source treatment is applied, the model-estimated time frame to achieve the background RO is also over 1000 years, at no cost. Computer modeling also predicts that Alternative 1 would achieve the 80 percent mass removal interim goal in over 780 years.

Limitations

This alternative does not provide plume containment and does not directly reduce the plume core Cr(VI) mass; therefore, Cr(VI) concentrations over 50 μg/L would persist for hundreds of years.

6.2.2 Containment (Alternative 2)

Conceptual Approach

The Containment Alternative (Alternative 2) was developed to address the ROs of Section 5, with primary emphasis on the plume containment RO. Figure 6-2 illustrates the general configuration of Alternative 2. The main operational features of this alternative include plume containment/hydraulic control via groundwater extraction (generally north of Highway 58), followed by treatment and productive use of extracted groundwater via agricultural application (also north of Highway 58). These features were developed to prevent further plume expansion, reduce Cr(VI) mass, minimize or eliminate exposure outside the Project Area, and provide productive use of the extracted groundwater for agriculture.

Alternative 2 was structured around groundwater plume containment with extraction wells (primary means of control) and injection wells (limited secondary means of control) distributed in the northern diffuse portion of the plume as a hydraulic barrier. Groundwater would be extracted from the toe (northern edge) of the plume and applied to agricultural fields for Cr(VI) reduction near or outside the toe of the plume. Infiltration from the agricultural fields would play a role in maintaining hydraulic control of the plume, so their locations are important. Additional properties around or beyond the toe of the plume, potentially with existing or previous agricultural operations, would be used to treat the volume of water needed to support hydraulic control. If needed, groundwater with background Cr(VI) concentrations would be extracted from a location outside of the plume and injected as another means of hydraulic control.

Implementation Details

As shown in Figure 6-2, the conceptual approach for Alternative 2 assumes that groundwater extraction wells would be installed at the toe of the plume to complement the existing wells in the DVD and SCRIA extraction areas. These new wells would expand containment and increase the total amount of groundwater extracted under this alternative to approximately 950 gpm.

Once extracted, the groundwater would be piped to AUs for reuse via flood or drip application (drag-drip or subsurface drip). Groundwater from the various extraction wells would be distributed to the root zone, where rhizospheric microorganisms would reduce Cr(VI) to Cr(III) in the shallow subsurface. The presence of historical agricultural nitrate in extracted groundwater would be expected to promote plant growth, while nitrate concentrations in groundwater would be expected to decline through plant uptake. This scenario increases farm land and agricultural production, without increasing the amount of imported water from the MWA or other areas.

As indicated above, fresh water from one or more extraction wells located outside of the plume would be injected as needed to supplement groundwater extraction, provide robust hydraulic control, and avoid excessive drawdown of the upper aquifer. Initially, four injection wells already installed as part of the northwest interim remediation measure would be targeted for injection. Other wells would be added or subtracted as necessary.

Implementation of Alternative 2 is likely to require the acquisition of additional properties and/or easements within the Project Area. These acquisitions could be both inside and outside the Remedial Area for installation and maintenance of remedial infrastructure. Groundwater use on acquired properties would be restricted to non-potable use as appropriate for the duration of the remedy.

Over time, optimization of the initial system might include modifications to the location, number, and pumping rates of extraction wells.

Estimated Time Frame and Cost to Reach Background

Computer modeling of this alternative indicates that the plume would be contained and drawn to the hydraulic containment extraction wells. Alternative 2 is projected to achieve the 50 μg/L chromium MCL RO in approximately 120 years. Because Site background concentrations are so low and no plume core/source treatment is applied, the model-estimated time frame to achieve the background RO is approximately 260 years, at a cost of approximately \$36M NPV. Computer modeling also predicts that Alternative 2 would achieve the 80 percent mass removal interim goal in approximately 95 years.

Limitations

Current AUs are limited in their water flow and application rate. The complexity of the geology near the toe of the plume (including thinning of the Upper and Lower Aquifers, bedrock rise, and distribution of the blue clay aquitard), plume size, and variable agricultural pumping by others, add substantial complexity to maintaining hydraulic control. Because this alternative does not directly reduce the plume core Cr(VI) mass, Cr(VI) concentrations over 50 μg/L would persist for decades.

Aquifer pumping under this alternative will result in the lateral and vertical mixing of groundwater within the hydrogeological unit pumped and may result in localized changes (increases or decreases) in TDS and nitrate concentrations. Increases in TDS or nitrate may result in localized exceedances of drinking water standards for beneficial use; however, concentrations of these constituents should not significantly increase over levels consistent with similar agricultural operations. As compared to similar agricultural operations using spray irrigation, the modes of applying irrigation water under this alternative would result in reduced incremental addition of TDS to groundwater because evaporative losses would be significantly reduced under the alternative.

The purchase of property or easements for additional AUs beyond the toe of the plume would be necessary for Alternative 2, as the total flow extracted for hydraulic containment (about 950 gpm) exceeds the permitted maximum annual average discharge rate for the existing DVD LTU (520 gpm). Acquisition of these properties and/or easements may be difficult. Modifying existing AUs near the toe of the plume is preferred over the installation of new AUs in an area not previously used for agriculture, as this would reduce the overall cost, utilize existing infrastructure, and minimize new construction. However, the addition of new AUs is preferred over other groundwater treatment options.

6.2.3 Plume-Wide In-Situ Treatment (Alternative 3)

Conceptual Approach

The Plume-Wide In-Situ Treatment Alternative (Alternative 3) was developed to address the ROs of Section 5, with plume containment via groundwater extraction and injection in the northern diffuse portion of the plume, and Cr(VI) treatment by amending extracted groundwater with carbon (e.g., ethanol) and injecting the carbon-amended water to create reducing conditions (IRZs) in the aquifer. Figure 6-3 illustrates the general configuration of Alternative 3. This alternative and its associated network of extraction and injection wells was developed to achieve a level of containment similar to Alternative 2, but it treats extracted groundwater through carbon-amended injection. This alternative reduces chromium mass, and minimizes net aquifer drawdown by re-injecting extracted and amended water in portions of the plume exhibiting higher Cr(VI) concentrations as well as to the periphery to provide further hydraulic control (where necessary). Emphasis in this alternative is placed on the rapid reduction of Cr(VI) concentrations in the plume core (>50 μg/L) to expedite re-establishing the beneficial use RO for the Upper Aquifer.

Implementation Details

As shown in Figure 6-3 and noted above, the conceptual approach for Alternative 3 is to utilize extraction wells at the toe of the plume to provide hydraulic containment, add carbon amendment to the extracted water, and inject the carbon-amended water into wells to create IRZs. The organic carbon source promotes biological growth resulting in reducing conditions capable of converting Cr(VI) into Cr(III), which precipitates out of solution within the aquifer due to its low solubility. The total amount of groundwater extracted under this alternative would be approximately 1000 gpm.

There are two general IRZ methods defined by the proximity of extraction and injection wells: distant (far-field) extraction/injection (e.g., SCRIA IRZ) and localized (near-field) extraction/injection (e.g., Central IRZ). The distant or far-field IRZ configuration would use groundwater from the extraction wells within the toe of the plume as feed water that would be amended with carbon and then injected into wells, located within the southern core area and periphery of the plume, to promote in-situ reduction of Cr(VI). The injections within the plume core would target the highest Cr(VI) concentrations within the plume, while injections along the periphery would be designed for hydraulic control purposes to restrict the plume from migrating to the east and north. Injections upgradient of the Source Area would provide additional treatment to the Source Area if needed and flush the impacted groundwater toward the reactive zone created by the carbon-amended injections. Injection wells would be cycled on and off by area to optimize the distribution and effect of the injected amendment. Since the injection wells would be located a substantial distance from the extraction wells, larger recirculation loops would be established in this type of IRZ application.

To supplement the large recirculation loops created with the far-field IRZ configuration, Alternative 3 would incorporate a localized recirculation system in the core or central portion of the plume to maintain the existing Central Area IRZ. Extraction wells and injection wells would be located near to one another and groundwater recirculated to create a treatment transect across the plume. Similar to the more distant IRZ extraction/injection configuration, the extracted groundwater would be amended with an organic carbon substrate prior to reinjection. The recirculation system would create a reactive zone that is roughly perpendicular to the direction of groundwater flow, therefore treating the groundwater as it flows through the zone.

Additional hydraulic control northwest of the plume would come from "freshwater" injections as needed. Fresh water from an extraction well located outside of the plume is already being pumped over to the northwest boundary of the plume and injected into four injection wells at a rate of up to 80 gpm. The freshwater injection is intended to supplement extraction efforts, to prevent plume migration toward the northwest, and to reduce drawdown of the aquifer. Freshwater injection would only be used on an as-needed basis.

Implementation of Alternative 3 is likely to require the acquisition of additional properties and/or easements within the Project Area. These acquisitions could be both inside and outside the Remedial Area for installation and maintenance of remedy infrastructure. Groundwater use on acquired properties would be restricted to non-potable use as appropriate for the duration of the remedy.

Over time, optimization of the initial system might involve shifting injection/extraction lines to optimize the distribution of amended groundwater, shifting injections from the Source Area to the center and toe portions of the plume, or discontinuing IRZ operation in select areas as the plume is remediated.

Estimated Time Frame and Cost to Reach Background

Computer modeling of this alternative suggests that chromium concentrations within the plume core are remediated first, with lower concentrations toward the periphery remediated over time based on the location of the injection wells. Alternative 3 is projected to achieve the 50 μg/L chromium MCL RO in approximately 8 years. Because Site background concentrations are so low, the model-estimated time frame to achieve the background RO is approximately 110 years, at a cost of approximately $130M NPV. Computer modeling also predicts that Alternative 3 would achieve the 80 percent mass removal interim goal in approximately 10 years.

Limitations

The creation of reactive zones to treat groundwater would reduce Cr(VI) to Cr(III), but operational data to date suggest that it will be difficult to establish uniform treatment results throughout the entire treatment area due to aquifer heterogeneity, presence of low permeability zones, and difficulty of evenly distributing carbon. Details regarding the spatial variability of treatment are included in Appendix B. Operational data also suggests that deleterious byproducts such as reduced iron, manganese, and arsenic will be generated, and will affect the ability to distribute carbon and maintain a robust treatment area, especially in portions of the plume where there is little downstream buffer area. For this reason, in-situ treatment is most applicable to the plume core.

Containment of the northern end of the plume will be challenging due to the complex hydrogeology, plume size, and variable agricultural pumping by others in the area. Acquisition of properties and/or easements potentially needed for implementation may be difficult or take considerable time.

6.2.4 Core In-Situ Treatment and Beneficial Agricultural Use (Alternative 4)

Conceptual Approach

Alternative 4 (Core In-Situ Treatment and Beneficial Agricultural Use) was developed to address the ROs of Section 5 with plume containment and Site-wide treatment using a combination of technologies based on area-specific requirements, while providing productive use of the extracted groundwater through agricultural application and recharge within the Site limits. Figure 6-4 illustrates the general configuration of Alternative 4. Other treatment methods such as infiltration galleries could be technically and economically feasible but were not selected for this alternative because they do not beneficially use groundwater. Alternative 4 attempts to apply different treatment methods to areas where they would be most effective, based on actual Site remediation experience. Treatment methods for Alternative 4 include agricultural application within and adjacent to the northern diffuse portion of the plume, and in-situ treatment via amending groundwater with carbon to create IRZs in the plume core. This approach is similar to the general treatment approach presently operating at the Site, but on a larger scale. Extracted groundwater would be either: 1) applied to AUs; 2) carbon amended and injected in the plume core to establish IRZs in a distant (far-field) type recirculation loop configuration; or 3) carbon amended and injected nearby the extraction wells in a localized near-field IRZ configuration (e.g., the Source and Central Area IRZs). Like Alternative 3, an emphasis in Alternative 4 is reduction of Cr(VI) concentrations in the plume core to re-establish the 50 μg/L chromium MCL RO in the most timely manner.

Implementation Details

As shown in Figure 6-4, the conceptual approach for Alternative 4 includes groundwater extraction in the northern diffuse portion of the plume and has been configured to achieve a similar level of hydraulic containment as Alternative 2. Unlike Alternative 2, Alternative 4 treats extracted groundwater using two methods: agricultural application and IRZ treatment. The IRZ application methods would be the same as those discussed in Alternative 3; however, the IRZ application of Alternative 4 is only in the plume core. In total, about 1000 gpm would be extracted from the toe of the plume for hydraulic control purposes.

Of the total withdrawn at the toe of the plume, approximately 800 to 900 gpm of groundwater extracted from the toe of the plume would be piped to existing or new AUs for agricultural application via flood or drip irrigation (drag-drip or subsurface). Modeling indicates that maximum hydraulic control is achieved with AUs located just outside the toe of the plume; therefore, any new AUs would be preferentially located in these areas (where feasible) and within the proposed Project Area. Approximately 100 to 200 gpm extracted from the toe of the plume and on the northeastern edge of the core would be amended with an organic carbon substrate and injected in the plume core downgradient of the Source Area to promote in-situ reduction of the higher concentrations of Cr(VI). Additional IRZ recirculation areas of extraction and injection wells would be used to create reactive zones within the Source Area and the Central Area, adjacent to the SCRIA injections. The net flow from the recirculation systems would be approximately 0 gpm, as all extracted groundwater from within the recirculation system would be reinjected into the aquifer once it is amended with carbon. Through agricultural application, this scenario also increases farming land and agricultural production in the area without increasing the amount of regionally imported water from the MWA.

As with other alternatives that include plume containment, additional hydraulic control of the plume would be derived from freshwater injections, on an as-needed supplemental basis. Fresh water from an extraction well located outside of the plume would be pumped to the boundary of the plume and into injection wells.

Implementation of Alternative 4 is likely to require the acquisition of additional properties and/or easements within the Project Area. These acquisitions could be both inside and outside of the Remedial Area for installation and maintenance of remedy infrastructure. Groundwater use on acquired properties would be restricted to non-potable use, as appropriate for the duration of the remedy.

Over time, optimization of the initial system might involve shutting down certain IRZ recirculation zones in the Source Area, Central Area, and/or plume core (fate and transport modeling and cost estimates assume the IRZ is discontinued after 5 years of operation).

Estimated Time Frame and Cost to Reach Background

Computer modeling of this alternative suggests that chromium concentrations within the plume core are remediated first, while lower concentrations toward the periphery are remediated over a longer period of time, based on the location of extraction wells within the core and toe of the plume. Alternative 4 is projected to achieve the 50 μg/L chromium MCL RO in approximately 6 years. Because Site background concentrations are so low, the model-estimated time frame to achieve the background RO is approximately 150 years, at a cost of approximately $50.2M NPV. Computer modeling also predicts that Alternative 4 would achieve the 80 percent mass removal interim goal in approximately 13 years.

Limitations

The creation of IRZs to treat the impacted groundwater is subject to the same spatial treatment distribution limitations discussed in Alternative 3. These arise from the complex hydrogeology present at the Site, plume size, and variable agricultural pumping, as discussed in detail in Section 4 and Appendix B. In addition, deleterious byproducts such as reduced iron, manganese, and arsenic would likely be generated and would require additional monitoring and management. While plume containment is a fundamental component of this alternative, past containment efforts have been complicated by the complex hydrogeology, plume size, and agricultural pumping in the area.

Similar to Alternative 2, Alternative 4 involves either property purchase and/or easements for additional AUs, as the total flow extracted under hydraulic containment exceeds the maximum annual average discharge rate for the existing DVD AU (520 gpm approved by the LRWQCB). Modifying existing AUs near the toe of the plume is preferred over installation of new AUs in areas not previously used for agriculture as this would reduce the overall cost; however, the addition of new AUs is preferred over other groundwater treatment options because of the long-term cost effectiveness and the beneficial groundwater use inherent in AU treatment. Acquisition of properties and/or easements potentially needed for implementation may be difficult or take considerable time.

6.2.5 Plume-Wide Pump and Treat (Alternative 5)

Conceptual Approach

Plume-Wide Pump and Treat (Alternative 5) was developed to address the ROs of Section 5 with plume containment and ex-situ treatment to reduce contaminant mass while providing supplemental containment through recharging the treated groundwater to the periphery of the plume. Figure 6-5 illustrates the general configuration of Alternative 5. This alternative provides a similar level of hydraulic containment as Alternative 2, although with a differing groundwater withdrawal configuration. This configuration accomplishes both plume containment and core mass reduction, as opposed to the containment-only approach provided in Alternative 2. The goal of this configuration is to achieve rapid reduction of Cr(VI) concentrations in the plume core and to re-establish the 50 μg/L chromium MCL RO.

Implementation Details

As shown in Figure 6-5, the conceptual approach for Alternative 5 includes extraction wells located within the toe of the plume (similar to Alternative 2) plus additional groundwater extraction in the vicinity of the Source Area/SCRIA. Additional extraction wells would be installed as needed to establish pumping zones in both the core and toe of the plume. Approximately 1000 gpm would be extracted, with individual flows varying by well location and hydrogeologic constraints. The extracted groundwater would be piped to one or more on-Site, ex-situ treatment facilities.

Multiple ex-situ treatment technologies exist for Cr(VI) in water. Based on the technology screening, the work described in Section 4, and the screening evaluation summarized in Section 6.1, three technology process options were selected for final screening; they are chemical reduction/precipitation, MBfR, and ion exchange. Chemical reduction/precipitation is a common method applied to CrVI water treatment, and is used successfully at PG&E's Topock site. Ion exchange and MBfR have been evaluated and may be potentially applicable to the lower concentration portions of the Site but they currently exhibit greater performance uncertainty. Therefore, for the purpose of costing Alternative 5 in this FS, chemical reduction/precipitation was the assumed method of ex-situ water treatment based on the proven nature of this technology. Additional study (including potential bench-scale studies or other work) may be advisable to further refine the method of treatment if Alternative 5 is selected.

The groundwater would be treated to promote reduction of Cr(VI) to Cr(III), which has extremely low solubility and would precipitate out of the solution. Following treatment, the water would be filtered to remove precipitated metals, reinjected into the aquifer via injection wells installed along the perimeter of the plume, and provide supplemental plume hydraulic control. The treatment residue left on the filter would be managed and disposed of at an appropriate facility.

Additional hydraulic control northwest of the plume would come from freshwater injections as required. Fresh water from an extraction well located upgradient of the Site would be pumped to the boundary of the plume into injection wells on an as-needed supplemental basis. The freshwater injection, together with the withdrawal near the toe of the plume, is intended to supplement extraction to contain the plume and minimize drawdown of the aquifer, only on an as-needed basis.

Implementation of Alternative 5 is likely to require the acquisition of additional properties and/or easements within the Project Area. These acquisitions could be both inside and outside the Remedial Area and would be for installation and maintenance of remedy infrastructure. Groundwater use on acquired properties would be restricted to non-potable use as appropriate for the duration of the remedy.

Over time, optimization of the initial system would include modifications to the location and number of extraction wells to target select areas of the plume core or periphery.

Estimated Time Frame and Cost to Reach Background

Computer modeling of this alternative suggests that chromium concentrations throughout the plume decline at about the same rate, and that the plume would contract inward toward the extraction centers. Alternative 5 is projected to achieve the 50 μg/L chromium MCL RO in approximately 50 years. Because Site background concentrations are so low, the model-estimated time frame to achieve the background RO is approximately 140 years, at a cost of approximately \$218M NPV. Computer modeling also predicts that Alternative 5 would achieve the 80 percent mass removal interim goal in approximately 37 years.

Limitations

While this alternative extracts groundwater from the entire plume, treatment facilities require significant infrastructure and frequent operation and maintenance visits. Further, treatment plant water quality discharge criteria below background concentrations would not be reliable. Compared to other water treatment methods such as agricultural application, costs tend to be higher. Modeling suggests that pump and treat is expected to be less effective at reducing the plume core to background conditions than other technologies such as in-situ reduction. While plume containment is a fundamental component of this alternative, past containment efforts have been complicated by the complex hydrogeology, plume size, and variable agricultural pumping in the area. Alternative 5 reinjects treated groundwater and therefore does not use it for beneficial purposes. Acquisition of properties and/or easements potentially needed for implementation may be difficult or take considerable time.

6.3 Comparative Analysis of Alternatives

The goal of the comparative analysis is to evaluate the five alternatives relative to the requirements established in Resolution No. 92-49, Part III.C, and the derived Site-specific ROs defined in Section 5. A selected alternative is required to satisfy the following key criteria: effectiveness, feasibility (implementability), and cost. The ROs defined in Section 5 are all included within the effectiveness criterion. This section discusses how each alternative performs relative to these three key evaluation criteria. Tables 6-3 and 6-4 provide a summary comparison of the five alternatives.

6.3.1 Effectiveness

Effectiveness measures an alternative's ability to satisfy the requirements of the CAO, ROs, and Resolutions 68-16 and 92-49. Specifically, the alternatives are evaluated on the relative ability to satisfy the following measures of effectiveness:

- **Achieve Background Conditions for Chromium:** Cleanup to background conditions refers to the ability of the alternative to achieve background chromium concentrations within the limits of the Remedial Area in a reasonable time frame. Background values for this evaluation are specifically defined in Section 2. Given the long time frames to achieve the background RO, the estimated time to achieve the interim goal of reducing 80 percent of the Cr(VI) mass in the Remedial Area is also presented.
- **Restore Beneficial Use:** Re-establishment of the beneficial use designation relative to chromium impacts in groundwater, based on the achievement of the chromium MCL.

Alternatives were evaluated against their ability to achieve this level of cleanup within a reasonable time frame.

- **Chromium Plume Containment:** Containment is defined as: no further migration or expansion of the Cr(VI) plume outside the defined Project Area (as defined in Section 5). This includes the area inside the 3.1 μg/L Cr(VI) contour (Figure 6-2) plus an external buffer zone that considers some plume edge vacillation caused by local and regional hydrological influences. Alternatives will be evaluated against their ability to achieve plume containment.
- **Productive Use of Groundwater Resource:** The groundwater remediation process to achieve the 50 μg/L chromium MCL RO is anticipated to take a decade or more. This objective was included to maintain the highest possible productive use of groundwater during the treatment period, given the combined chromium and historical agricultural impacts (e.g., TDS and nitrate). Under these conditions, it is assumed that this use will be agricultural irrigation. Sustainability aspects are also included as part of this evaluation. Alternatives were evaluated against their ability to productively use or accommodate the use of groundwater beyond those intended solely for remediation, and their ability to lower the carbon footprint of the project.

Table 6-4 provides a summary table of the comparative effectiveness, implementability, and cost of the selected alternatives.

6.3.1.1 No Further Action (Alternative 1)

The No Further Action alternative was included in this analysis and was evaluated consistent with standard recommended practices (USEPA 2000); however, this alternative does not address containment, mass reduction, or (where concentrations exceed the chromium MCL) beneficial use. A discussion of the alternative components was presented in Section 6.2.1; the following is a discussion of how Alternative 1 performs relative to the four measures of effectiveness. Table 6-4 provides a summary the alternative's effectiveness, implementability, and cost.

- *Cleanup to Background Conditions for Chromium*: Alternative 1 would not provide plume containment or target the plume core. Fate and transport modeling suggests that achieving background chromium concentrations would take over 1000 years. With no active containment or source treatment, Alternative 1 exhibits a low likelihood of achieving this criterion.
- *Restore Beneficial Use:* Alternative 1 would not reduce the footprint of Cr(VI) mass in the plume core, where concentrations exceed the chromium MCL in a reasonable time frame. In fact, the lack of plume core treatment in Alternative 1 may result in an expansion of the plume core area. Fate and transport modeling suggests that achievement of the chromium MCL would take over 1000 years. As a result, Alternative 1 has a low ability to restore the beneficial use.

- *Chromium Plume Containment:* Alternative 1 would not provide plume containment because no pumping is performed.
- *Productive Use of Groundwater Resource:* Alternative 1 does not pump groundwater; therefore, no agricultural or other productive use would be realized.

6.3.1.2 Containment (Alternative 2)

The primary goal of the Containment Alternative (Alternative 2) is plume containment. A detailed discussion of the alternative components was presented in Section 6.2.2; the following is a discussion of how Alternative 2 performs relative to the four measures of effectiveness. Table 6-4 provides a summary table of effectiveness, implementability, and cost.

- *Cleanup to Background Conditions for Chromium*: Alternative 2 is a containment-only option that does not target the plume core. Fate and transport modeling suggests that achieving background chromium concentrations would take 260 years. Given this long time frame, Alternative 2 exhibits a low likelihood of achieving this criterion. This low achievement ranking is significantly improved when the 80 percent Cr(VI) mass removal interim goal of 95 years is factored in. The significant time difference between achieving 80 percent Cr(VI) mass removal and background chromium conditions highlights the difficulty of removing the final 20 percent of the Cr(VI) mass.
- *Restore Beneficial Use:* Alternative 2 contains the plume but does not reduce the footprint of Cr(VI) mass in the plume core, where concentrations exceed the chromium MCL, in a reasonable time frame. As a result, Alternative 2 has a low to moderate ability to restore the beneficial use. Alternative 2 does not significantly reduce diffuse plume Cr(VI) concentrations or the plume footprint in a reasonable time frame. Fate and transport modeling suggests that achievement of the chromium MCL would take about 120 years. Additionally, the pumping of groundwater and treatment within AUs will result in aquifer mixing and localized changes in TDS and nitrate concentrations, including potential increases that exceed drinking water standards.
- *Chromium Plume Containment:* The primary intent of Alternative 2 is to achieve a robust level of plume containment. Modeling results indicate that Alternative 2 would establish hydraulic control at the plume boundaries and effectively contain the plume. Modeling also suggests that the greatest hydraulic control over the plume is developed when AUs are located just outside the toe of the plume in the Project Area.
- *Productive Use of Groundwater Resource:* Alternative 2 would apply extracted groundwater to agricultural fields for Cr(VI) reduction and treatment. The application of the extracted groundwater for treatment within the AUs would produce livestock fodder crops, thus benefitting the local farming community and using the resource for its current highest productive use (given the historical agricultural impacts of nitrates and TDS). Use of groundwater in this

manner is beneficial to water supply in the basin as it uses an otherwise marginal or unusable resource for agricultural crop production (as opposed to using higher quality fresh imported water or deep aquifer water for fodder crop production).

6.3.1.3 *Plume-Wide In-Situ Treatment (Alternat*ive 3)

Plume-Wide In-Situ Treatment (Alternative 3) primarily consists of extracting groundwater to achieve containment and amending the extracted water with carbon before reinjection to reduce Cr(VI) mass while managing hydraulic containment. A detailed discussion of this alternative was presented in Section 6.2.3; the following is a discussion of how Alternative 3 performs relative to the four measures of effectiveness. Table 6-4 provides a summary table of effectiveness, implementability, and cost.

- *Cleanup to Background Conditions for Chromium:* Alternative 3 primarily involves the use of IRZ methods plume-wide, targeting Cr(VI) mass in source and lower concentration areas. This alternative also involves significant withdrawal and recirculation flows at the northern diffuse portion of the plume for containment and to produce the water necessary for IRZ carbon amending and injection. High groundwater extraction and recirculation rates, combined with aggressive plume core treatment, results in one of the lowest estimated treatment time frames. As discussed in the limitations of this alternative, effective plume-wide reduction of Cr(VI) concentrations to background conditions depends upon the distribution of carbon amendment during IRZ treatment. Because of the plume size and complex hydrogeology, complete distribution will be difficult to accomplish in some portions of the plume. Because of the plume size and aquifer heterogeneity, it is likely that some portions of the aquifer will not reach background chromium concentrations. Fate and transport modeling of this alternative suggests that background concentrations could be achieved plume-wide in 110 years. Based on this evaluation, Alternative 3 exhibits a moderate likelihood of achieving this criterion. This moderate ranking is further improved when the interim 80 percent Cr(VI) mass removal interim goal of 10 years is factored in (the shortest duration of the evaluated alternatives). The significant time difference between achieving 80 percent Cr(VI) mass removal and background chromium concentrations highlights the difficulty of removing the final 20 percent of the Cr(VI) mass and achieving background concentrations.
- *Restore Beneficial Use:* Alternative 3 specifically uses IRZ treatment to contain the Cr(VI)-impacted groundwater and focuses on mass reduction across the entire plume. Through treatment, the chromium MCL RO is achieved and all chromium-related impacts to the beneficial uses of the aquifer are removed. This alternative reduces the contaminant mass and footprint of the plume in a comparatively rapid time frame. Fate and transport simulations suggest that Alternative 3 could restore the aquifer to the chromium MCL in approximately 8 years. However, pilot test results show that the use of plume-wide IRZ treatment in Alternative 3 would generate a larger distribution of by-products such as arsenic, iron, and manganese that would once again restrict beneficial

uses of the aquifer. Extensive plume-wide use of IRZ treatment would also likely result in the formation of iron, manganese, and arsenic byproducts which may remain in portions of the aquifer for some period of time at concentrations above drinking water standards. While these byproducts are not expected to persist in the aquifer, their presence may reduce future productive uses of groundwater while they are present.

- *Chromium Plume Containment:* Alternative 3 was developed to achieve a similar level of plume containment as Alternative 2 (Containment), thus addressing the containment requirements as defined in the CAO and Resolutions 68-16 and 92-49. The key difference between Alternatives 2 and 3 is the way extracted groundwater is managed. Alternative 3 focuses on intra-plume circulation/treatment cells (IRZs), while Alternative 2 incorporates AUs located at the toe of the plume. Like Alternative 2, Alternative 3 injects a limited volume of fresh groundwater at one or more key perimeter locations to further support plume containment in this direction. Fate and transport modeling results indicate that this alternative would effectively contain the plume.
- *Productive Use of Groundwater Resource*: Alternative 3 involves the use of extracted and carbon-amended groundwater to treat wide areas of the plume. Unlike Alternative 2, Alternative 3 does not use AUs for water treatment; therefore, it does not aid in production of agricultural crops and does not directly utilize water for agricultural benefit like Alternatives 2 and 4. From a sustainability perspective, no agricultural crop production is enhanced; however, Alternative 3 recycles 100 percent of the extracted water through direct reinjection, thus minimizing groundwater basin drawdown. As stated above, plume-wide use of IRZ treatment will likely result in the formation of iron, manganese, and arsenic byproducts. While these byproducts are not expected to persist in the aquifer, their presence may reduce future productive uses of groundwater while they are present.

6.3.1.4 Plume Core In-Situ Treatment and Beneficial Agricultural Use (Alternative 4)

Core In-Situ Treatment and Beneficial Agricultural Use (Alternative 4) applies a combination of technologies to contain and treat the plume to reduce its mass, while incorporating productive use of extracted groundwater to facilitate agriculture in the Site vicinity. This alternative applies effective technologies to areas where they would to be the most productive while producing the least amount of negative impacts. A detailed description of Alternative 4 is presented in Section 6.2.4; the following is a discussion of how Alternative 4 performs relative to the four measures of effectiveness. Table 6-4 provides a summary table of effectiveness, implementability, and cost.

- *Cleanup to Background Conditions for Chromium*: Alternative 4 targets the treatment of Cr(VI) concentrations that are greater than the MCL via in-situ reduction and uses AU treatment to treat water generated as part of hydraulic containment of the plume. Specifically, this alternative incorporates the Central Area IRZ, Source Area IRZ, and SCRIA IRZ (expanded from their current configurations). Fate and transport modeling suggests that plume-wide background chromium conditions would be achieved in about 150 years. However, because of the plume size and aquifer complexity, there is the potential that portions of the aquifer would be recalcitrant to IRZ treatment and result in areas that would not achieve background chromium conditions as currently defined. As a result, Alternative 4 exhibits a moderate likelihood of achieving this criterion. The cleanup time frame to achieve background conditions is substantially improved when one considers that the 80 percent Cr(VI) mass removal interim goal is predicted to be achieved in 13 years (the second shortest duration of the evaluated alternatives). The significant time difference between achieving 80 percent Cr(VI) mass removal and background highlights the difficulty of removing the final 20 percent of the Cr(VI) mass and achieving background chromium concentrations.

- *Restore Beneficial Use*: Alternative 4 combines AUs and IRZs to contain the plume, reduce Cr(VI) concentrations/mass, and reduce the Cr(VI) footprint. Specifically, Alternative 4 focuses on Cr(VI) mass reduction by aggressive IRZ treatment in the plume core to achieve the chromium MCL RO and restore beneficial use as quickly as possible. Use of IRZ treatment within the plume core in Alternative 4 will likely result in the localized formation of iron, manganese, and arsenic byproducts within the plume core. These byproduct concentrations may exceed drinking water standards. While these byproducts are not expected to persist in the aquifer, they will reduce the beneficial use of groundwater while they are present in concentrations that exceed drinking water standards. Alternative 4 will attempt to minimize the production of secondary byproducts and restrict their generation to areas near the plume core (away from nearby domestic users). Specifically, this alternative incorporates the Central Area IRZ, Source Area IRZ, and SCRIA IRZ (expanded from their current configuration). Containment and reduction of Cr(VI) concentrations in the toe of the plume will be accomplished through extraction and treatment via agricultural application to AUs. Fate and transport simulations suggest that Alternative 4 would restore the aquifer to the chromium MCL in approximately 6 years.
- *Chromium Plume Containment:* The groundwater extraction configuration of Alternative 4 was developed to exhibit a similar level of containment to Alternative 2 (Containment). The majority of groundwater extracted from the toe of the plume will be applied to AUs for Cr(VI) treatment, while the remainder will be extracted, amended with carbon, and injected inside the plume to reduce plume mass and footprint, targeting areas of higher Cr(VI) concentration. Similar to Alternatives 2 and 3, Alternative 4 includes the limited injection of fresh groundwater into the northwest side of the plume to further improve containment in that direction. In addition, three extraction wells would be located east of the SCRIA to improve plume capture and reduce cleanup duration. To evaluate the effectiveness of this alternative on plume containment, a groundwater fate and transport model was used to evaluate the plume containment characteristics. Modeling results indicate that Alternative 4 establishes robust hydraulic influences over the plume boundaries and is

anticipated to effectively contain the plume. Modeling also suggests that the greatest hydraulic control over the plume is developed when AUs are located just outside the toe of the plume within the Project Area.

- *Productive Use of Groundwater Resource:* Aggressive core treatment combined with plume containment and agricultural application results in the highest productive use of groundwater for the alternatives considered in this FS. Through this treatment approach, Site groundwater would be used at its highest current productive use, agricultural application and fodder crop production. The agricultural application is also beneficial to water supply in the basin because it uses an already marginal or unusable resource (nitrate/TDS) for crop production instead of the need for local farmers to import fresh water for the same fodder crop. This is especially important if other fodder crop farming operations could be relocated to this area and use Site water. The use of plume core IRZ treatment will likely result in the localized formation of iron, manganese, and arsenic byproducts. Since these byproducts are not expected to persist in the aquifer and plume core groundwater is not proposed to be used in AUs, their presence is not expected to reduce the productive use of groundwater in this alternative.

6.3.1.5 Plume-Wide Pump and Treat (Alternative 5)

The Plume-Wide Pump and Treat Alternative (Alternative 5) involves the extraction and ex-situ treatment of groundwater to establish containment and reduce contaminant mass in the aquifer over time. A detailed discussion of this alternative was presented in Section 6.2.5; the following is a discussion of how Alternative 5 performs relative to the four measures of effectiveness. Table 6-4 provides a summary table of effectiveness, implementability, and cost.

- *Cleanup to Background Conditions for Chromium:* Alternative 5 incorporates Cr(VI) mass reduction in the form of extracting groundwater near the Source Area as well as the more dilute northern diffuse portions of the plume. Aggressive Cr(VI) mass reduction is not a primary characteristic of pump and treat approaches and Alternative 5 pump and treat type remedies generally exhibit slower overall rates of remediation due to the nature of this approach compared to other more focused active remedies that target zones of higher chromium concentrations. Fate and transport modeling suggests that achieving background chromium concentrations could potentially occur in approximately 140 years. Because of the plume size and aquifer complexity, there is the potential for areas or vertical zones to be recalcitrant to treatment and therefore not achieve background chromium conditions as currently defined. As a result, Alternative 5 exhibits a low to moderate likelihood of achieving this criterion. This low to moderate achievement ranking is further reduced when the interim 80 percent Cr(VI) mass removal threshold of 37 years is factored in. This is the longest duration among the alternatives considered to achieve the 80 percent mass removal threshold of the aggressive alternatives (Alternatives 3, 4, and 5) considered. The significant time difference between achieving 80 percent

Cr(VI) mass removal and background highlights the difficulty of removing the final 20 percent of the Cr(VI) mass and achieving background concentrations.

- *Restore Beneficial Use:* Alternative 5 provides containment of the Cr(VI)-impacted groundwater and reduces the Cr(VI) mass and plume footprint. Aggressive source mass reduction is not the primary characteristic of Alternative 5. Since Cr(VI) removal and mass reduction are primarily through extraction and ex-situ treatment versus aggressive in-situ treatment of the plume core, achievement of the 50 μg/L chromium MCL RO is estimated to take 50 years based on fate and transport modeling. Thus, Alternative 5 provides a lower level of beneficial use restoration compared to Alternatives 3 and 4, but better than Alternative 2.
- *Chromium Plume Containment:* The location of the extraction well network for Alternative 5 differs from other alternatives, but was developed to attain a similar level of containment as Alternative 2. Also similar to Alternative 2, Alternative 5 injects a limited volume of fresh groundwater into the northwest side of the plume to further support containment in this area. To evaluate the effectiveness of this alternative on plume containment, a groundwater fate and transport model was used to evaluate plume hydraulic control. Modeling results indicate that Alternative 5 establishes hydraulic control over the plume footprint and is anticipated to effectively contain the plume.
- *Productive Use of Groundwater Resource:* Alternative 5 does not use AUs for the water treatment; therefore, it does not maximize the productive agricultural use of the resource like Alternatives 2 and 4. As a result, Alternative 5 exhibits a low to moderate likelihood of achieving this criterion. From a sustainability perspective, Alternative 5 recycles nearly 100 percent of the extracted water through direct reinjection, thus minimizing groundwater basin drawdown.

6.3.2 Implementability

Implementability is defined by how readily constructed and technically feasible the alternative is considering Site-specific factors that may affect constructability of the alternative, technical complexity of the alternative, administrative feasibility (e.g., availability of property, permitting), availability of services and materials to implement the alternative, and other relevant implementability considerations.

6.3.2.1 No Further Action (Alternative 1)

The No Further Action Alternative is easily implemented from a constructability standpoint as this alternative requires no further action. This alternative does not address the requirements in the CAO or Resolutions 68-16 or 92-49, and is included as a basis for comparing other active alternatives.

6.3.2.2 Containment (Alternative 2)

The Containment Alternative is relatively easy to implement as this approach uses some existing infrastructure and additional monitoring wells and AUs to treat the extraction flow rate to achieve the desired level of hydraulic control and containment. This alternative applies technologies currently used at the Site and is reasonably flexible to adjustments of the extraction well network to improve containment if needed.

For this alternative to be effective from an implementability standpoint, it is assumed that additional AUs can be constructed near/outside the toe of the plume as flood or drip operations to meet the additional treatment/discharge demand. It is also assumed that clean groundwater suitable for clean water injection in the northwest area is available. Potential challenges for implementing this alternative relate to accessing the non-PG&E owned property needed for extraction wells, pipelines, or AUs.

Overall, this alternative is easy to implement.

6.3.2.3 Plume-Wide In-Situ Treatment (Alternative 3)

The Plume-Wide In-Situ Treatment Alternative is difficult to implement. While this alternative uses IRZs, a technology already field tested at this Site, this alternative utilizes an extensive and complicated network of piping to extract, amend, and distribute the carbon-amended water for reinjection plume-wide. This alternative also requires equipment installation/expansion for the carbon-amending system, more rigorous operation and maintenance and process control systems, coordinating the delivery of carbon for IRZs, potential bio-fouling mitigation, deleterious byproduct formation, and other technical challenges inherent to IRZ approaches on the scale and magnitude of Alternative 3 (as discussed in Section 4 and Appendices B and C). This alternative is somewhat flexible insofar as adding or relocating extraction/injection wells and is relatively straightforward; however, major changes, if required, may involve significant piping infrastructure and related control systems.

Permitting for Alternative 3 would likely be accomplished through an amended version of the existing General Permit. Additional provisions would be added for the expanded IRZ injection areas as appropriate. Provisions for the treatment of water via the DVD LTU or other AUs as appropriate would be removed.

Overall, this alternative is difficult to implement.

6.3.2.4 Core In-Situ Treatment and Beneficial Agricultural Use (Alternative 4)

The Core In-Situ Treatment and Beneficial Agricultural Use Alternative is moderately easy to implement. It consists of technologies already being used at the Site and applies them in areas proximate to existing treatment areas (DVD AU, Gorman AUs, Central Area IRZ, Source Area IRZ, and SCRIA IRZ) and expands on these approaches. Specifically, Alternative 4 combines major elements from Alternative 2 with a more modest scale version of the IRZ program for plume core treatment compared to Alternative 3. Therefore, the challenges inherent to Alternative 3 apply to this alternative but at a smaller scale. This is because the scope of IRZ for Alternative 4 capitalizes on a large portion of the existing infrastructure at the Site, with moderate expansion of certain remediation components by adding wells to improve carbon distribution. The primary challenge to implementation would be establishment of new AUs outside the toe of the plume within the Project Area on property not currently owned by or under access agreement with PG&E.

Similar to Alternative 2, Alternative 4 is anticipated to consist of a modification to the General Permit. A modification/simplification of the agricultural treatment permit process and a modification of the monitoring program consistent with the other agricultural application processes are critical to cost-effective implementation of this approach.

Overall, this alternative is moderately easy to implement.

6.3.2.5 Plume-Wide Pump and Treat (Alternative 5)

The Plume-Wide Pump and Treat Alternative is very difficult to implement. Similar to Alternative 3, Alternative 5 involves an extensive new piping network to collect extracted groundwater, deliver it to an ex-situ treatment plant, and distribute treated water to an injection well network spread across the plume. Therefore, Alternative 5 shares several implementability challenges with Alternative 3.

This alternative includes a large ex-situ treatment plant consisting of a treatment train with multiple process units. The operations for the ex-situ treatment system require a far more intensive and complicated operation and maintenance program to maintain system performance and operation (e.g., system adjustments, material delivery coordination, equipment maintenance, well rehabilitation, and waste management) compared to the other alternatives.

Similar to other alternatives, potential challenges to implementing this alternative relate to access to non-PG&E owned property needed for extraction, injection, conveyance, or treatment systems.

Permitting of Alternative 5 would likely be accomplished through an amended version of the existing General Permit. Provisions for the treatment of water via the DVD LTU or other AUs as appropriate would be removed. Provisions in the General Permit for operation of the IRZs and their associated monitoring programs would be removed and replaced with more conventional WDR groundwater reinjection and monitoring provisions.

Overall, this alternative is very difficult to implement.

6.3.3 Cost

The development of representative costs for each of the alternatives considered utilized the United States Environmental Protection Agency guidance for preparing feasibility studies (USEPA 2000). Quantities and unit costs were selected based on contractor experience both at the Hinkley Site and at other sites with similar impacts and subsurface conditions. Primary assumptions or considerations that were taken into account in the preparation of the alternative costs include:

- Costs were based on 2010 values;
- Future capital and O&M costs were adjusted using a discount value of 3.17 percent, which accounts for inflation;
- A 20 percent contingency was used on capital costs and a contingency of 10 percent was used on O&M costs, based on engineering judgment; and
- Remedy durations to meet the key ROs for each alternative were estimated through the use of fate and transport modeling simulations.

Based on these assumptions, the costs presented have an approximate expected accuracy range of -30 percent to +50 percent. Table 6-3 summarizes the estimated time frame to reach the 50 μg/L chromium MCL, 80 percent mass removal, and background, as well as the NPV cost estimate to reach background for each of the five alternatives. A detailed explanation and breakdown of the alternative cost estimates is presented in Appendix D (Remedial Alternatives Cost Estimates). The resultant estimated costs for each of the alternatives are:

- Alternative 1 costs are $0;
- Alternative 2 costs are $36M;
- Alterative 3 costs are $130M;
- Alternative 4 costs are $50.2M; and
- Alternative 5 costs are $218M.

6.3.4 Alternative Selection Summary

Based on the Site remediation history to date, technology screening, alternative descriptions, and evaluation and comparative analysis presented above, Alternative 4 best meets the FS evaluation criteria. Alternative 4 has the highest potential to:

- Achieve background conditions in one of the shortest time frames;
- Achieve 80 percent mass removal in a reasonable time frame, approximately 13 years;
- Restore beneficial use (reduce chromium concentrations to levels below the MCL) in the shortest time frame (less than 10 years);
- Contain the plume;
- Make productive use of groundwater during remediation, via agricultural irrigation;
- Be implemented more easily, including the potential for a more rapid full deployment; and
- Have a reasonable cost that balances cost with RO achievement.

Because Alternative 4 leverages Site-proven and currently operating technologies and methods, implementability is the least complicated and most certain among the options. Estimated costs are also the lowest among the alternatives considered to treat the entire plume (Alternatives 3, 4 and 5), due to the shortest projected time frames to achieve the ROs and the use of existing systems and infrastructure. Table 6-4 presents a comparative evaluation of each of the screening criteria presented in Section 6.3. The estimated remediation time frames are reasonable for the following reasons:

- Very low background concentrations;
- Large plume;
- Complex hydrogeology and Site conditions;
- Groundwater would quickly meet MCL/beneficial use criterion;
- Plume would be contained;
- Groundwater would productively be used for agriculture;
- Remedy assists in containing/removing nitrate; and
- Potentially quicker plume remediation using other alternatives results in more undesirable byproducts.

For these reasons, Alternative 4 is the preferred selection for the final Site remedy. Critical for implementation of Alternative 4 would be development of a permitting and monitoring program that balances regulatory needs with the agricultural approach and operational conditions the alternative relies upon. Section 7 discusses the conceptual implementation of this alternative.

7. RECOMMENDED REMEDIAL ACTION ALTERNATIVE

Based on a comprehensive evaluation of regulatory requirements, Site conditions, and available remedial technologies, PG&E recommends Alternative 4, Core In-Situ Treatment and Beneficial Agricultural Use, as the final remedy. Alternative 4 represents the best balance of technologies to meet the groundwater ROs of cleanup to background chromium conditions in a reasonable time frame, restoring the beneficial use (meeting the chromium MCL) of the impacted aquifer, containing the plume, and productively using the groundwater resource for its highest and best use during remediation. This alternative incorporates all of the Site-specific remedial testing and experience to address the plume containment and mass reduction ROs, using a combination of treatment technologies that not only reduce contaminant mass in a reasonable time frame but productively uses extracted groundwater.

Benefits of Alternative 4 include:

- Proven effectiveness for both agricultural application (northern diffuse plume) and IRZ treatment of the plume core;
- Robust plume containment;
- Rapid/Focused treatment of the plume core to meet the chromium MCL within 10 years of startup;
- Long-term plume treatment in an attempt to achieve background levels for chromium;
- Productive use of extracted groundwater for agricultural purposes (the highest beneficial use, considering the TDS and nitrate levels, a legacy of historical agriculture);
- Groundwater would be recharged back into aquifer, minimizing drawdown;
- Reduction (via removal and treatment) of nitrates in the groundwater;
- Minimal use of imported fresh water that could be used for other purposes;
- A small visual footprint that improves local project aesthetics;
- A sustainable approach that minimizes energy usage by not operating larger water treatment plants or moving large volumes of water across the entire plume; and
- A sustainable supplement of agriculture to the area.

The advantages of Alternative 4 over the other alternatives include:

- In comparison to Alternative 1 (No Action), Alternative 4 includes active treatment and control of the plume to meet the ROs. Alternative 1 allows the plume to migrate uncontrollably, and would not meet the ROs.
- Alternative 4 directly treats the chromium mass, reducing it more rapidly than Alternative 2.
- In comparison to Alternative 3 (Plume-Wide In-Situ Treatment), the two alternatives have similar estimated remediation time frames. However, Alternative 4 provides a greater productive use of the extracted groundwater through the growth of fodder crops within AUs, does not have the potential to generate widespread production of deleterious byproducts such as iron, manganese, and arsenic (which could require further treatment or mitigation),

significantly reduces the construction and operation and maintenance requirements, and costs far less.

- In comparison to Alternative 5 (Plume-Wide Pump and Treat), Alternative 4 is anticipated to achieve the chromium MCL RO up to 5 times sooner and has a higher likelihood of achieving background conditions more rapidly because of active treatment of the plume core. A primary drawback of Alternative 5 is the need for a large, complex groundwater treatment system. This system would require a sizeable building to house the pumping systems, filtration units, treatment components, and chemicals required for operation. Truck traffic around the Site and treatment building would be needed to deliver materials and pick up wastes generated by the treatment system operation. Alternative 5 would have the worst sustainability rating due to the high energy needs for operation. Lastly, since no AUs would be used for water treatment, there would be no economic benefit to the community from the growth of fodder crops.

Although Alternative 4 (In-Situ Treatment and Beneficial Agricultural Use) is the best alternative for remediation of the plume, it still includes challenges inherent in the remediation of an extremely large plume in a complex hydrogeologic setting. These challenges include:

- **Low Chromium Background Levels:** The low background chromium concentrations present in groundwater in the vicinity of the Site will be difficult for any technology to achieve, especially in a reasonable time frame.
- **Large Plume Size:** The large plume size poses a significant challenge to achieving background concentrations within a reasonable time frame, especially when taken in context with the above discussion regarding aquifer heterogeneity. Remediation experience at the Site indicates that localized treatment to background is possible; however, aquifer heterogeneities such as fine-grained layers/lenses can result in zones of lower treatment efficiency and persisting concentrations of Cr(VI) in excess of background. In an attempt to address this challenge, groundwater modeling will be used to design the initial remediation well field. Data will be collected to evaluate hydraulic flow patterns and optimize Cr(VI) treatment efficiencies. It is recommended that a formal groundwater remedy review process be developed jointly with the LRWQCB and conducted approximately every 5 years.
- **Impacts to Groundwater:** The extensive pumping and reinjection or land application of groundwater would have an averaging effect on TDS concentrations in groundwater. Some areas of the plume would experience reduced TDS concentrations, while other areas will see increases. TDS concentrations will also increase near AUs due to evapotranspiration associated with all agriculture. The use of IRZ treatment for the plume core will likely result in the localized formation of iron, manganese, and arsenic byproducts in excess of drinking water standards. These byproducts are only expected to be produced in the plume core and are not expected to persist,
- **Appropriate and Representative Permitting and Monitoring Program:** Project permits and monitoring programs should be developed to appropriately reflect the type of activities performed. Since the majority of the extracted water is to be treated by agricultural application within AUs and this water already meets the chromium 50 μg/L MCL, AU operations should be regulated like an agricultural operation. This includes identification of a monitoring program commensurate with similar agricultural operations.

The monitoring plan should also be written to recognize that both favorable and potentially unfavorable groundwater changes would occur temporarily during remediation efforts, and that as long as these changes are appropriately managed within the Project Area, reactive mitigation measures should not be necessary. Examples of such conditions include temporary or semi-permanent changes in TDS and IRZ-produced byproducts such as iron, manganese, and arsenic, as well as vacillations in chromium concentrations at the edge of the Remedial Area. Details of the monitoring plan should be jointly developed with the LRWQCB once this FS has been approved and the specifics of the plan included in the final remedy implementation documentation. Lastly, AU operations should use staff and resources that reflect the level of expertise needed for agriculture rather than hazardous material management.

Given these Site conditions and challenges, remediation to background is likely to take several decades. In an effort to keep the groundwater remedy focused on achieving reasonable chromium concentrations, a 5-year remedy progress evaluation review cycle is proposed. Under Resolution 92-49, the groundwater remedial progress will be evaluated against the technical and economic reasonableness criteria, and adjustments to the groundwater remedy will be recommended. If continued treatment to background conditions proves to be unreasonable or infeasible, alternate ROs may be appropriate.

Potential key topics to be reviewed and evaluated during each 5-year performance review cycle include:

- Is the remedy on track to meet ROs in a timely manner?
- Has there been any significant change in local groundwater use that affects remedy?
- Has there been any change in regulatory requirements that would affect ROs?
- Is the monitoring plan appropriate and providing the necessary information?
- Is byproduct formation manageable?
- What remedial modifications should be implemented to improve performance?
- Are ROs reasonably attainable, or should they be modified?

Upon completion of each 5-year review cycle, PG&E would meet with the LRWQCB to discuss the most appropriate path forward to complete the Site clean-up.

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TABLE 6-1
TECHNOLOGY SCREENING MATRIX
PACIFIC GAS AND ELECTRIC COMPANY
HINKLEY, CALIFORNIA

General Response Actions	Remedial Technology Types	Process Options	Descriptions	Primary Screening Comments	Pass Preliminary Screen?	Effectiveness(1)	Ease of Implementability(2)	Relative Cost	Screening Comment	Retain?
No Action	None	Not applicable	No further actions taken.	Included as a baseline.	Yes	See screening comment.	High	None	Retained as a baseline.	Yes
Natural Attenuation	Monitored Natural Attenuation (MNA)	Routine monitoring and attenuation modeling	Natural processes result in concentration reductions. Model groundwater data over time to develop a forecasted timeframe when groundwater meets cleanup criteria and monitor until criteria is met.	MNA is a common technology that may be applicable to natural reduction of Cr(VI).	Yes	See screening comment.	High	Very low	Results of MNA evaluation indicate that portions of the Upper Aquifer have some reductive capacity, which can reduce low levels of Cr(VI) in groundwater. However, the magnitude of this reductive capacity did not appear sufficient for use as a primary component of a plume-wide remedy. May be feasible as a remedy component, but not as a stand-alone technology.	Yes
Institutional Controls	Access and Use Restrictions	Engineered barriers, deed restrictions, purchase property	Various measures to limit certain activities and property uses. For example, install barriers to limit access, administrative measures to limit exposure, purchase properties within and at leading edge of plume, obtain deed restrictions in impacted areas, or similar activity and use limitations.	Approach helps reduce exposure but does not address issues in the CAO or stop the plume migration. Could be used as an interim control measure.	Yes	See screening comment.	Medium	Low to high depending on approach used.	Approach helps reduce exposure if appropriately enforced but does not address issues in the CAO or stop the plume migration. Could be used as an interim control measure. Property easements and/or acquisition may be needed to facilitate access and remedy implementation.	Yes
	Alternative Water Supply	Supply clean water from south of site, new community well, or bottled water	Develop a logistical plan to supply alternative water supply to town and a monitoring program to limit the use of currently impacted domestic groundwater wells. In order to supply clean water from outside of the plume a groundwater piping infrastructure from the new well(s) locations would need to be developed to support the town.	Approach helps reduce exposure but does not address issues in the CAO or stop the plume migration. Could be used as an interim control measure.	Yes	See screening comment.	Low	High	Approach helps reduce exposure if appropriately enforced but does not address issues in the CAO or stop the plume migration. Cost prohibitive due to infrastructure needed.	No
Containment	Capping	Engineered, native soil, imported soil caps	Cover impacted areas with an impermeable cap to mitigate infiltration and aid in GW transport retardation. Various cap technologies could be used including engineered, native soils or imported soil caps.	Due to the limited rainfall in region, influences of area agricultural pumping, and depth of contaminated groundwater, capping the impacted area would have little effect on managing plume migration or mitigating contamination issues.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
	Physical Barriers	Stabilizers, sealants, liners, grout, sheet piling, ground freezing, slurry walls	Install a vertical or horizontal physical barrier that limits the migration of the impacted groundwater; would likely be incorporated in conjunction with a groundwater extraction system.	Barrier could be effective in groundwater containment if used with an appropriate groundwater extraction system, specifically in localized areas. Due to the extent and mobility of the plume along with the required depths, this approach does not warrant additional evaluation.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
	Hydraulic Barriers	Use of extraction/injection wells or trenches to control hydraulic gradient	Groundwater extraction/injection wells are used to control the movement of groundwater and create a hydraulic barrier.	The use of hydraulic barriers is an effective way to control plume migration and would meet requirements established in the CAO with respect to containment issues.	Yes	• Containment	High	Moderate capital cost with low to moderate O&M cost.	The use of hydraulic barriers is an effective way to control plume migration and would meet requirements established in the CAO with respect to containment issues.	Yes
Treatment	In-Situ Biological Treatment	Aerobic bioremediation	An oxidative substrate is added to the subsurface to aerobically degrade the contaminant of concern.	Not applicable for Cr(VI) as this material is already in an oxidized state and needs to be reduced rather than oxidized.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		Anaerobic bioremediation (In-situ reactive zone [IRZ] treatment)	Carbon-amendment (with electron donors) is delivered to the subsurface within the target zone to stimulate anaerobic biodegradation/redox transformation of contaminant of concern. IRZs are established by injection of an organic carbon source such as ethanol or lactate to stimulate the growth of naturally occurring microbes in the subsurface. In turn, the Cr(VI) to trivalent chromium [Cr(III)] conversion occurs through direct microbial reduction and/or indirect chemical reduction by reduced iron and sulfide. Cr(III) is removed from groundwater through precipitation of relatively insoluble chromium hydroxides and iron-chromium hydroxides.	Existing site experience with technology. Cr(VI) reduces to trivalent chromium resulting in reduction of Cr(VI) dissolved mass; this technology is suitable for additional investigation.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Medium	Moderate capital cost, moderate O&M cost.	Viable technology that is implementable with moderate costs. The IRZs established through groundwater recirculation and carbon amendment have proven to be an effective treatment option at the Site. Byproducts may be formed and may require management.	Yes
		Phytoremediation	Plants and their associated rhizospheric microorganisms are used to remove, degrade, or contain contaminants in groundwater.	Groundwater contamination is too deep for this direct application.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
	In-Situ Physical/ Chemical Treatment	Air sparging	Air is injected into the subsurface to volatilize contaminant and enhance aerobic conditions to accelerate aerobic biological remediation of plume.	Air sparging does not work for Cr(VI), which is not volatile and already exists in an oxidized state.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		Electrokinetic treatment	Electrical fields are created by application of low-voltage power to subsurface electrodes to alter redox state. Can be used to immobilize certain constituents in-situ.	This technology has been used to a limited extent in treating Cr(VI).	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	Cost prohibitive due to size of plume.	Typically used in lower-permeability formations and in areas of high contaminant concentrations. The size of the groundwater plume, low concentration of Cr(VI), and relatively high permeability of the aquifer are not well-suited for this technology.	No
		Dual phase extraction	A high-powered vacuum system is applied to simultaneously remove soil vapors, groundwater, and other liquid (i.e., nonaqueous-phase liquid) from low-permeability or heterogeneous subsurface environments.	Cr(VI) is not volatile and this technology has not been proven to reduce Cr(VI) concentrations.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No

TABLE 6-1
TECHNOLOGY SCREENING MATRIX
PACIFIC GAS AND ELECTRIC COMPANY
HINKLEY, CALIFORNIA

General Response Actions	Remedial Technology Types	Process Options	Descriptions	Primary Screening Comments	Pass Preliminary Screen?	Effectiveness(1)	Ease of Implementability(2)	Relative Cost	Screening Comment	Retain?
Treatment (cont.)	In-Situ Physical/ Chemical Treatment	Permeable reactive barriers (e.g., zero-valent iron PRBs) Note: for in-situ IRZ as a "biobarrier," see above	Permeable treatment walls are installed using trenches, fracturing, boreholes, or other means to create a barrier wall across the flow path of a contaminant plume. As groundwater moves through the treatment wall, contaminants are passively removed in the treatment zones by physical and/or chemical processes.	Permeable reactive barriers using iron or other reducing materials can create reducing groundwater conditions resulting in transformation of Cr(VI) to trivalent chromium [Cr(III)].	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	High cost due to depth of contamination.	Generally applicable to Cr(VI), but traditional trench installation methods and depths would be at the high end of technology limits and significant length required reduce technology feasibility. Other methods, such as fracturing or installing boreholes to create the walls, are less effective since these methods do not provide a continuous barrier.	No
		In-Situ air stripping (circulating cells, vacuum vapor extraction)	Air is sparged into the subsurface at a high rate to strip the contaminants of concern out of the groundwater; process also oxidizes the treatment area.	Air stripping does not work for Cr(VI), which is not volatile and already exists in an oxidized state.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		In-Situ chemical oxidation	Injection of an oxidant such has hydrogen peroxide or potassium permanganate to oxidize the impacted areas.	Chemical oxidation has not been proven to reduce Cr(VI) concentrations since it already exists in an oxidized state.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		In-Situ chemical reduction (abiotic)	Chemical reagents(s) such as calcium polysulfide, dithionite, etc. capable of acting as a reducing agent (i.e., electron donor) are injected into the subsurface to promote in-situ reduction of Cr(VI).	Technology has been used at other sites to reduce Cr(VI) concentrations in situ.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Medium	Moderate capital cost, moderate O&M cost.	Potentially viable technology that may be implementable with moderate costs, although chemical handling issues and anticipated small radius of influence relative to large plume area reduce its feasibility as a stand-alone treatment alternative. Byproducts may be formed and may require management.	Yes
	In-Situ Thermal Treatment	Steam injection, 6-phase heating, electrical resistance	Heat is used to volatilize, oxidize, or mobilize the contaminant of concern.	Not applicable for Cr(VI) as this material needs to be reduced and is not volatile.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
	Ex-Situ Biological Treatment	Aerobic bioremediation	An oxidative substrate is added to a bioreactor to aerobically degrade the contaminant of concern.	Not applicable for Cr(VI) as it is already in an oxidated state and needs to be reduced.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		Anaerobic bioreactor (membrane biofilm reactor [MBfR])	Contaminants and electron donors are combined in a bioreactor to stimulate anaerobic biodegradation or redox changes. The MBfR process uses hydrogen as the electron donor, to develop a biofilm of indigenous bacteria on hollow filter membranes in an ex-situ reactor. As groundwater is moved through the reactor, the Cr(VI) that comes in contact with the biofilm serve as electron acceptors, and is reduced.	May be applicable to reduce Cr(VI).	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	Moderate capital cost, moderate O&M cost.	Potentially viable technology for lower Cr(VI) concentration pending further bench/pilot studies. Unsuccessful for higher concentration Cr(VI) based on bench study, therefore, not considered a primary water treatment technology candidate.	Yes
		Agricultural application (land application)	Plants and soil with their associated rhizospheric (root zone) microorganisms are used to remove, degrade, or contain chemical contaminants in groundwater applied for irrigation. Reduction of Cr(VI) through interaction with electron donors in soil and organic matter; uptake and reduction by plant roots; adsorption onto colloids and organic matter followed by micorbial reduction; complexation with organic functional groups involved in reduction.	Existing site experience with technology. Potential component of Cr(VI) treatment.	Yes	• Achieve Background • Restore Beneficial Use • Containment • Productive Use	High	Low to moderate capital cost with low O&M cost.	Viable technology that is implementable with low/moderate costs. Agricultural land application technology has been highly effective in treating plume groundwater at site. May generate TDS/nitrate condition in groundwater that may require management.	Yes
	Ex-situ Physical/ Chemical Treatment	Chemical oxidation	Groundwater is extracted from the subsurface and an oxidant such as hydrogen peroxide or potassium permanganate is introduced to the flow to oxidize the impacted groundwater.	Not applicable for Cr(VI) as this material is already in an oxidated state and needs to be reduced.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		Chemical reduction/ precipitation	Dissolved contaminants are transformed into an insoluble solid, facilitating the contaminant's subsequent removal from the liquid phase by sedimentation or filtration. Usually uses pH adjustment, addition of a chemical precipitant, and flocculation.	Potential component of ex-situ Cr(VI) treatment system.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	Moderate to high capital cost with moderate to high O&M cost.	Potentially viable technology that is implementable, although construction and operating costs are generally moderate to high.	Yes
		Air stripping	Extracted water is passed through an air stripper to strip the contaminant of concern from the groundwater to the air.	Cr(VI) is not volatile and therefore will not strip out of water; technology has not been proven for Cr(VI).	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		Filtration	Solid particles are isolated/removed by running a fluid stream through a porous medium or filter bag. The driving force is either gravity or pressure across the filtration medium.	Potential component of ex-situ Cr(VI) treatment system.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	Moderate capital cost, high O&M cost.	Potential component of ex-situ Cr(VI) treatment system.	Yes
		Ion exchange	Ions from the aqueous phase are removed by exchange with another ion on the exchange medium/resin; potentially requires pH adjustment to optimize performance.	Has been used to remove Cr(VI) from liquids. Potential ex-situ Cr(VI) treatment method for consideration.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	High capital cost, moderate O&M cost.	Potential component of ex-situ treatment, although effectiveness of ion exchange with site groundwater has not been evaluated at bench/pilot scale; effect of potential competing ions on treatment effectiveness and cost, as well as potential byproducts from resin use, remains to be determined.	Yes
		Electrocoagulation process	Electricity is passed through iron plates to generate ferrous iron to reduce the chromium and precipitate it from solution. The resulting sludge is settled in a clarifier for disposal.	Technology may be appropriate, but would be harder to manage and offers no clear advantage over chemical dosing; energy intensive.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Low	High capital cost, high O&M cost.	This technology is not likely feasible at the Site due to high capital and O&M costs and the size of the existing diffuse plume and treatment flows; cost prohibitive.	No

TABLE 6-1
TECHNOLOGY SCREENING MATRIX
PACIFIC GAS AND ELECTRIC COMPANY
HINKLEY, CALIFORNIA

General Response Actions	Remedial Technology Types	Process Options	Descriptions	Primary Screening Comments	Pass Preliminary Screen?	Effectiveness(1)	Ease of Implementability(2)	Relative Cost	Screening Comment	Retain?
Treatment (cont.)	Ex-Situ Physical/ Chemical (cont.)	Evaporation technology	Contaminants are concentrated using dry air to evaporate water vapor from contaminated water stream. Water vapor is then condensed and the concentrated water is heated or further concentrated for waste management.	Technology has been used to reduce the volume of Cr(VI) contaminated water; energy consumption is high; potential problems with formation in salt.	Yes	• Achieve Background • Restore Beneficial Use • Containment	Medium	High capital cost, high O&M cost.	This technology is not likely feasible at the Site due to high capital and O&M costs and the size of the existing plume and treatment flows. Reduced groundwater availability for agriculture render technology unattractive.	No
		Liquid-phase carbon adsorption	Groundwater is pumped through a series of canisters or columns containing activated carbon to which dissolved organic contaminants adsorb. Periodic replacement or regeneration of saturated carbon is required.	Generally not applicable to Cr(VI).	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
Discharge/Injection	Injection of Treatment Reagent	Direct push injection of reagent/substrate	Treatment reagent/substrate is injected into temporary injection points.	Potential application method for localized areas for treatment reagent/substrate delivery.	Yes	Delivery mechanism, see screening comments.	High	Depends on approach.	A pilot test of direct push injections was performed at the Site. The distribution of injected amendment throughout target areas was demonstrated to be somewhat unpredictable, and would likely require very close injection spacing, thus limiting the applicability of this technology on a full-scale. The application of this technology may be appropriate on a smaller, more focused scale - depending on local site conditions and/or constraints. Further evaluation and testing would be appropriate prior to implementation.	Yes
	Management of Treated or Untreated Groundwater	Off-Site management at permitted facility	Groundwater is pumped from the plume and piped or shipped to an off-Site treatment facility.	Project area is located in a remote area and no facility is located within a suitable distance for this option considering the plume extent and extraction flows; off-Site disposal would reduce groundwater available to surrounding agricultural operations.	No	Process does not meet primary technical screening and was not evaluated for effectiveness, implementability, and relative cost.				No
		On-Site reuse	Treated and/or untreated groundwater is used on-Site.	Possible option for consideration.	Yes	Water management mechanism, see screening comments.	High	Depends on treatment approach.	Promotes productive use and agricultural operations by retaining water for reuse.	Yes
		Discharge to surface water	Groundwater is treated ex-situ by an approved treatment method then discharged to surface receiving streams.	Possible option for consideration.	Yes	Water management mechanism, see screening comments.	Medium	Moderate capital cost, low to moderate O&M cost.	Preference is to keep water within project boundaries, and return to aquifer if possible.	No
		Discharge to evaporation ponds	Surface impoundments are used to contain treated or untreated groundwater until it evaporates.	Possible option for management of water, though the technology would reduce groundwater available to surrounding agricultural operations.	Yes	Water management mechanism, see screening comments.	Medium	Moderate to high capital cost for new ponds.	Space requirements and reduced groundwater availability for agriculture render technology unattractive; not retained for further evaluation.	No
	Methods of Delivery to Groundwater (see above under Treatment section for agricultural application and IRZ technology summary)	Injection wells	Groundwater is injected into on-Site wells.	Existing site experience with technology. Potential application at this Site. May help flush the groundwater and enhance movement.	Yes	Delivery mechanism, see screening comments.	High	Depends on approach.	Approach is a good option for recirculating treated, including carbon-amended (dosed), or untreated water and for managing containment of plume.	Yes
		Infiltration gallery	Groundwater is injected into on-Site infiltration gallery (e.g., buried perforated piping).	Potential application at this Site. May help flush the groundwater and enhance movement.	Yes	Delivery mechanism, see screening comments.	High	Depends on approach.	Approach may be a good option for applying carbon-amended (dosed) water for treatment or for other water discharge. Supports hydraulic control if located outside or downgradient of contaminant plume in clean/dosed water application scenarios. Minimizes potential TDS impacts.	Yes

NOTES
(1) Effectiveness is evaluated for each process option in terms of four criteria components: achieving background, restoring beneficial use, containment, and productive use. The main effectiveness criteria component(s) addressed by each particular process option is/are listed.
(2) Ease of implementability is evaluated in this table for the specific process option on a stand-alone basis (i.e., the discrete technology element). Table 6-4 evaluates the Ease of Implementability for the combined alternatives, which may include one or more discrete process options.
High - Alternative easy to implement.
Medium - Alternative moderately difficult to implement.
Low - Alternative difficult to implement.

TABLE 6-2
COMBINED RETAINED TECHNOLOGIES
PACIFIC GAS AND ELECTRIC COMPANY
HINKLEY, CALIFORNIA

RETAINED PROCESS OPTIONS	ALTERNATIVE				
	1	2	3	4	5
	No Further Action	Containment	Plume-wide In-Situ Treatment	Core In-Situ Treatment and Beneficial Agricultural Use	Plume-Wide Pump and Treat
No Action	X				
Engineered Barriers, Deed Restrictions, Purchase Property		X	X	X	X
Hydraulic Barriers		X	X	X	X
In-Situ Anaerobic Bioremediation (IRZs)			X	X	
Agricultural Application		X		X	
On-Site Groundwater Reuse/Injection Wells			X	X	X
Ex-Situ Filtration					X
Ex-Situ Chemical Reduction/Precipitation					X
In-Situ Chemical Reduction	Technologies retained but not included as core elements of the remedial alternatives because there are other technologies included above that are more applicable considering past Site experience or other considerations				
Ex-Situ Ion Exchange					
Ex-Situ Anaerobic Bioreactor (e.g., MBfR)					
Infiltration Gallery					
Monitored Natural Attenuation					
Direct-Push Injection of Reagent/Substrate					

TABLE 6-3
ESTIMATED TIME AND COSTS TO REACH CHROMIUM REMEDIATION GOALS
PACIFIC GAS AND ELECTRIC COMPANY
HINKLEY, CALIFORNIA

ALTERNATIVE	Estimated Time to MCL (50 µg/L) in years	Estimated Time to 80% Chromium Mass Removal in years	Estimated Time to Background (3.1 µg/L) in years	NPV Cost to Background ($M)
1: No Action	>1000	>780	>1000	$0M
2: Containment	120	95	260	$36.0M
3: Plume-Wide In-Situ Treatment	8	10	110	$130M
4: Core In-Situ Treatment and Beneficial Agricultural Use	6	13	150	$50.2M
5: Plume-Wide Pump and Treat	50	37	140	$218M

Notes:
µg/L = micrograms per liter chromium
NPV = Net present value
$M = Millions of dollars
The number of years included are estimated by fate and transport modeling.

TABLE 6-4
SUMMARY OF COMPARATIVE EVALUATION OF ALTERNATIVES
PACIFIC GAS AND ELECTRIC
HINKLEY, CALIFORNIA

Alternative	Effectiveness				Ease of Implementability	NPV Cost ($ Millions)
	Achieves Background Conditions	Restore Beneficial Use	Chromium Plume Containment	Productive Use of GW Resource		
1: No Further Action	Not addressed	Not addressed	Not addressed	Not addressed	High	$0M
2: Containment	Medium	Medium	High*	High*	High	$36.0M
3: Plume-Wide In-Situ Treatment	High*	High*	High*	Medium	Low	$130M
4: Core In-Situ Treatment and Beneficial Agricultural Use	High*	High*	High*	High*	Medium	$50.2M
5: Plume-Wide Pump and Treat	Medium	Medium	High*	Medium	Low	$218M

Notes:
High - Alternative likely to meet or support attainment of effectiveness criteria as a primary or likely element. Alternative easy to implement.
Medium - Alternative likely to have a nominal or moderate effect on attainment of relative effectiveness criteria. Alternative moderately difficult to implement.
Low - Alternative unlikely to have even a nominal or moderate effect in attainment of relative effectiveness criteria. Alternative difficult to implement.
Not addressed - Alternative does not address relative effectiveness criteria. Little or no positive effect of alternative on effectiveness driver.
NPV Cost for duration to achieve background chromium concentrations (3.1 μg/L) as estimated by fate and transport modeling.
*As best as can be estimated due to Site conditions.