Perchlorate Treatment Technology Update

FEDERAL FACILITIES FORUM ISSUE PAPER

1.0 INTRODUCTION

Perchlorate contamination is becoming a more widespread concern in the United States as sources of such contamination continue to be identified and as more sensitive analytical methods are developed that can detect this compound in soil and groundwater. Perchlorate contamination is of particular concern because of the persistent and toxic nature of this chemical and because its physical and chemical properties make it challenging to treat. In addition to its use as an oxidizer in propellants and explosives, perchlorate has a wide variety of uses in areas ranging from electronics manufacturing to pharmaceuticals.

A number of issues associated with perchlorate contamination are being discussed by government, private, and other organizations and interested parties. These issues include health effects and risks, regulatory standards and cleanup levels, degradation processes, and treatment technologies. The U.S. Environmental Protection Agency's (EPA) Federal Facilities Forum (http://www.epa.gov/tio/tsp/fedforum.htm – see box) has prepared this issue paper to provide information about technologies available for treatment of perchlorate contamination in environmental media, including technologies that have been used to date and others that show potential for treating such contamination. A brief overview of key perchlorate issues is provided to give the reader context; however, these issues are not addressed in depth in this paper.

Federal Facilities Forum

The Federal Facilities Forum supports the federal facilities programs in each of the ten EPA regional offices. The group was organized in 1996 to exchange up-to-date information related to federal facility remediation issues at Superfund and RCRA sites. The Forum promotes communication between the regions and Headquarters and works primarily to communicate the current policy issues to each regional office as it is developed through the Federal Facilities Restoration and Reuse Office (FFRRO) at EPA Headquarters (http://www.epa.gov/fedfac/).

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Acronyms and Symbols

AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
AWWARF	American Water Works Association Research Foundation
bgs	Below ground surface
BOD	Biochemical Oxygen Demand
Cal EPA	California Environmental Protection Agency
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
ClO_4^-	Perchlorate
ClO_3^-	Chlorate
ClO_2^-	Chlorite
Cl^-	Chloride
Cr^{6+}	Hexavalent chromium
CRREL	Cold Regions Research and Engineering Laboratory
CTAC	Cetyl Trimethyl Ammonium Chloride
°C	degrees Celsius
DCE	Dichloroethene
DO	Dissolved oxygen
DoD	United States Department of Defense
DOE	United States Department of Energy
DVB	Divinyl benzene
DWEL	Drinking water equivalent level
EDR	Electrodialysis reversal
EOS	Edible oil substrate
EPA	United States Environmental Protection Agency
ERDC	United States Army Engineer Research and Development Center
ESI-MS	Electrospray ionization mass spectrometry
ESTCP	Environmental Security Technology Certification Program
FBR	Fluidized bed reactor
FDA	United States Food and Drug Administration
$FeCl_3$-HCl	Ferric chloride-hydrochloric acid
FFRRO	Federal Facilities Restoration and Reuse Office
FRTR	Federal Remediation Technologies Roundtable
ft	Foot
FY	Fiscal year
°F	degrees Fahrenheit
GAC	Granular activated carbon
GAC/IX	Granular activated carbon/ion exchange
GEDIT	Gaseous Electron Donor Injection Technology
gpd	Gallons per day
gpm	Gallons per minute
GWRTAC	Ground-Water Remediation Technologies Analysis Center
HDPE	High-density polyethylene
HFMBfR	Hollow-Fiber Membrane Biofilm Reactor
HFTW	Horizontal flow treatment well
HMX	Cyclotetramethylene Trinitramine
HRC	Hydrogen release compound
IC/MS	Ion Chromatography/Mass Spectrometry
IHD	Indian Head Division
IRIS	Integrated Risk Information System
IRZ	In situ reactive zone
ISB	In situ bioremediation
ITRC	Interstate Technology Regulatory Council
LANL	Los Alamos National Laboratory
lb	Pound
LHAAP	Longhorn Army Ammunition Plant
LOQ	Limit of quantification
MBR	Membrane bioreactor
MCL	Maximum contaminant level
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
MMR	Massachusetts Military Reservation
MNA	Monitored natural attenuation
MRL	Minimum reporting level
MTBE	Methyl Tertiary-Butyl Ether
NAS	National Academy of Sciences
NAVFAC	Naval Facilities Engineering Command
NaCl	Sodium chloride
NaOH	Sodium hydroxide
NCEA	National Center for Environmental Assessment
NDMA	Nitrosodimethylamine
NGWA	National Ground Water Association
NH_4OH	Ammonium hydroxide
NIROP	Naval Industrial Reserve Ordnance Plant
nm	Nanometers
NRC	National Research Council
NSWC	Naval Surface Warfare Center
NWIRP	Naval Weapons Industrial Reserve Plant

ORNL	Oak Ridge National Laboratory
ORP	Oxidation reduction potential
OSRTI	Office of Superfund Remediation and Technology Innovation
OSWER	Office of Solid Waste and Emergency Response
O_2	Oxygen
PBR	Packed bed reactors
PCE	Tetrachloroethene
PCL	Protective cleanup level
PHG	Public health goal
ppb	Parts per billion
ppm	Parts per million
PQL	Practical quantification limits
PRB	Permeable reactive barrier
psi	Pounds per square inch
PWS	Public water supply
QC	Quality control
RCRA	Resource Conservation and Recovery Act
RDX	Royal Demolition Explosives
RfD	Reference dose
RO	Reverse osmosis
SAMNA	Surface Application and Mobilization of Nutrient Amendments
SBA	Strong-base anion
SDWA	Safe Drinking Water Act
SERDP	Strategic Environmental Research and Development Program
TCA	Trichloroethane
TCE	Trichloroethene
TDS	Total dissolved solids
TNT	Trinitrotoluene
TSS	Total suspended solids
UCMR	Unregulated Contaminant Monitoring Regulation
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USGS	United States Geological Survey
UV	Ultraviolet
VOC	Volatile organic compounds
WQCB	Water Quality Control Board
W/cm^2	Watts per square centimeter
µg/kg	Micrograms per kilogram
µg/L	Micrograms per liter
ZVI	Zero-valent iron

Appendix A to this paper provides a list of web sites and resources pertaining to perchlorate, and Appendix B identifies the members of the Federal Facilities Forum.

1.1 Overview of Perchlorate Contamination and Environmental Occurrence

Perchlorate is both a naturally occurring and manmade anion that is typically found in the form of perchloric acid and salts such as ammonium perchlorate, potassium perchlorate, and sodium perchlorate. Ammonium perchlorate, an oxidizer, is the most prevalent form of this compound; has been widely used in solid propellants, fireworks, and flares; and is a constituent of many munition components. Perchlorate compounds are also used in a number of other manufacturing operations, including electroplating, production of pharmaceuticals, paints and enamels, and tanning and leather finishing (EPA FFRRO, 2005). Other compounds that contain perchlorate are Chilean nitrates and manufactured sodium chlorate, which contain perchlorate as an impurity (Urbansky, 2000). Listed below are several uses of perchlorate (ITRC, 2005).

Table 1-1. Example Uses of Perchlorate (EPA FFRRO, 2005)

Example Uses of Perchlorate	
Air bag initiators for vehicles	Flash powder for photography
Bleaching agent	Leather tanning
Chemical laboratories in analytical testing	Oxygen generators
Ejection seats	Paints and enamels
Electroplating operations	Perchloric acid production and use
Electropolishing	Production of matches
Engine oil testing	Propellant in rocket engines
Etching of brass and copper	Road flares
Fireworks	

Perchlorate was first manufactured in the U.S. in 1908 at the Oldbury Electrochemical plant in Niagara Falls, New York. Manufacture of ammonium perchlorate began in the 1940s, primarily for use by the defense industry and later by the aerospace industry. Other perchlorate-containing salts were more common before 1953. Over the years, the number of perchlorate manufacturers has varied. Before the mid-1970s, there were at least five perchlorate manufacturing plants in the U.S., but from 1975 through 1998, only two plants manufactured the compound (American Pacific in Henderson, Nevada, and then in Cedar City, Utah, and Kerr-McGee in Henderson, Nevada). Currently there is only one U.S. manufacturer of ammonium perchlorate, American Pacific's Western Electro Chemical Company (WECCO) Plant in Cedar City, Utah (http://www.american-pacific-corp.com/utah/index.html) (EPA FFRRO, 2005).

Perchlorate continues to be used in a variety of operations. As shown in Figure 1-1, there were more than 100 perchlorate users located in 40 states as of April 2003 (Mayer, 2004).

Because of historical issues associated with the detection of perchlorate contamination, the nationwide occurrence of this compound in the environment is still being determined. Figure 1-2 shows that, as of September 2004, 35 states and Puerto Rico had reported perchlorate contamination in groundwater or surface water (EPA FFRRO, 2005).

Figure 1-2 was compiled using data collected by EPA's FFRRO for the following types of sites: U.S. Department of Defense (DoD) facilities, facilities of other federal agencies, private sites, locations of Unregulated Contaminant Monitoring Regulation (UCMR) detections, and Texas Tech University's West Texas Study locations. For each site identified, the compilation includes data about perchlorate concentrations in drinking water, groundwater, surface water, and soil, as available. The maximum concentrations reported were as follows: drinking water was 811 micrograms per liter (µg/L); groundwater was 3,700,000 µg/L; surface water was 120,000 µg/L; and soil was 2,000 milligrams per kilogram (mg/kg). The list of sites includes more than 40 sites on the National Priorities List (Superfund sites); however, it should be noted that perchlorate concentrations at some of these sites were relatively low compared with other sites in the compilation (EPA FFRRO, 2005).

Figure 1-1. Perchlorate Manufacturers and Users, April 2003 (Mayer, 2004)

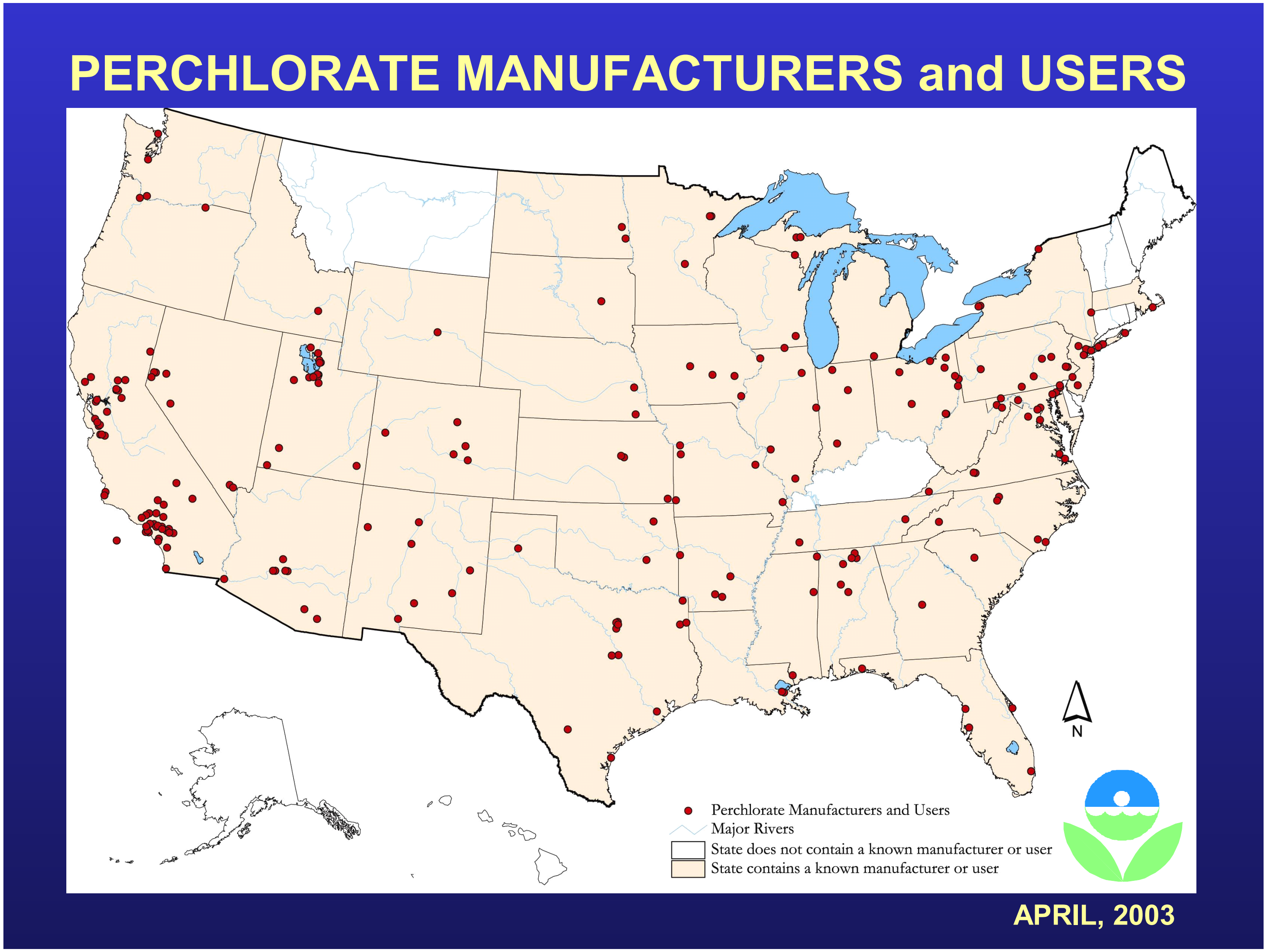
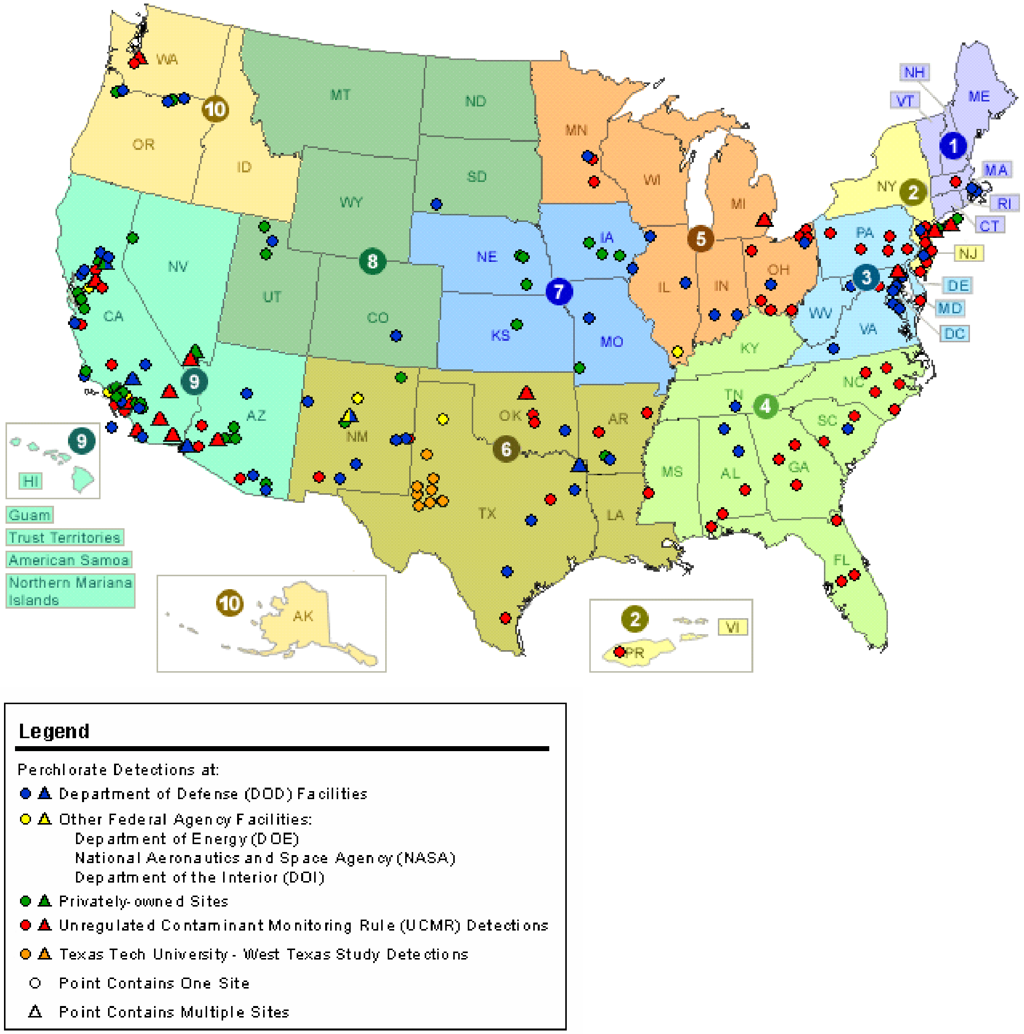


Figure 1-2. National Perchlorate Detections by EPA Region, September 23, 2004 (EPA FFRRO, 2005)



Note: This map presents data available as of September 2004. Please visit the EPA FFRRO web site (http://www.epa.gov/fedfac/documents/perchlorate.htm) for updated information about perchlorate detections.

Based on data in the UCMR database, as of August 2004, 145 public water supply (PWS) systems had reported at least one detection of perchlorate based on 583 samples that tested positive for the compound. The August 2004 update of the UCMR database provides perchlorate sample analytical data from 3,460 PWSs. The database is available at http://www.epa.gov/ogwdw000/data/ucmrgetdata.html (Mayer, 2004).

In addition to national data on perchlorate detections, more detailed information is available for specific regions of the country. For example, EPA Region 9 has compiled a summary of perchlorate releases in the region (see Figure 1-3) that covers drinking water contamination, monitoring well detections, and Colorado River contamination as of September 2004. As shown in Figure 1-3, these releases involved 28 sites, including 11 Superfund sites. The lower Colorado River, which stretches from Lake Mead (near Las Vegas) to the border with Mexico, had measurable concentrations of perchlorate over its entire length. In California, more than 6,500 water supply wells were tested for perchlorate, with detections reported in 354 wells, or 5.4 percent (Mayer, 2004). Figure 1-4 shows perchlorate detections and manufacturers and users in EPA Region 6. This figure shows approximately two dozen confirmed perchlorate detections in that region (Villarreal, 2004).

1.2 Overview of Human Health and Environmental Concerns for Perchlorate

Perchlorate exerts its most commonly observed health effect on or through the thyroid gland in the form of a decrease in thyroid hormone output. The thyroid gland takes up iodide ions from the bloodstream and uses the iodide to regulate metabolism along with other functions. In this iodide uptake process, the presence of ions larger than iodide, such as perchlorate, can reduce thyroid hormone production and thus disrupt metabolism. This property of perchlorate makes it useful as a medical treatment for Graves' disease (hyperthyroidism), but can also make perchlorate a health concern (Urbansky, 1998; EPA NCEA, 2004).

Primary pathways for exposure to perchlorate in humans include ingestion of contaminated drinking water and food (EPA FFRRO, 2005). Recent studies have detected perchlorate in samples of lettuce and milk. Additional studies of perchlorate uptake in food crops are currently being conducted by the U.S. Food and Drug Administration (FDA, 2004).

1.3 National Academy of Science Review of Perchlorate Toxicity

In January 2005, the National Research Council (NRC) of the National Academy of Science (NAS) published the results of its review of perchlorate toxicity in a report titled "Health Implications of Perchlorate Ingestion." The NRC reviewed the adverse health effects of perchlorate ingestion from clinical, toxicological, and public health perspectives as well as EPA's 2002 draft toxicity assessment for perchlorate (http://www.nap.edu/catalog/11202.html).

The NRC found that daily ingestion of up to 0.0007 milligrams of perchlorate per kilogram of body weight can occur without adversely affecting the health of the most sensitive populations. The committee that wrote the NRC report did not include a corresponding drinking water concentration with its reference dose (RfD) because the assumptions used to derive drinking water standards involve public policy choices that were beyond the committee's charge. On February 18, 2005, EPA adopted the findings of the NRC and established an official RfD of 0.0007 mg/kg/day of perchlorate in the Integrated Risk Information System (IRIS) (http://www.epa.gov/iris/subst/1007.htm). This RfD equates to a drinking water equivalent level (DWEL) of 24.5 µg/L (EPA IRIS, 2005).

Figure 1-3. Perchlorate Releases in EPA Region 9, April 2003 (Mayer, 2004)

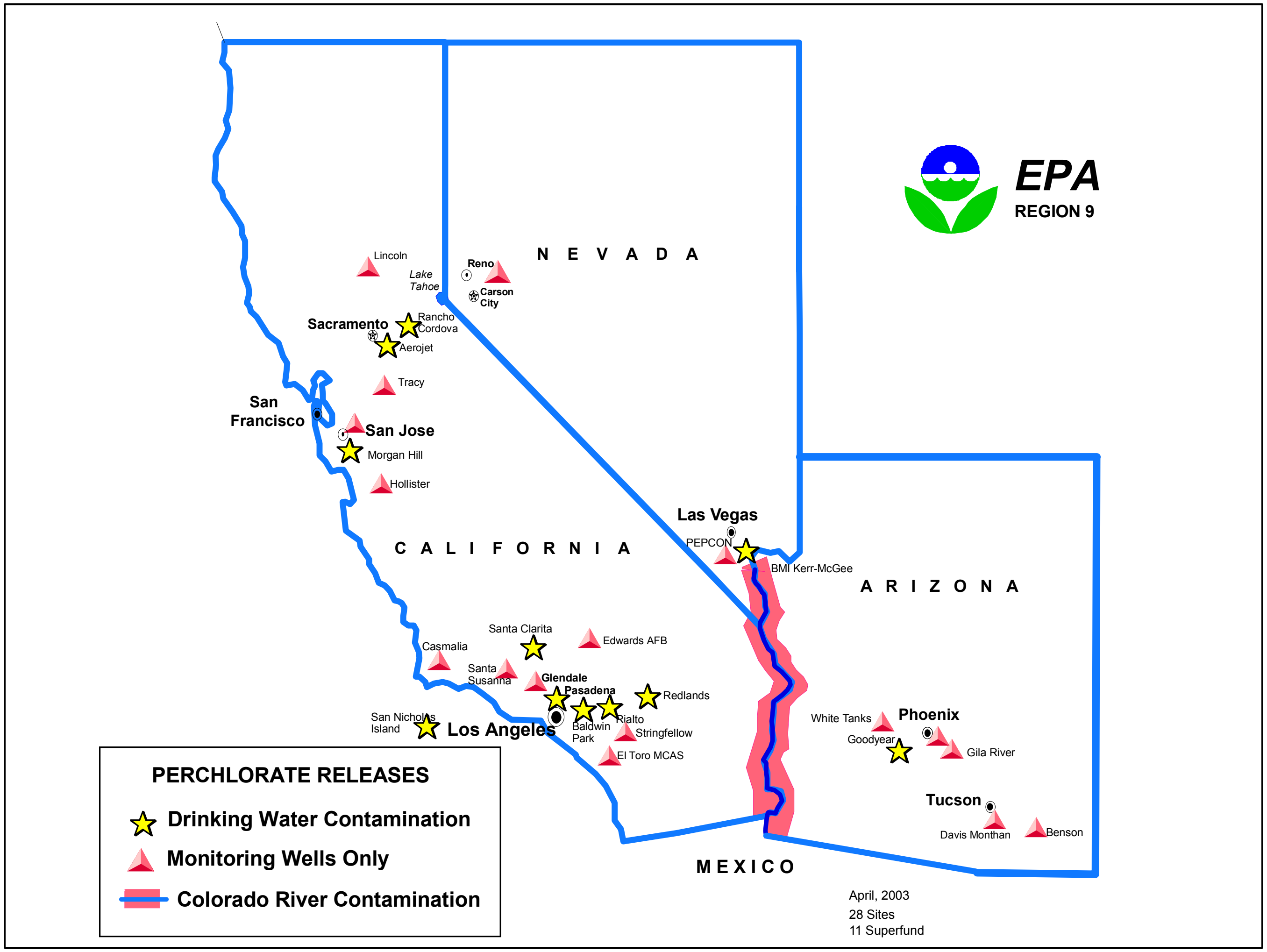
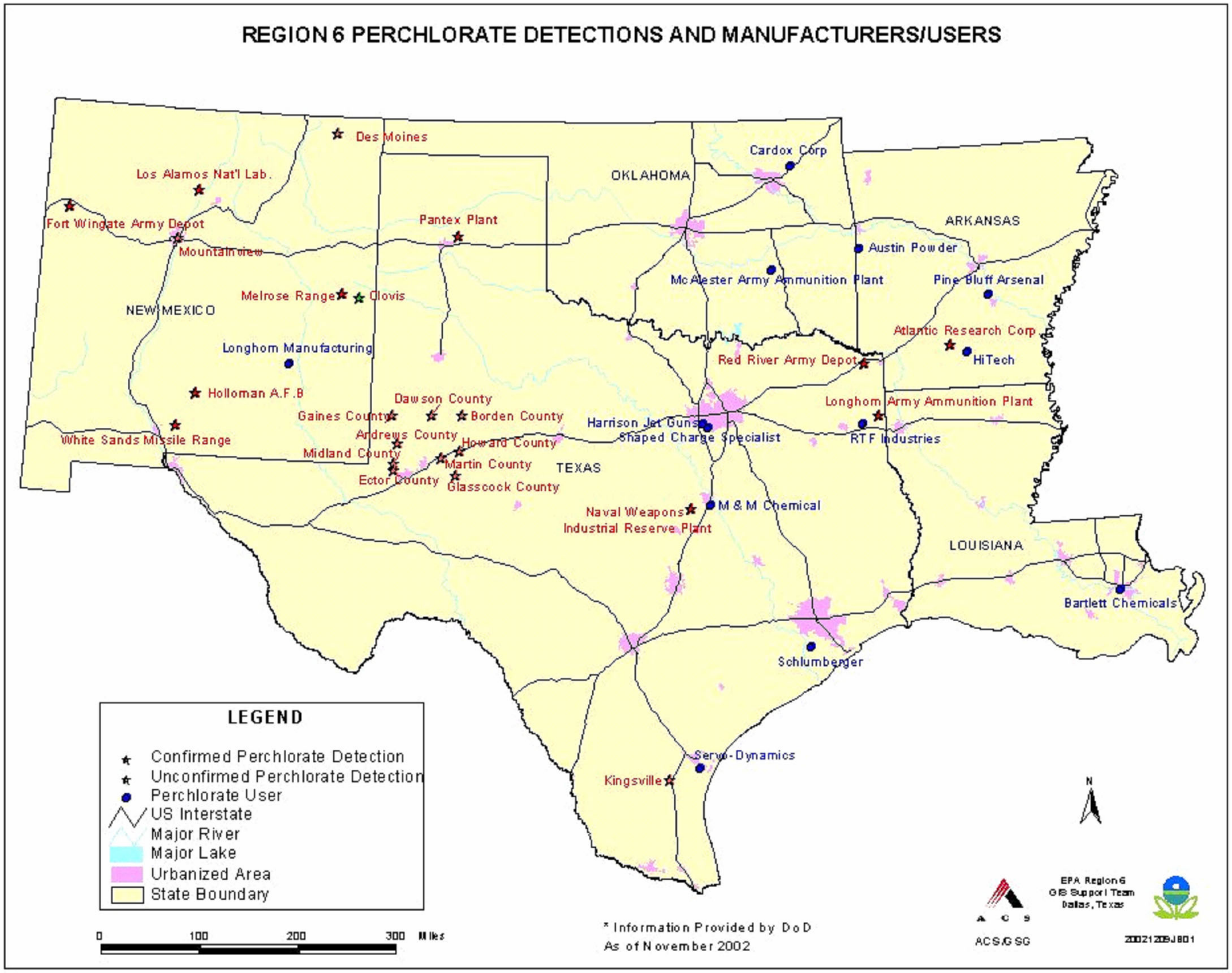


Figure 1-4. Perchlorate Detections and Manufacturers/Users in EPA Region 6, November 2002 (Villarreal, 2004)



The NRC emphasized that the reference dose should be based on inhibition of iodide uptake by the thyroid in humans, which is not an adverse effect but the key biochemical reaction that is caused by exposure to perchlorate. The NRC called this a “conservative, health-protective approach to perchlorate risk assessment.” The adverse effect for which this is a precursor is hyperthyroidism, which may occur at much higher doses. The NRC also found that humans are much less susceptible to disruption of thyroid function or formation of thyroid tumors than rats, and therefore the effect of perchlorate on rats is not a good indicator of its effects on human health (NRC, 2005; EPA, 2005d).

1.4 Overview of Regulatory Status of Perchlorate

At this time, there is no federal cleanup standard for perchlorate in groundwater or soil such as a maximum contaminant level (or MCL, an enforceable drinking water standard under the Safe Drinking Water Act [SDWA]). Rather, cleanup levels have been identified on a site-specific basis under federal statutes such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), Resource Conservation and Recovery Act (RCRA), and SDWA. In addition, several states have identified advisory levels for perchlorate, as shown in Table 1-2. Based on review of the available toxicological information, Health Canada recommends a drinking water guidance value of 6 µg/L (Health Canada, 2005).

Table 1-2. State Advisory Levels for Perchlorate (EPA FFRRO, 2005; Cal EPA, 2005)

State	Advisory Level	Comment
Arizona	14 µg/L	1998 health-based guidance level; based on child exposure; to be reviewed after EPA issues final Reference Dose (RfD)
California	6 µg/L – public health goal (PHG) for perchlorate in drinking water	Emphasized human clinical study; includes 10X uncertainty factor; California EPA (Cal EPA) is anticipating a proposed maximum contaminant level (MCL) in 2005
Massachusetts	1 µg/L	Precautionary recommendation to local water districts for children and at-risk populations
Maryland	1 µg/L	None
New Mexico	1 µg/L – only for monitoring	Drinking water screening level
New York	5 and 18 µg/L	5 µg/L for drinking water planning level; 18 µg/L for public notification level
Nevada	18 µg/L – public notice standard	For contaminated groundwater
Texas	17 and 51 µg/L	17 µg/L for residential protective cleanup level (PCL); 51µg/L for industrial/ commercial PCL

2.0 PHYSICAL AND CHEMICAL PROPERTIES AND ANALYTICAL METHODS

This section provides information about select physical and chemical properties of several perchlorate compounds as well as information about analytical methods for perchlorate in various media.

2.1 Physical and Chemical Properties of Perchlorate

Perchlorate is a highly soluble, mobile compound that dissolves and moves like a salt in water. Table 2-1 summarizes select physical and chemical properties of three common perchlorate salts as well as perchloric acid. As this table shows, the densities of the salts range from 1.95 to 2.53 g/cm^3. The solubilities of perchlorate salts are relatively high, with ammonium perchlorate's solubility reported as 200 g/L at 25^{o}C.

2.2 Selected Analytical Methods for Perchlorate

The chemistry of the perchlorate ion, especially the relatively high solubility of its salts in water, creates challenges in sample analysis for this compound (Urbansky, 1998). Prior to 1997, the perchlorate detection limit achieved by standard ion chromatography was >400 µg/L. However, analytical methods now available can achieve detection limits of 4 µg/L or lower. Table 2-2 summarizes selected analytical methods for perchlorate along with their target reporting limits.

Current EPA Methods

The two EPA methods currently available for analysis for perchlorate in drinking water and other waters are Method 314.0 (EPA, 1999) and Method 9058 (EPA, 2000). Both methods are based on use of an ion chromatography instrument, but they differ in the preferred columns. Method 314.0 has more alternatives for cleanup (pretreatment) procedures to cope with interfering ions. Both methods include requirements for matrix spikes (also called "laboratory fortified sample matrices") to verify the performance of the method for the sample matrix involved. Such quality control (QC) samples are used to confirm that acceptable sample detection limits are attained. The main limitations of the methods stem from interference from other ions that can cause raised sample detection limits, false negatives, and false positives.

In addition, variations of the two current EPA analytical methods are being studied. For example, EPA (2001a) conducted a study using a method similar to Method 314.0 to measure trace perchlorate in dissolved or leached fertilizers. This study demonstrated that careful use of matrix spikes for each fertilizer material to verify the perchlorate detection limit for that material enabled Method 314.0 to be extended to non-drinking water matrices. Ellington and Evans (2000) used a variety of cleanup techniques to determine low concentrations of perchlorate in plant materials. Kang and others (2003) developed online preconcentration methods for removing interferents as a substitute for the offline procedures included in EPA methods.

Magnuson and others (2000) used a different technology for perchlorate analysis. An organic salt of the perchlorate was extracted from an aqueous sample and then determined by electrospray ionization mass spectrometry (ESI-MS) without a chromatographic separation step. Urbansky and others (2000) then used both this ESI-MS procedure and the Method 314.0 procedure to analyze bottled waters and found that the methods produced comparable results.

Table 2-1. Physical and Chemical Properties of Selected Perchlorate Compounds

Property	Ammonium Perchlorate	Sodium Perchlorate	Potassium Perchlorate	Perchloric Acid
CAS No.	7790-98-9	7601-89-0	7778-74-7	7601-90-3
Formula	NH_4ClO_4	$NaClO_4$	$KClO_4$	$HClO_4$
Formula Weight	117.49	122.44	138.55	100.47
Color/Form	White, orthorhombic crystals	White, orthorhombic crystals; white, deliquescent crystals	Colorless crystals or white, crystalline powder; colorless, orthorhombic crystals	Colorless, oily liquid
Melting Point	Decomposes/ explodes	480 ^{o}C	525 ^{o}C	-112 ^{o}C
Density	1.95 g/cm^3	2.52 g/cm^3	2.53 g/cm^3	1.768 g/cm^3
Solubility	200 g/L of water at 25 ^{o}C	209.6 g/100 mL of water at 25 ^{o}C	15 g/L of water at 25 ^{o}C	Miscible in cold water
Additional Solubility Information	Soluble in methanol; slightly soluble in ethanol, acetone; almost insoluble in ethyl acetate, ether	209 g/100 mL water at 15 ^{o}C; 284 g/100 mL water at 50 ^{o}C; soluble in alcohol	Soluble in 65 parts cold water, 15 parts boiling water; practically insoluble in alcohol; insoluble in ether	Not provided

Source: National Library of Medicine. Specialized Information Services. 2004. Hazardous Substances Data Bank. **http://toxnet.nlm.nih.gov/**. Downloaded October 4.

Table 2-2. Selected Analytical Methods for Perchlorate

Method	Description	Target Reporting Limit	Source
Current EPA Methods			
Method 314.0	Uses an ion chromatography instrument that includes an anion separator column, an anion suppressor device, and a conductivity detector. Includes alternatives for cleanup (pretreatment) procedures to cope with interfering ions.	0.1 µg/L is target reporting limit for perchlorate in drinking water	EPA. 1999. "Method 314.0. Determination of Perchlorate in Drinking Water using Ion Chromatography." Revision 1.0. National Exposure Research Laboratory, Office of Research and Development. November.
Method 9058	Uses an ion chromatography instrument that includes an anion separator column, an anion suppressor device, and a conductivity detector.	4 µg/L is limit of quantitation (LOQ). Method detection limit is 0.7 µg/L in groundwater.	EPA. 2000. "Method 9058. Determination of Perchlorate using Ion Chromatography with Chemical Suppression Conductivity Detection." Revision 0. SW-846 Update IVB. November.

Method	Description	Target Reporting Limit	Source
Methods Under Development			
Method 314.1; expected in 2005	Uses a preconcentrator to remove common interferents, including chloride, carbonate, and sulfate. In addition, provides for use of a second column to confirm identity of perchlorate.	0.5 – 1 µg/L	EPA. 2005e. E-mail message with comments on perchlorate issue paper. From Jan Dunker (United States Army Corps of Engineers [USACE]) to John Quander (EPA Office of Superfund Remediation Technology Innovation). April 1.
Method 331.0 – "Determination of Perchlorate in Drinking Water by Liquid Chromatography Electrospray Ionization Mass Spectrometry," expected in 2005	Uses a different chromatographic method to separate perchlorate from other ions, which may be more effective in reducing interference. Tandem mass spectrometry provides a tool to eliminate sulfate interference. The method quantitates perchlorate against an isotopically labeled (oxygen-18) internal standard. This method may provide versatility needed for difficult matrices.	0.02 µg/L	EPA. 2005e. E-mail message with comments on perchlorate issue paper. From Jan Dunker (USACE) to John Quander. April 1.
Method 332.0 – "Determination of Perchlorate in Drinking Water Using Ion Chromatography with Suppressed Conductivity and Mass Spectrometric Detection," expected in 2005	Substitutes an electrospray ionization mass spectrometry (ESI-MS) detector for the conductivity detector of Method 314.0. Provides confirmation of identity of perchlorate or definite evidence of false positive results from interferents. Can handle relatively high concentrations of total dissolved solids.	0.1 µg/L Ion Chromatography/Mass Spectrometry (IC/MS) and 0.02 µg/L (IC/MS-MS)	EPA. 2005e. E-mail message with comments on perchlorate issue paper. From Jan Dunker (USACE) to John Quander. April 1.
Method 6850 – "Determination of Perchlorate Using High Performance Liquid Chromatography/Mass Spectrometry"	Uses the technology of Method 331.0 to separate perchlorate from other ions and the technology of Method 332.0 to confirm the identity of perchlorate and quantitate it.	Practical quantitation limits (PQL) are 0.2 µg/L for water (drinking water, simulated groundwater, and Great Salt Lake water), 2 µg/L for soil, and 6 µg/L for biota (grass). Method detection limits are about 1/3 of the PQLs.	EPA. 2004b. E-mail message regarding perchlorate analysis. From Mike Carter, (EPA Federal Facilities Restoration and Reuse Office [FFRRO]) to John Quander. July 14.

Method	Description	Target Reporting Limit	Source
"Rapid Determination of Perchlorate Anion in Foods by Ion Chromatography – Tandem Mass Spectrometry"	Developed in support of an ongoing program for collection and analysis of foods to measure perchlorate content. Samples are extracted by food-specific methods. Extracts are then separated by ion chromatography as in Method 332.0 and determined by the technology (including the internal standard) used in Method 331.0.	LOQs are 0.5 µg/L for drinking water, 1 µg/L for fruits and vegetables, and 3 µg/L for milk	FDA. 2004. "Draft Rapid Determination of Perchlorate Anion in Lettuce, Milk, and in Bottled Water by HPLC/MS/MS." Revision 0. Dated March 17. Downloaded July 15 from http://www.cfsan.fda.gov/~dms/clo4meth.html.
Field Screening Method for Perchlorate in Water and Soil	A field screening colorimetric method for perchlorate was developed by the U.S. Army Corps of Engineers (USACE). This method was published as a report (ERDC/CRREL TR-04-8) which is available for download at http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/TR04-8.pdf.	Detection limits: 1 ug/L for water; 0.3 ug/g for soil	USACE. 2004. Field Screening Method for Perchlorate in Water and Soil. U.S. Army Engineer Research and Development Center (ERDC)/Cold Regions Research and Engineering Laboratory (CRREL) TR-04-8. April.

Status of Methods Under Development

EPA is now in the final stages of developing two new methods and one revised method for perchlorate analysis (EPA, 2004a). Method 332.0, "Determination of Perchlorate in Drinking Water Using Ion Chromatography with Suppressed Conductivity and Mass Spectrometric Detection," is due for release in 2005 (EPA FFRRO, 2005). This method substitutes an ESI-MS detector for the conductivity detector of Method 314.0. The inherent advantage of the new method is that the mass spectral data (especially the ratio of the concentrations of perchlorate ion masses of 99 and 101 daltons, which are derived from the two masses, 35 and 37 daltons, of natural chlorine) provide confirmation of the identity of the perchlorate or definite evidence of false positive results from interferents. This method can handle relatively high concentrations of total dissolved solids, but sulfate may still pose a problem. The natural abundance of sulfur-34 causes just over 4 percent of bisulfate ions to have a mass of 99 daltons, which distorts the perchlorate ion ratios. Some analytical methods use the 83- and 85-dalton masses, which correspond to the perchlorate ion less one oxygen atom, to minimize interference.

Method 331.0, "Determination of Perchlorate in Drinking Water by Liquid Chromatography Electrospray Ionization Mass Spectrometry," is also due for release in 2005. The new method uses a different chromatographic method to separate perchlorate from other ions, which may be more effective in reducing interference. The tandem mass spectrometry provides a tool to eliminate the sulfate interference problem. The method quantitates perchlorate against an isotopically labeled (oxygen-18) internal standard. Although more expensive than ion chromatography methods, Method 331.0 may provide the versatility needed for difficult matrices.

In addition, Method 314.1 is due for release in 2005. This variation uses a preconcentrator to remove common interferents, including chloride, carbonate, and sulfate. In addition, it provides for use of a second column to confirm the identity of perchlorate, as is done in Method 8081A and similar chromatography methods.

Other methods are being developed outside of EPA's Office of Water. For example, a new Method 6850 for analysis for perchlorate in various wastes is being developed by EPA's Office of Solid Waste (EPA, 2004b); and the U.S. Food and Drug Administration (FDA) has published a draft analytical method for perchlorate in water, milk, and lettuce (FDA, 2004). The latter method is intended to support a collection and analysis program for those foods (FDA, 2003). This method combines elements of Method 332.0 (ion separation) and Method 331.0 (identity confirmation and quantitation) and uses the 83- and 85-dalton masses to minimize interference.

DoD is also working on development and improvement of methods for perchlorate analyses, including variations of Method 331.0. Additional information about these efforts was provided at a recent symposium (DoD, 2004).

In October 2004, EPA hosted the 14th Annual Quality Assurance Conference in Dallas, Texas. The conference presentations included a number of papers evaluating perchlorate analytical methodologies and discussing methods under development (http://www.epa.gov/Arkansas/6pd/qa/index.htm).

3.0 TREATMENT TECHNOLOGIES

Technologies used for treating perchlorate contamination in drinking water, groundwater, and soil have included the following ex situ and in situ approaches:

- Ion Exchange
- Bioreactor
- Liquid Phase Carbon Adsorption
- Composting
- In Situ Bioremediation
- Permeable Reactive Barrier
- Phytotechnology
- Membrane Technologies (Electrodialysis and Reverse Osmosis).

Ex situ technologies may require treatment of residuals; however, this document does not discuss residuals treatment in detail.

This section provides an overview of these technologies. This includes a description of their underlying principles, the mechanisms by which they reduce the concentration or amount of perchlorate in environmental media, factors that affect their performance, and technical limitations. Summary information is provided for about 50 sites where these technologies have been or are being used for full-scale perchlorate treatment or field demonstration. To compile the site-specific information, EPA evaluated available source materials such as recent conference proceedings. EPA also contacted Remedial Project Managers and others during the summer and fall 2004 to solicit up-to-date information on each treatment project.

Site-specific information includes technology design, operation, and performance data. These projects include efforts at full-scale and field demonstration (i.e., pilot scale), of which some are ongoing and others completed. Table 3-1 summarizes the total number of projects described in this section, indicating about half are full-scale projects and the other half are pilot-scale projects.

Table 3-1. Number of Perchlorate Treatment Projects Discussed in Issue Paper

Technology	No. of Projects	
	Full-Scale	**Pilot-Scale**
Ion Exchange	15	3
Bioreactor	4	5
Granular Activated Carbon	2	2
Composting	1	3
In Situ Bioremediation	1	10
Permeable Reactive Barrier	2	1
Phytotechnology	0	1
Electrodialysis	0	2
Reverse Osmosis	0	0
TOTAL	25	27

Cleanup goals vary by site and type of project. Technology performance data are presented relative to cleanup goals. Treatment technologies often are applied to achieve specified goals that vary by site, end use, and other factors. Performance information has not been independently verified for accuracy or completeness.

3.1 Ion Exchange

Summary

Ion exchange is an ex situ technology used to remove perchlorate from drinking water, groundwater, surface water, and environmental media at full scale. Among the projects identified for this report, ion exchange is the most frequently used ex situ treatment technology for perchlorate. The most commonly used ion exchange media are synthetic, strongly basic, anion exchange resins. Ion exchange has been used at sites to reduce perchlorate concentrations to less than 4 µg/L. Its effectiveness is sensitive to a variety of untreated water contaminants and characteristics. It has also been used as a polishing step for other water treatment processes such as biological treatment of perchlorate.

Technology Principles

Ion exchange is a physico-chemical process in which ions held electrostatically on the surface of a solid are exchanged for ions of similar charge in a solution. Ion exchange materials used for perchlorate treatment typically consist of resins made from materials that contain ionic functional groups to which exchangeable ions are attached. This technology removes perchlorate ions from the aqueous phase by replacing them with the anion present in the ion exchange resin medium (Federal Remediation Technologies Roundtable [FRTR], 2005; Gu et al., 1999; EPA Office of Solid Waste and Emergency Response [OSWER], 2002).

Monofunctional and bifunctional anion exchange resins are commonly used in perchlorate treatment. Bifunctional resins, which consist of two functional groups, can address a broader range of ionic strengths than monofunctional resins can. The resin used for ion exchange typically is made from synthetic materials, inorganic materials, or natural polymeric materials that contain ionic functional groups to which exchangeable ions are attached (FRTR, 2005). Because dissolved perchlorate is usually in an anionic form, and weak base resins tend to be effective over a smaller pH range, strong base resins are typically used for perchlorate treatment. Some resins used for perchlorate removal include poly vinylbenzyl chloride backbone cross-linked with divinyl benzene (DVB), to form quarternary ammonium strong-base anion (SBA) exchange sites (Gu et al., 1999; Gu et al., 2002).

Resins may be categorized by the ion exchanged with the one in solution. For example, resins that exchange a chloride ion are referred to as chloride-form resins. Another way of categorizing resins is by the type of ion in solution that the resin preferentially exchanges. For example, resins that preferentially exchange sulfate ions are referred to as sulfate-selective resins. Nitrate-selective resins have been found useful for perchlorate removal (EPA OSWER, 2002). Some common chloride-form resins for perchlorate removal include SBA Type I acrylic and styrenic resins, nitrate select resins, and perchlorate-selective bifunctional resins (Boodoo, 2003a).

The order of exchange for most strong-base resins is as follows (in order of decreasing adsorption preference from top to bottom and left to right [EPA OSWER, 2002]):

$HCrO_4^- > CrO_4^{2-} > ClO_4^- > SeO_4^{2-} > SO_4^{2-} > NO_3^- > Br^- > (HPO_4^{2-}, HAsO_4^{2-}, SeO_3^{2-}, CO_3^{2-}) > CN^- > NO_2^- > Cl^- > (H_2PO_4, H_2AsO_4^-, HCO_3^-) > OH^- > CH_3COO^- > F^-$

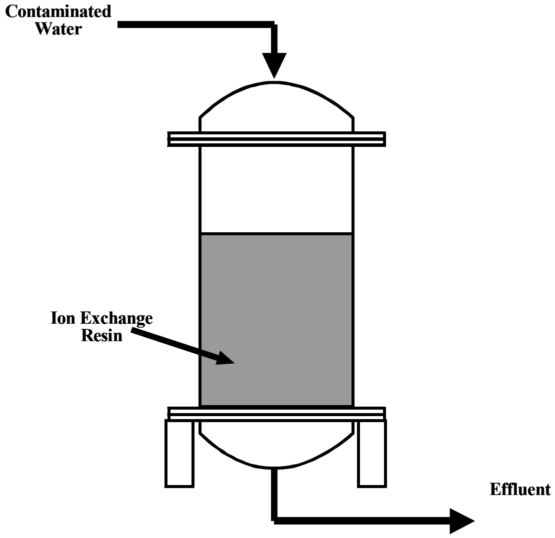
Technology Description

Ion exchange resins are usually packed into a column, and as contaminated water is passed through the column, contaminant ions are exchanged for other ions such as chlorides or hydroxides in the resin (FRTR, 2005). Figure 3.1-1 shows a simplified view of an ion exchange column. Ion exchange is often preceded by treatments such as filtration and oil-water separation to remove organics, suspended solids, and other contaminants that can foul the resins and reduce their effectiveness. Ion exchange resins must be periodically regenerated to remove the adsorbed contaminants and replenish the exchanged ions (FRTR, 2005). Regeneration of a resin typically occurs in three steps:

1. Backwashing
2. Regeneration with a solution of ions
3. Final rinsing to remove the regenerating solution

The regeneration process results in a backwash solution, a waste regenerating solution, and a waste rinse water. The volume of spent regeneration solution ranges from 1.5 to 10 percent of the treated water volume depending on the feed water quality and type of ion exchange unit (EPA OSWER, 2002). One study (Gu et al., 1999) showed that nearly 110,000 bed volumes of water contaminated with approximately 50 µg/L perchlorate can be treated by a bifunctional resin before breakthrough occurs. Sodium chloride (NaCl), ammonium hydroxide (NH_4OH), ferric chloride-hydrochloric acid ($FeCl_3{}^-HCl$) and sodium hydroxide (NaOH) are some commonly used regenerants for perchlorate-laden resins. The regeneration process may require 3 to 5 bed volumes of regenerant solution and 2 to 3 bed volumes of water for rinsing. Furthermore, the regeneration water and spent resin containing high levels of perchlorate would require additional treatment (e.g., biological reduction) prior to disposal or reuse (Gingras and Batista, 2002; Gu and Brown, 2000). Technology providers have recently focused on improving the regeneration processes used for ion exchange.

Figure 3.1-1. Ion Exchange System for Perchlorate Removal (EPA OSWER, 2002)



Ion exchange operations can use multiple beds in series to reduce the need for bed regeneration; beds first in the series (lead beds) require regeneration first, and fresh beds can be added at the end of the series (lag beds). Using multiple beds can also allow continuous operation because some beds can be regenerated while others continue to treat water (EPA OSWER, 2002; Boodoo, 2003b). Ion exchange beds are typically operated as fixed beds in which the water to be treated is passed over an immobile ion exchange resin. One variation on this approach is to operate the bed in a non-fixed, countercurrent fashion in which water is applied in one direction, usually downward, while spent ion exchange resin is removed from the top of the bed. Regenerated resin is added to the bottom of the bed. This method may reduce the frequency of resin regeneration (EPA OSWER, 2002).

Type, Number, and Scale of Identified Projects Treating Wastes Containing Perchlorate

Ion exchange of perchlorate in environmental media and drinking water is commercially available. Information is available on 15 full-scale applications, including 11 applications for environmental media, and four applications for drinking water. Three pilot-scale applications for groundwater also have been identified.

Perchlorate-Contaminated Media Treated

- Groundwater
- Drinking water

Summary of Performance Data

Table 3.1-1 summarizes available performance data for this technology. For the 14 groundwater projects (11 full scale and three pilot scale), influent perchlorate concentrations ranged from 10 µg/L to 350,000 µg/L. Effluent concentrations of perchlorate ranged from non-detect at a detection limit of 0.35 µg/L (Project 16, Table 3.1-1) to 2,000 µg/L. Of the four drinking water projects, performance data were available for only one project. The initial concentration of perchlorate in this project ranged from 20 to 50 µg/L, while the final concentration was below the detection limit of 4 µg/L. As discussed above, cleanup goals varied by site and type of project. Where provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end use, and other factors.

A case study at the end of this section discusses use of ion exchange to remove perchlorate from groundwater at the Aerojet General Corp. Superfund Site, in Rancho Cordova, CA (Gu and Brown, 2000; Lu, 2003; EPA, 2004c; EPA, 2004l; EPA, 2004p; Calgon Carbon Corp., 1998; Cal EPA, 2004).

Table 3.1-1. Ion Exchange Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Aerojet General Corp. Superfund Site, Rancho Cordova, CA; Ion Exchange; Groundwater; Full-scale; Ongoing	This is a Superfund site with perchlorate-contaminated groundwater. Other contaminants of concern at this site include nitrates and chlorinated solvents. An ion exchange system consisting of a non-regenerable perchlorate-selective resin is being used for perchlorate removal at this site. The system is currently operating at a flow rate of 400 gallons per minute (gpm) and is expected to operate at 1,500 gpm by June 2005.	Period of Performance: August 2004 – Ongoing The average initial concentration of perchlorate was 50 µg/L. Effluent concentrations are less than 4 µg/L.	1. EPA. 2004c. E-mail message regarding perchlorate treatment. From Charles Berrey (EPA Region 9) to Sashi Vissa (Tetra Tech EM Inc.). September 13. 2. California Environmental Protection Agency (Cal EPA). 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January.
Castaic Lake Water Agency, Whittaker Berm Area, Whittaker, CA; Ion Exchange; Drinking Water; Full-scale; Ongoing	This is a state-lead site. Additional information on technology design and operation was not provided.	Period of Performance: Not available Technology performance data not provided.	EPA. 2004q. E-mail messages regarding perchlorate detection. From Kevin Mayer (EPA Region 9) to John Quander (EPA Office of Superfund Remediation and Technology Innovation). November 9.
City of Pomona, CA; Ion Exchange; Full-scale; Groundwater; Ongoing	Groundwater at this site is contaminated with perchlorate. A full-scale, fixed-bed, non-regenerable anion exchange resin is being used for perchlorate removal from groundwater. The system is operating at a flow rate of 10,000 gpm.	Period of Performance: Not available Technology performance data not provided.	Cal EPA. 2004. Perchlorate Contamination Treatment Alternatives: Draft. January.
Fontana Union Water Co., Fontana, CA; Ion Exchange; Full-scale; Drinking Water; Ongoing	A fixed bed, non-regenerable anion exchange resin is being used at full scale for removal of perchlorate in drinking water wells at this site.	Period of Performance: January 2004 – Ongoing Technology performance data not provided.	The Interstate Technology Regulatory Council (ITRC). 2005. Overview: Perchlorate Overview. Draft. March.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Frank Perkins Road Treatment System, Massachussetts Military Reservation, Cape Cod, MA; Ion Exchange; Full-scale; Groundwater; Ongoing	Treatment system operates at 220 gpm and treats perchlorate- and explosives-contaminated groundwater. Treatment train entails a series of three units with the ion exchange resin unit placed between two granulated activated carbon canisters (each packed with 2,000 pounds of granular activated carbon (GAC) media. The treatment system is composed of three mobile treatment units each with a capacity of treating 100 gpm.	Period of Performance: September 2004 – Ongoing In October 2004, influent concentration of perchlorate was approximately 33 µg/L. Effluent concentration is below the detection limit (reporting limit = 0.35 µg/L)	EPA. 2004l. E-mail message regarding perchlorate treatment. From Jane Dolan (EPA Region 1) to John Quander. November 9.
Kerr McGee, Henderson, NV; Ion Exchange; Groundwater; Full-scale; Shut down. (ISEP-Perchlorate Destruction Modules [PDMs] System)	A regenerable anion exchange system initiated operation in March 2002 to treat groundwater contaminated with perchlorate. The full-scale treatment system included 30 anion exchange units mounted on a turntable attached to a rotating multi-port valve. During one turntable rotation, each resin column was subjected to a cycle of adsorption, rinsing, and regeneration (with salt brine). The perchlorate removed from the ion exchange columns was then destroyed by reaction with ammonia in two high temperature catalytic PDMs. The flow rate of the system was 825 gpm.	Period of Performance: March 2002 – October 2002 Initial perchlorate concentrations ranged up to 350,000 µg/L. Effluent perchlorate concentrations ranged from 500 to 2,000 µg/L. The removal efficiency was approximately 99%. Elevated concentrations of dissolved solids and sulfate caused maintenance problems. The system was shut down in October 2002 due to corrosion in the heat exchangers in the perchlorate destruction modules. The ISEP-PDM system was replaced by a system of twelve anion exchange columns known as the "Plant Ion Exchange System."	1. EPA Region 9. 2004. "Perchlorate in Henderson, NV – Significant controls are operating". July. 2. Cal EPA. 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January. 3. EPA Region 9. 2005i. E-mail message regarding perchlorate treatment. From Larry Bowerman (EPA Region 9) to John Quander. June 24.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Kerr McGee, Henderson, NV; Ion Exchange; Groundwater; Full-scale; Shut down. (Plant Ion Exchange System and Wash Ion Exchange System)	The Plant Ion Exchange System began operation in October 2002 to treat groundwater contaminated with perchlorate. The full-scale treatment system included twelve single-use anion exchange columns configured in 4 parallel trains of 3 columns each. When the resin was saturated with perchlorate, it was removed and sent off-site for incineration. The flow rate of the system was 750 gpm. The Wash Ion Exchange System began operation in November 1999. Initially it included two single-use ion exchange columns configured in series (a third column was added in October 2002). This system treated about 350 gpm containing about 100,000 µg/L perchlorate, removing 97-99%.	Period of Performance: November 1999 – June 2004 Initial perchlorate concentrations ranged from 80,000 to 350,000 µg/L. Effluent concentrations ranged from 500 to 2,000 µg/L. The removal efficiency was 98 to 99.8%. The Plant Ion Exchange System was shut down in March 2004 when a new biologically based treatment plant (the FBR Plant) began operation. The Wash Ion Exchange System operated from November 1999 until it was shut down in June 2004.	1. EPA Region 9. 2004. “Perchlorate in Henderson, NV – Significant controls are operating.” July. 2. Cal EPA. 2004. “Perchlorate Contamination Treatment Alternatives: Draft.” January. 3. EPA Region 9. 2005i. E-mail message regarding perchlorate treatment. From Larry Bowerman (EPA Region 9) to John Quander. June 24.
Lawrence Livermore National Laboratory, CA; Ion Exchange; Groundwater; Full-scale; Ongoing	Groundwater at this site is contaminated with perchlorate, TCE, and nitrate. A regenerable, nitrate-selective anion exchange resin is being used for perchlorate removal. The system flow rate is approximately 3.5 gpm.	Period of Performance: November 2000 – Ongoing Initial concentration of perchlorate in groundwater was 10 µg/L. Perchlorate in treated effluent is being reduced to less than 4 µg/L.	1. EPA. 2004i. E-mail message regarding perchlorate treatment. From Kathi Setian (EPA Region 9) to John Quander. December 15. 2. Cal EPA. 2004. “Perchlorate Contamination Treatment Alternatives: Draft.” January.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Lockheed Propulsion Company – Tippicanoe Treatment Facility, City of Riverside, CA (Redlands Plume); Ion Exchange; Full-scale; Drinking Water; Ongoing	A fixed bed, non-regenerable anion exchange system is being applied at full-scale to address perchlorate contamination in drinking water at this site. The treatment system consists of 10 ion exchange vessels, each loaded with approximately 36,000 pounds of a strong-base, quarternary amine resin (CAL-RES 2103). The system is operating at 6,000 gpm.	Period of Performance: 2001 – Ongoing The average initial perchlorate concentration ranged from 20 to 50 µg/L. Average concentration of perchlorate in effluent is being reduced to below detection limit with a detection limit of 4 µg/L.	1. Lu, Owen. 2003. A Perchlorate Treatment Implementation Success Story. September 10. http://www.tribalwater.net/perchlorate/riversidePublicUtility.pdf 2. Cal EPA. 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January.
National Aeronautics and Space Administration (NASA)/California Institute of Technology Jet Propulsion Laboratory, Pasadena, CA; Ion Exchange; Groundwater; Full-scale; Ongoing	Groundwater at this site is contaminated with perchlorate, nitrate, and volatile organics. An ion exchange system with a disposable resin is currently operating at full-scale at this site. The treatment system flow rate is 2 million gallons per day.	Period of Performance: July 2004 – Ongoing Influent perchlorate concentrations in groundwater range from 20 to 40 µg/L. Effluent concentrations of perchlorate are below detection limit with a detection limit of 4 µg/L.	EPA. 2004k. Record of telephone conversation between Sashi Vissa and Mark Ripperda (US EPA Region 9). September 23.
Olin Safety Flare Site, City of Morgan Hill, CA; Ion Exchange; Full-scale; Groundwater; Ongoing	A fixed bed, non-regenerable anion exchange system is being applied at full-scale to treat perchlorate-contaminated groundwater at this site. The system is operating at 800 gpm.	Period of Performance: Not available – Ongoing Initial perchlorate concentration in groundwater is approximately 10 µg/L. Effluent perchlorate concentrations are less than 4 µg/L.	1. Cal EPA. 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January. 2. EPA. 2004q. E-mail messages regarding perchlorate detection. From Kevin Mayer to John Quander. November 9.
Olin Safety Flare Site, West San Martin Colony and County Wells, CA; Ion Exchange; Full-scale; Groundwater; Ongoing	A non-regenerable, nitrate-selective anion exchange system is being applied at full-scale to treat perchlorate-contaminated groundwater at this site. The ion exchange system at this site is operating at 10,000 gpm.	Period of Performance: Not available – Ongoing Initial perchlorate concentration in groundwater is 15 µg/L. Effluent perchlorate concentrations are less than 4 µg/L.	1. Cal EPA. 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January. 2. EPA. 2004q. E-mail messages regarding perchlorate detection. From Kevin Mayer to John Quander. November 9.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Rialto-Colton Site, San Bernardino County, CA; Ion Exchange; Full-scale; Groundwater; Ongoing	Groundwater at this site is contaminated with perchlorate and trichloroethene (TCE). Six fixed bed, non-regenerable anion exchange systems are currently operating at this site for perchlorate removal. A seventh regenerable system is under construction. Total treatment capacity is approximately 16,000 gpm.	Period of Performance: August 2003 – Ongoing Perchlorate concentrations in untreated water varied from approximately 4 to 20 µg/L. Perchlorate concentrations in treated water are less than 4 µg/L.	1. EPA. 2004p. E-mail message regarding perchlorate treatment. From Wayne Praskins (EPA Region 9) to Sashi Vissa. December 8. 2. Cal EPA. 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January.
San Gabriel Valley Area 2 Superfund Site, (also known as Baldwin Park Operable Unit); Los Angeles County, CA; Ion Exchange; Full-scale; Groundwater; Ongoing	Groundwater at this site is contaminated with perchlorate, nitrosodimethylamine (NDMA), and volatile organic compounds (VOCs). One regenerable anion exchange system has been operating since 2001. Two additional regenerable systems have been constructed and are in the start-up phase. A fourth non-regenerable system is in construction. Total treatment capacity of the four systems is approximately 25,900 gpm.	Period of Performance: 2001 – present Perchlorate concentrations in the untreated water at the operating treatment system have varied from approximately 40 to 75 µg/L since treatment was installed. Perchlorate concentration in treated water have been less than 4 µg/L.	1. Calgon Carbon Corp. 1998. Case Study: Calgon Carbon Corp. - ISEP® Continuous Ion Exchange. December. Available at http://www.perchlorateinfo.com/perchlorate-case-15.html. Downloaded July 2004. 2. EPA. 2004p. E-mail message regarding perchlorate treatment. From Wayne Praskins (EPA Region 9) to Sashi Vissa. December 8.
West Valley Water Co., West San Bernardino, CA; Ion Exchange; Full-scale; Drinking Water; Ongoing	A fixed bed, non-regenerable anion exchange resin is being used at full scale for removal of perchlorate in drinking water wells at this site.	Period of Performance: May 2003 – Ongoing Technology performance data not provided.	ITRC. 2005. Overview: Perchlorate Overview. Draft. March.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Edwards Air Force Base (AFB), CA; Ion Exchange; Groundwater; Pilot-scale; Completed	Groundwater at this site is contaminated with perchlorate, nitrate, and volatile organics. A perchlorate-selective anion exchange resin was used to remove perchlorate from groundwater. This pilot study involved the use of both bifunctional (two quarternary ammonium groups) and monofunctional resin columns in parallel. Each ion exchange column was 2 inches in diameter and 12 inches in depth. The system flow rate ranged from 0.11 to 0.15 gpm. A polishing column was used to capture residual perchlorate from the treated groundwater.	Period of Performance: Not available Average concentration of perchlorate in the influent groundwater was 450 µg/L. Effluent perchlorate concentrations were reduced to less than 3 µg/L.	1. Gu, Baohua, Brown, Gilbert M., and Ku, Yee-Kyoung. 2002. "Treatment of Perchlorate-Contaminated Groundwater Using Highly Selective, Regenerable Ion-Exchange Technology: A Pilot-Scale Demonstration." *Remediation*. Spring 2002. 2. Gu, Baohua and Brown, G.M. 2000. Bifunctional Anion Exchange Resin Pilot – Edwards AFB, CA. Available at: http://www.perchlorateinfo.com/perchlorate-case-10.html. Downloaded July 2004.
Massachusetts Military Reservation, MA; Ion Exchange; Groundwater; Pilot-scale; Completed	Study processed 900,000 gallons of groundwater. Samples were collected at the outlet of the treatment vessel. The system processed approximately 60,000 bed volumes at an empty-bed-contact time of approximately 5 minutes without breakthrough for a six month pilot test period.	Period of Performance: January 2004 – July 2004 Perchlorate influent concentration ranged from 1.88 to 3.9 µg/L. All effluent concentrations were below the detection level of 0.35 µg/L.	EPA. 2004l. E-mail message regarding perchlorate treatment. From Jane Dolan (EPA Region 1) to John Quander. November 9.
Vandenberg AFB, Lampac, CA; Ion Exchange; Pilot-scale; Groundwater; Ongoing	A perchlorate-selective, strong base anion resin is being used at this site for perchlorate removal. One ion exchange system is operating at the site as of November 2004. The flow rate (90-day average) is 3,800 gallons per day. The treatment system consists of two 560-gallon ion exchange vessels with 42 cubic feet of resin.	Period of Performance: Not available – Ongoing Technology performance data not provided.	EPA. 2004g. E-mail message regarding perchlorate treatment. From David Athey (California Water Quality Control Board) to Sashi Vissa. November 3.

Factors Affecting Ion Exchange Performance

- **Presence of Competing Ions** – Competition for the exchange ion can reduce the effectiveness of ion exchange if ions in the resin are replaced by ions other than perchlorate–such as nitrate, sulfate, and bicarbonate – resulting in a need for more frequent bed regeneration (FRTR, 2005; Boodoo, 2003a; Gingras and Batista, 2002; Gu and Brown, 2002).

- **Fouling** – Presence of organics, suspended solids, calcium, or iron, can foul ion exchange resins; this can reduce the effectiveness of the treatment system due to clogging of the resin bed (FRTR, 2005; EPA OSWER, 2002; Boodoo, 2003b; Gu et al., 2002).

- **Influent Water Quality** – Presence of oxidants in the influent water can impede performance of the ion exchange resin (FRTR, 2005).

Potential Limitations

Treated water from ion exchange systems using chloride-form resins could contain increased levels of chloride ions and thus be corrosive to the treatment system equipment. The ion exchange process can also lower the pH of treated waters (Boodoo, 2003a; EPA OSWER, 2002).

Spent regenerating solution from regenerable ion exchange resins used to remove perchlorate from water might contain a high concentration of perchlorate and other sorbed contaminants. Spent resin from a regenerable ion exchange system may require treatment prior to reuse. Used resin from a disposable ion exchange system may likewise require treatment prior to disposal (FRTR, 2005; Boodoo, 2003b; Gingras and Batista, 2002; Gu et al., 1999; EPA OSWER, 2002).

Summary of Cost Data

Costs of ion exchange generally compare favorably with costs for aboveground water treatment technologies, according to the FRTR http://www.frtr.gov/matrix2/section3/table3_2.html Factors affecting ion exchange cost include the approach used for bed regeneration and pretreatment activities. For example, the presence of suspended solids, oxidants, and calcium may require pretreatments that can increase costs.

Case Study: Aerojet General Corp. Superfund Site, Rancho Cordova, CA

The Aerojet General Corp. Superfund site has groundwater contaminated with perchlorate, nitrates, 1,4-dioxane, nitrosodimethylamine (NDMA), trichloroethene (TCE), tetrachloroethene (PCE), and chloroform. A full-scale, selective ion exchange system consisting of a non-regenerable perchlorate-selective resin is being used to remove perchlorate. The system currently operates at a flow rate of 400 gallons per minute (gpm), and the flow rate is expected to increase to 1,500 gpm by June 2005. Two or three separate ion exchange systems with capacities ranging from 800 to 3,500 gpm will be installed at this site in addition to the system currently operating. The first unit began operating at 400 gpm in August 2004. The average initial concentration of perchlorate is 50 µg/L. The concentration of perchlorate in treated effluent is less than 4 µg/L (Cal EPA, 2004; EPA, 2004c).

3.2 Bioreactor

Summary

A bioreactor frequently serves as an ex situ technology for removing perchlorate from contaminated groundwater and surface water at full scale. This technology uses microorganisms capable of reducing perchlorate into chloride and oxygen in the presence of an electron donor and an appropriate medium to support microbial growth. Bioreactors have been used at sites to reduce perchlorate concentrations to less than 4 µg/L.

Technology Principles

Bioreactors treat contaminated water aboveground in a reactor vessel. Contaminated water is placed in direct contact with microbes that selectively degrade the contaminant of concern.

Denitrification bacteria have been found to be capable of degrading perchlorate to chloride and oxygen. The process requires an electron donor and an appropriate substrate to support bacterial growth. Perchlorate serves as the oxygen source in this process. Some commonly used electron donors are acetic acid, ethanol, methanol, and hydrogen. Addition of nutrients such as ammonia and phosphorus may be required to enhance microbial growth (Evans et al., 2002; Evans et al., 2003; Clark et al., 2001; Hall, 2000a; Hall 200b).

Perchlorate-Contaminated Media Treated

- Groundwater
- Drinking Water

Chemicals and Nutrients Used for Perchlorate Removal by Bioreactors

- Acetic acid
- Ethanol
- Methanol
- Hydrogen
- Ammonia
- Phosphorus
- Urea

Perchlorate Transformation/Biodegradation

Microbial degradation of perchlorate proceeds according to the following anaerobic reduction process:

$$ClO_4^- \rightarrow ClO_3^- \rightarrow ClO_2^- \rightarrow Cl^- + O_2$$

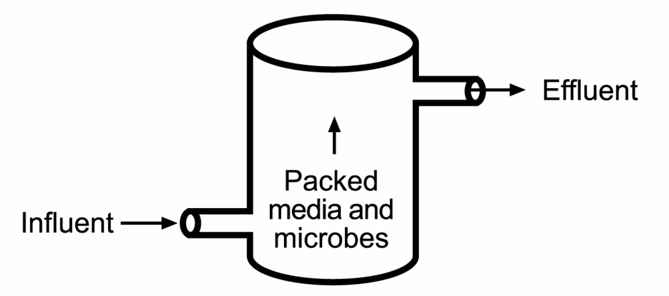
The rate limiting step in this process is degradation of perchlorate to chlorate. More than 30 different strains of perchlorate-degrading microbes have been identified, with many classified in the Proteobacteria class of the bacteria kingdom. Soil and groundwater samplings have confirmed the pervasiveness of perchlorate-reducing bacteria (Polk et al., 2001; Naval Facilities Engineering Command [NAVFAC], 2000).

Ongoing research suggests that perchlorate destruction involves a three-step reduction process catalyzed by two enzymes. A perchlorate reductase enzyme catalyzes reduction of perchlorate (ClO_4^-) to chlorate (ClO_3^-) and then to chlorite (ClO_2^-). A chlorite dismutase enzyme then causes a further breakdown of chlorite to chloride (Cl^-) and oxygen (O_2) (Polk et al., 2001; Sartain and Craig, 2003; EPA, 2001b; Beisel et al., 2004).

Technology Description

Fluidized bed reactors and packed bed reactors are two types of commercially available bioreactors. Packed or fixed bed bioreactors are made up of static sand or plastic media to support the growth of microbes, as shown in Figure 3.2-1. Fluidized bed bioreactors are made up of suspended sand or granular-activated carbon media to support microbial activity and growth of biomass. The activated carbon media are selected to produce a low-concentration effluent (i.e., at part-per-billion levels). Fluidized systems provide larger surface area for growth of microorganisms. The fluidized bed expands with the increased growth of biofilms on the media particles. The result of this biological growth is a system capable of additional degradative performance for target contaminants in a smaller reactor volume than with a fixed bed. However, the fluidized bed reactors generally require greater pumping rates than fixed beds (Evans et al., 2002; Polk et al., 2001; Hatzinger et al., 2000; NAVFAC, 2000; Nerenberg et al., 2003).

Figure 3.2-1. Bioreactor System for Perchlorate Treatment (Urbansky and Schock, 1999)



Type, Number, and Scale of Identified Projects

Bioreactors for perchlorate-contaminated water are commercially available. Information is available on three full-scale and five pilot-scale applications of bioreactors.

Summary of Performance Data

Table 3.2-1 summarizes available performance data for full- and pilot-scale treatment of perchlorate-contaminated water using bioreactor technology. As discussed above, cleanup goals varied by site and type of project. When provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end-use, and other factors.

Information is available on four full-scale applications, including three applications for environmental media and one for drinking water. Five pilot-scale applications, including four applications for environmental media and one for drinking water, have also been identified. For the seven groundwater projects, influent concentrations of perchlorate ranged from 55 to 200,000 µg/L, while the effluent concentration ranged from 2 to 18 µg/L. For the drinking water project, influent concentrations of perchlorate ranged from 75 to 2,500 µg/L, while the effluent concentrations were less than 4 µg/L (Clark et al., 2001; EPA, 2001b; EPA Region 9, 2004; Polk et al., 2001; Beisel et al., 2004; Sartain and Craig, 2003; Nerenberg et al., 2003; Evans et al., 2003; Catts, 1998).

A case study about Longhorn Army Ammunition Plant, provided at the end of this section, describes use of a full-scale fluidized bed bioreactor to remove perchlorate from groundwater.

Factors Affecting Bioreactor Performance

- **Dissolved Oxygen (DO)** – Lower levels of DO in influent water may limit aerobic activity to a small portion of the reactor, leaving most of the bioreactor available for perchlorate and nitrate degradation. One study suggests that the optimum range of DO concentration in the influent water to enable perchlorate destruction is 0.5 to 1.0 mg/L. When DO levels drop below 0.5 mg/L, anaerobic conditions develop that, in the presence of sulfates, result in the formation of hydrogen sulfide (EPA, 2001b; Hall, 2000a).

- **Presence of Nitrate** – One study indicated that removal of nitrate ions from the influent water is required to achieve complete destruction of perchlorate (NAVFAC, 2000).

- **Carbon and Nutrient Feed** – Consistent and adequate dosage of carbon source (electron donor) and nutrients are required for growth of microorganisms on the reactor bed (FRTR, 2005; Evans et al., 2002).

- **Backwash** – Control of excessive microbial growth with a backwash strategy is essential to eliminate short-circuiting and flow channeling in the bioreactor system (Evans et al., 2002; Hatzinger et al., 2000; NAVFAC, 2000; Nerenberg et al., 2003; Polk, 2001).

Table 3.2-1. Bioreactor Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Aerojet General Corp. Superfund Site, Rancho Cordova, CA; Bioreactor; Drinking Water; Full-scale; Ongoing	Drinking water at this site is contaminated with perchlorate, nitrates, and chlorinated solvents. A bioreactor is being used as part of a treatment train to treat perchlorate. The system consists of a bioreactor for perchlorate, nitrate and nitrite, an ultraviolet (UV) oxidation system for nitrosodimethylamine (NDMA), 1,4-dioxane and high concentration volatile organic compounds (VOCs), an air stripper for remaining VOCs, and a disinfection system to destroy pathogens. The bioreactor system at this site is a full scale unit with a capacity of approximately 7.8 million gallons per day (5,400 gallons per minute [gpm]). The system consists of four 22 feet tall, 14 feet wide, and 15 feet deep stainless steel reactor vessels. It is an upflow, fluidized bed system and includes use of an ethanol feed for enhanced bioremediation.	Period of Performance: October 1, 1999 – Ongoing An average influent perchlorate concentration of 2,500 µg/L is being reduced to less than 4 µg/L by the bioreactor system.	1. Clark, Robert, Kavanaugh, Michael, McCarty, Perry, and Trussell, R. Rhodes. 2001. “Review of Phase 2 Treatability Study Aerojet Facility at Rancho Cordova, California – Expert Panel Final Report.” July. 2. EPA. 2001b. “Phase 2 Treatability Study Report Aerojet GET E/F Treatment Facility Sacremento, California.” September. 3. California Environmental Protection Agency (Cal EPA). 2004. “Perchlorate Contamination Treatment Alternatives: Draft.” January. 4. EPA. 2004c. E-mail message regarding perchlorate treatment. From Charles Berrey (EPA Region 9) to Sashi Vissa (Tetra Tech EM Inc.). September 13.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Kerr McGee, Henderson, NV; Bioreactor; Groundwater; Full-scale; Ongoing	A fluidized-bed reactor (FBR) with a maximum capacity of 1,000 gpm successfully completed a 30-day Performance Test in November 2004. It is currently treating approximately 1,000 gpm of perchlorate contaminated water. The treatment system consists of four primary and four secondary FBRs, using sand and granulated activated carbon, respectively, as media.	Period of Performance: January 2004 – Ongoing Influent perchlorate concentration in ground water entering the FBR system is approximately 200,000 µg/L. Perchlorate concentrations in the FBR effluent are less than 18 µg/L.	1. EPA Region 9. 2004. “Perchlorate in Henderson, NV – Significant controls are operating.” July. 2. EPA Region 9. 2005i. E-mail message regarding perchlorate treatment. From Larry Bowerman (EPA Region 9) to John Quander. June 24.
Longhorn Army Ammunition Plant Superfund site, Karnack, TX; Bioreactor; Full-scale; Groundwater; Ongoing	Groundwater at this site is contaminated with perchlorate, metals, and volatile organics. A full-scale fluidized bed reactor system with a design flow rate of 35 to 50 gpm (actual average flow rate of 50 gpm) began operating at the site in February 2001. The reactor vessel is 5 feet in diameter and 21 feet tall. Components of the system include an FBR vessel with granular activated carbon (GAC) media and an FBR equipment skid. The FBR is inoculated with pre-conditioned GAC containing biosolids acclimated to perchlorate removal. Acetic acid and inorganic nutrients are added to the water. The influent water is distributed through a proprietary distribution header at the bottom of the reactor. Excess biomass is removed from the media bed to prevent the carbon particles from being carried out of the reactor.	Period of Performance: February 2001 – Present Within three weeks of inoculation of the FBR, the system began achieving the treatment goal of <13 µg/L daily maximum effluent concentration and <6 µg/L daily average concentration of perchlorate. The FBR has routinely achieved perchlorate effluent concentrations of <4 µg/L (analytical detection limit).	1. Polk, J., Murray, C., Onewokae, C., Tolbert, D.E., Togna, A.P., Guarini, W.J., Frisch, S., and Del Vecchio, M. 2001. “Case Study of Ex-Situ Biological Treatment of Perchlorate-Contaminated Groundwater.” Presented at the 4th Tri-Services Environmental Technology Symposium. June 18 – 20. 2. EPA. 2004d. E-mail message regarding perchlorate treatment. From Chris Villarreal (EPA Region 6) to Sashi Vissa. September 8.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Naval Weapons Industrial Reserve Plant, McGregor, TX; Bioreactor; Full-scale; Groundwater; Ongoing	Groundwater at this site is contaminated with perchlorate. A full-scale fluidized bed bioreactor has been operating at this site since January 2002. The FBR system is 21-feet tall with a 5-feet diameter. The influent flow rates have ranged from 15 to 400 gpm and have averaged 150 gpm.	Period of Performance: January 2002 – Ongoing Influent perchlorate concentrations in groundwater ranged from 540 to 4,800 µg/L. Perchlorate concentrations in the effluent have consistently been less than 4 µg/L except for two upsets, when the acetic acid lines had been crimped.	1. Sartain, Hunter S. and Craig, Mark (CH2MHill). 2003. "Ex Situ Treatment of Perchlorate-Contaminated Groundwater." Presented at In Situ and On-Site Bioremediation – The Seventh International Symposium. June 2 – 5. 2. Beisel, Thomas H., Craig, Mark, and Perlmutter, Mike. 2004. "Ex-Situ Treatment of Perchlorate Contaminated Groundwater." Presented at National Ground Water Association (NGWA) Conference on MTBE and Perchlorate. June 3 – 4. 3. EPA. 2004f. E-mail message regarding perchlorate treatment. From Bob Sturdivant (EPA Region 6) to Sashi Vissa. September 28.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
American Waterworks Association – Research Treatment Study, CA; DoD Facility; Bioreactor; Pilot-scale; Groundwater; Completed	This site is a Department of Defense (DoD) facility located in Southern California. Perchlorate concentrations in the groundwater at this site ranged from 300 to 1,000 µg/L. A pilot-scale bioreactor system was tested at this site. Components of the bioreactor system included the following: Baker tank, deaeration reactor, methanol tank, and patented Hall reactor. Groundwater was pumped and stored in the Baker tank for homogenization. Water was then drawn from the Baker tank into the top of the deaeration reactor. The deaeration reactor contained bio-balls that provided surface area for bacterial growth. The reactor is designed to reduce the dissolved oxygen concentration to 0.5 to 1.0 mg/L. From the bottom of the deaeration reactor, water was drawn into the bottom of the Hall reactor. The Hall reactor contains floating media (polyurethane-based sponge media) that is cut into one-centimeter cubes. The media provide support to the bacteria colonies. Methanol is fed into the two reactor vessels to serve as a carbon source. Temperatures ranging between 8 °C and 35 °C were maintained for the bioreactor system.	Period of Performance: December 1999 – March 2000 Perchlorate concentrations of 300 µg/L in the influent groundwater were reduced to non-detect levels (detection limits not provided).	1. Hall, Peter J. (EcoMat, Inc.). 2000a. "Perchlorate Treatment at a DoD Facility." 2. Hall, Peter. 2000b. Patented Hall Bioreactor. Available at: http://www.perchlorateinfo.com/perchlorate-case-43.html. Downloaded July 2004. 3. EPA. 2004o. Record of telephone conversation between Sashi Vissa and Kevin Mayer. September 24.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Lockheed Propulsion Company, Redlands, CA – Redlands Plume; Bioreactor; Pilot-scale; Drinking Water; Completed	This pilot-scale study involved the use of a packed-bed anaerobic bioreactor for biotreatment of perchlorate in groundwater. Other contaminants of concern at this site included nitrates and chlorinated VOCs. A constant supply of acetic acid was provided and a weekly backwash was performed. The bioreactors used in this demonstration were up-flow packed-bed reactors containing sand or plastic media. The plastic media floating in water was held down with a perforated plate. Reactor height was 7 ft. Groundwater was pumped to an equalization tank, followed by addition of acetic acid and ammonium phosphate at concentrations of approximately 50 mg/L and 4 mg-N/L, respectively. Biological reactions in the reactors were initiated by bioaugmentation of the columns with a perchlorate-respiring bacterial strain. Excess microbial growth was removed by backwashing with an air scour. This process also helped minimize short-circuiting.	Period of Performance: May 2001 – September 2001 Perchlorate concentration in the influent groundwater averaged 75 µg/L. The average concentration of perchlorate in effluent was less than the detection limit (4 µg/L) when treated at a flow rate of 1 gpm. At a flow rate of 2 gpm, the effluent perchlorate concentrations frequently exceeded 4 µg/L. Poor performance was observed during the first 2 months of system start up, which was attributed to the time required to develop an active biofilm on the media. During this time, a backwash strategy was developed to eliminate backpressures or clogging in the system.	1. Evans, Patrick, Chu, Allyson, Liao, Stephen, Price, Steve, Moody, Mieko, Headrick, Doug, Min, Booki, and Logan, Bruce. 2002. "Pilot Testing of a Bioreactor for Perchlorate-Contaminated Groundwater Treatment." Presented at the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds, May 20 – 23. 2. Evans, Patrick, Price, Steve, Min, Booki, and Logan, Bruce. 2003. "Biotreatment and Downstream Processing of Perchlorate Contaminated Groundwater." Presented at In Situ and On-Site Bioremediation – The Seventh International Symposium. June 2 – 5.
Massachussetts Military Reservation, Cape Cod, MA; Bioreactor; Groundwater; Pilot-scale; Completed	A pilot-scale FBR was tested at this site to treat perchlorate in groundwater. Other contaminants at this site include RDX, HMX, and nitrate. Acetic acid was used as electron donor.	Period of Performance: Not available Influent perchlorate concentration in groundwater was 100 µg/L. Perchlorate in effluent was less than the detection limit of 4 µg/L.	The Interstate Technology Regulatory Council (ITRC). 2005. Overview: Perchlorate Overview. Draft. March.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
NASA/California Institute of Technology Jet Propulsion Laboratory, Pasadena, CA; Bioreactor; Groundwater; Pilot-scale; Completed	Groundwater at this site is contaminated with perchlorate, nitrate, and volatile organics. The pilot-scale fluidized bed reactor being tested at this site is a fixed-film reactor column that fosters the growth of microorganisms on a hydraulically fluidized bed of media (activated carbon). The reactor vessel is 15 feet tall and 20 inches in diameter. The basic components of the system are the bioreactor, granular activated carbon bed media, a fluid distribution system in the bottom of the reactor, feed and influent pumps, a nutrient addition system, a pH control mechanism and a bed height control component when required. Nitrogen and phosphorous (in the form of dibasic ammonium phosphate and urea) and ethanol are pumped continually into the reactor. Activated carbon also was used to adsorb organics from the groundwater, leading to secondary removal of degradable organics.	Period of Performance: October 2000 – December 2000 Influent perchlorate concentrations in groundwater ranged from 350 to 740 µg/L. Perchlorate concentrations in the effluent water were reduced to non-detectable levels with a detection limit of 4 µg/L. The only waste byproduct generated from this system was a small volume of excess biosolids. These solids are removed from the system on a continuous basis.	1. Naval Facilities Engineering Command (NAVFAC). 2000. NASA/California Institute of Technology Jet Propulsion Laboratory, Anoxic FBR. Pasadena, CA. Available at: http://www.perchlorateinfo.com/perchlorate-case-40.html. Downloaded July 2004. 2. EPA. 2004k. Record of telephone conversation between Sashi Vissa and Mark Ripperda (US EPA Region 9). September 23.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
San Gabriel Valley Superfund Site, La Puente, CA; Bioreactor; Groundwater; Pilot-scale; Completed	This is a Superfund site with perchlorate and nitrate contamination in groundwater. A pilot-scale hollow-fiber membrane biofilm reactor (HFMBfR) for perchlorate removal was tested at this site. This technology uses hydrogen gas as an electron donor to fuel microbial reduction of perchlorate to chloride ion. A key feature of the HFMBfR is that hydrogen gas diffuses through the wall of a composite membrane, and an autotrophic biofilm naturally develops on the outside of the membrane, where the bacteria reduce perchlorate. The pilot plant included two HFMBfRs in series, followed by an aeration basin and a granular media filter. The HFMBfR consisted of a bundle of hydrophobic hollow-fiber membranes collected into a hydrogen-supplying manifold at one end and sealed at the other. The hollow fiber membranes were 280 micrometers (µm) in diameter with a 40-µm wall. They were made of two materials: a 1-µm layer of dense polyurethane encased within microporous polyethylene. Hydrogen was supplied under pressure to the interior of the fibers and diffused through the wall to a biofilm growing on the fiber surface.	Period of Performance: December 1997 – March 1998 The influent perchlorate concentration was 55 µg/L, which was reduced to 2 µg/L in the effluent.	1. Nerenberg, Robert, Rittmann, Bruce E., Gillogly, Thomas E., Lehman, Geno E., and Adham, Samer S. 2003. “Perchlorate reduction using a hollow-fiber membrane biofilm reactor: kinetics, microbial ecology, and pilot-scale studies.” Presented at In Situ and On-Site Bioremediation – The Seventh International Symposium. June 2 – 5. 2. Catts, John J., 1998. Biological Treatment at Low Concentrations in Water-Phase 2 La Puente, CA. Available at: http://www.perchlorateinfo.com/perchlorate-case-13.html. Downloaded July 2004.

Potential Limitations

Normally, the treated effluent is suitable for discharge, but when applied for drinking water treatment, the effluent from bioreactors might require further treatment to remove biosolids present in the effluent (Evans, 2002). Fluidized bed bioreactors usually require a thorough mixing and upward flow of the fluid inside the reactor. One key advantage of a fluidized bed system is availability of a large surface area for growth of biomass. However, to maintain required flow inside the reactor vessel relatively greater pumping rates are required (EPA, 2001b). Moreover, because fixed-bed systems are more susceptible to accumulation of biosolids, they require periodic back-flushing to avoid plugging or clogging the bed (Evans et al., 2002; Hatzinger et al., 2000; Polk et al., 2001; NAVFAC, 2000; Nerenberg et al., 2003).

Summary of Cost Data

Costs of bioreactors generally are about the same as costs for above-ground treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Case Study: Longhorn Army Ammunition Plant Superfund Site, Karnack, TX

The Longhorn Army Ammunition Plant Superfund site has groundwater contaminated with perchlorate and volatile organics. A full-scale fluidized bed reactor (FBR) system with a treatment capacity of 50 gallons per minute (gpm) began operating at the site in February 2001. Components of the system include a FBR vessel with granular activated carbon (GAC) media and an FBR equipment skid. The reactor vessel is 5 feet in diameter and 21 feet tall. The FBR is inoculated with pre-conditioned GAC containing biosolids acclimated to perchlorate removal. The influent water is distributed through a proprietary distribution header at the bottom of the reactor. Excess biomass is removed from the media bed to prevent escape of carbon particles from the reactor. Contaminated groundwater is fed into the equalization tank and then pumped into the FBR vessel at an average flow rate of 30 to 35 gpm. Acetic acid and inorganic nutrients are added to serve as electron donor and bacterial feed, respectively.

Within three weeks of inoculation of the FBR, the system began achieving the treatment objective of <350 µg/L effluent concentrations. In normal operations, the FBR has removed perchlorate to achieve concentration levels below the analytical limit of 4 µg/L (Polk et al., 2001; EPA, 2004d).

3.3 Liquid Phase Carbon Adsorption

Summary

Liquid phase carbon adsorption using granular activated carbon (GAC) is an ex situ technology to remove perchlorate from contaminated groundwater and surface water. Among the projects identified for this report, GAC has been used infrequently for treatment of perchlorate. In this technology, GAC is the adsorbent to remove contaminant ions from water as it passes through the GAC bed. However, GAC has a relatively small treatment capacity for perchlorate removal, and research is underway to identify methods to improve the treatment capacity of a GAC system for perchlorate removal, including use of "tailored GAC." Tailored GAC technology is currently being tested on a pilot-scale at one site. As discussed above, GAC also has been used in conjunction with bioreactors, including the role of substrate for biodegradation processes.

Technology Principles

Liquid-phase carbon adsorption typically involves use of adsorbent media such as GAC, activated alumina, or other proprietary media packed into a column (FRTR, 2005; Graham et al., 2004). GAC is an organic sorbent commonly used to remove organic and metallic contaminants from groundwater, drinking water, and wastewater. GAC media are usually regenerated by thermal techniques to desorb and volatilize contaminants. An off-gas treatment unit then captures the volatilized contaminants and treats the off-gas before release into the atmosphere (Graham et al., 2004). GAC media are generally considered cost-effective for water treatment when used for removal of non-polar contaminants with low water solubility (Graham et al., 2004; FRTR, 2005). Due to the issues discussed above, activated carbon is generally considered ineffective for removal of inorganic contaminants such as perchlorate from water.

Because GAC media lose effectiveness relatively fast when used for perchlorate removal, this technology is disadvantaged with low treatment capacities (Graham et al., 2004). Current research is seeking higher treatment capacities for perchlorate removal using GAC. An innovative approach to this, referred to as "tailored GAC," involves treatment of GAC with a quarternary amine (cetyl trimethyl ammonium chloride [CTAC]) to create ion exchange sites on the carbon. The carbon with ion exchange sites might become a cost-effective alternative to the polymers associated with standard ion exchange resins – perhaps with capability to simultaneously remove perchlorate and organic contaminants from groundwater (Graham et al., 2004; EPA, 2004l).

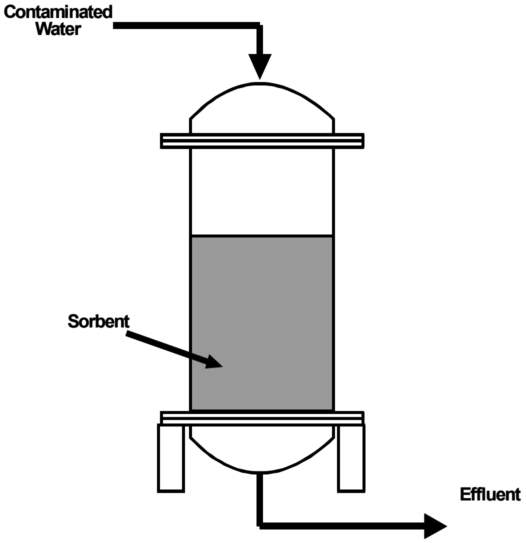
Carbon adsorption technology can apply multiple beds in series to reduce the need for media regeneration; beds first in the series will require regeneration first, and fresh beds can be added at the end of the series. Multiple beds can also allow continuous operation because some beds can be regenerated as others continue to treat water (Graham et al., 2004).

Technology Description

GAC is used as the adsorption media in liquid-phase carbon adsorption technology, typically for removal of VOCs from contaminated media. In this technology, contaminants are adsorbed to the surface of the activated carbon medium. GAC is usually packed into a column as shown in Figure 3.3-1. When contaminated water is passed through a GAC bed, contaminants are adsorbed to the media. When adsorption sites are filled with contaminant ions, the column must be regenerated or disposed of and replaced with new media (Graham et al., 2004; FRTR, 2005). Thermal decomposition of perchlorate-contaminated GAC is a possible regeneration method for spent GAC (Behrens and Minier, 1996; EPA, 2005c).

Recently, there has been discussion among experts about the types of mechanisms and effectiveness of tailored GAC for treatment of perchlorate. In addition, there have been questions raised about the potential use of tailored GAC for treatment of water contaminated with perchlorate and explosives such as Royal Demolition Explosives (RDX), cyclotetramethylene trinitramine (HMX), and trinitrotoluene (TNT) and VOCs (i.e., co-contaminated groundwater). For sites that have co-contaminated groundwater, practitioners have suggested the potential for use of treatment trains consisting of standard GAC/Ion Exchange (GAC/IX) resins or tailored GAC/standard GAC. For example, a treatability study was recently conducted at the Massachussetts Military Reservation (MMR) site about innovative options for ex-situ removal of perchlorate and explosives in groundwater (Weeks, et al., 2004). Discussion is ongoing about the lifecycle cost comparisons of these types of technologies and treatment trains. Technical issues include the effectiveness of these technologies for contaminant removal, and whether levels of other common groundwater ions such as nitrate and sulfate will "plug" the tailored GAC and result in faster breakthrough times for perchlorate. Further discussion about these issues is beyond the scope of this paper.

Figure 3.3-1. Granulated Activated Carbon (GAC) Adsorption for Perchlorate Removal (EPA OSWER, 2002)



Perchlorate-Contaminated Media Treated

- Groundwater
- Drinking Water

Type, Number, and Scale of Identified Projects

Two full-scale and two pilot-scale applications have been identified that used GAC for perchlorate removal from groundwater and drinking water.

Summary of Performance Data

Table 3.3-1 summarizes performance data for treatment of perchlorate-contaminated water using GAC. As discussed above, cleanup goals varied by site and type of project. Where provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end-use, and other factors.

Information was available on two full-scale and two pilot-scale applications. For the two groundwater projects, influent perchlorate concentrations ranged from 1.8 to 5 µg/L, while the effluent concentrations were less than 0.35 µg/L. For the two drinking water projects, influent concentrations of perchlorate ranged from 75 to 92 µg/L. Effluent concentrations were not provided for these two projects (Graham et al., 2004; FRTR, 2005; EPA, 2004l).

Factors Affecting GAC Performance

- **Flow Rate** – Increasing the rate of flow through the adsorption column can decrease adsorption of contaminants (Graham et al., 2004; FRTR, 2005).
- **Polarity and Water Solubility** – Water-soluble contaminants with high polarity can reduce the ability of GAC to remove contaminants from water (FRTR, 2005).
- **Fouling** – Presence of suspended solids, organics, silica, or mica can foul adsorption media (Graham et al., 2004).

Table 3.3-1. Granulated Activated Carbon (GAC) Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Edwards Air Force Base (AFB), CA; GAC-adsorption; Full-scale; Drinking Water; Ongoing	Perchlorate contamination at this site is being treated by a liquid-phase activated carbon system. The system includes three 2,000 pound (lb) canisters in series. This GAC system was originally constructed in 2001 for removal of volatile organic compounds (VOCs). It is currently being used for perchlorate removal.	Period of Performance: May 2001 – Ongoing Initial perchlorate concentration was 92 µg/L. Final concentration of perchlorate was not provided.	The Interstate Technology Regulatory Council (ITRC). 2005. Overview: Perchlorate Overview. Draft. March.
Pew Road Treatment System; Massachussetts Military Reservation, Cape Cod, MA; GAC; Groundwater; Full-scale; Ongoing	Beginning in August 2004, this full-scale treatment system currently operates at 100 gallons per minute (gpm) and treats perchlorate and explosives contaminated groundwater. A treatment train uses a series of three units with each packed with 2,000 lbs of GAC media.	Period of Performance: August 2004 – Ongoing In October 2004, influent concentration of perchlorate was approximately 5 µg/L. Effluent concentration is below the detection limit (reporting limit = 0.35 µg/L)	EPA. 2004l. E-mail message regarding perchlorate treatment. From Jane Dolan (EPA Region 1) to John Quander (EPA Office of Superfund Remediation and Technology Innovation). November 9.
Lockheed Propulsion Company, Redlands, CA - Redlands Plume; GAC-adsorption; Pilot-scale; Drinking Water; Ongoing	This demonstration study involved the use of an activated carbon tailored with cetyltrimethyl ammonium chloride (CTAC) for the removal of perchlorate and organic contaminants from groundwater. Other contaminants of concern at this site include nitrates and VOCs. Four adsorbers, each 10 feet in diameter and capable of holding 20,000 lbs of GAC are being tested at the site. The four adsorbers are operated as two treatment trains at a flow rate of 325 gpm. Each train consists of two GAC vessels with 10,000 pounds of mesoporous bituminous coal based activated carbon. The first bed in each train (lead bed) is treated with two different organic monomers using an in situ tailoring technique. The two lag beds are left untailored to serve as scavenger beds. These lag beds capture monomer that leaches from the lead beds.	Period of Performance: May 2004 – Ongoing Perchlorate concentration in the influent groundwater averaged 75 µg/L. Effluent perchlorate concentrations were not provided. This project will continue until the effluent perchlorate concentrations are reduced to 6 µg/L for more than two sampling events.	Graham, James R., Cannon, Fred S., Parette, Robert, Headrick, Douglas, and Yamamato, Gary. 2004. "Commercial Demonstration of the Use of Tailored Carbon for the Removal of Perchlorate Ions from Potable Water." Presented at National Groundwater Association Conference on MTBE and Perchlorate, Costa Mesa, CA. June 3-4.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Massachussetts Military Reservation, Cape Cod, MA; Tailored GAC; Groundwater; Pilot-scale; Completed	Study processed over 2,700,000 gallons of groundwater through three sets of GAC media (or 900,000 gallons through each medium).	Period of Performance: January 2004 – July 2004 Influent concentrations of perchlorate were 1.88 to 3.9 µg/L. All effluent concentrations were below the detection level of 0.35 µg/L.	EPA. 2004l. E-mail message regarding perchlorate treatment. From Jane Dolan (EPA Region 1) to John Quander. November 9.

Potential Limitations

GAC adsorption for perchlorate might require pretreatment for removal of suspended solids from streams to be treated. If not removed, suspended solids in a liquid stream may accumulate in the adsorption column, causing a pressure drop. The accumulated solids must then be removed by backwashing (FRTR, 2005). Waste streams with high amounts of suspended solids, oil, and grease may foul the carbon. Spent carbon from the adsorption unit may require treatment prior to ordinary or hazardous waste disposal (FRTR, 2005; Graham et al., 2004). Contaminants with high water solubility and polarity can reduce the ability of GAC to remove contaminants from water (FRTR, 2005).

Summary of Cost Data

Costs for GAC are generally about the same as costs for aboveground water treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Case Study: Lockheed Propulsion Company, Redlands Plume Site, Redlands, CA

The Redlands Plume site, located in the City of Redlands, California, is a municipal water supply site. Groundwater at the site is contaminated with perchlorate, nitrate, and volatile organics. An organic, cation-tailored, activated carbon is being tested at pilot scale for removal of perchlorate and organic contaminants from groundwater. The system began operating in May 2004. Four adsorbers, each 10 feet in diameter and capable of holding 20,000 pounds of GAC are under examination at this site. The four adsorbers operate as two treatment trains at a flow rate of 325 gpm. Each train consists of two GAC vessels with 10,000 pounds of mesoporous, bituminous, coal-based, activated carbon. The first bed in each train, called the lead bed, is treated with two different organic monomers using an in situ tailoring technique. The two lag beds are left untailored to serve as scavenger beds. These lag beds capture any monomer that might leach from the lead beds. Perchlorate concentration in the influent groundwater at this site ranges from 60 to 90 µg/L. Effluent perchlorate concentrations were not available. This project will continue until two or more sampling events show an effluent perchlorate concentration of 6 µg/L (Graham et al., 2004).

3.4 Composting

Summary

Composting is an ex situ technology that has been used only infrequently to treat perchlorate in contaminated soil. It is a biological process that uses indigenous microorganisms to degrade perchlorate in the presence of appropriate soil amendments that support microbial growth. This technology has been found to reduce perchlorate concentrations in soil to as low as 0.1 mg/kg.

Technology Principles

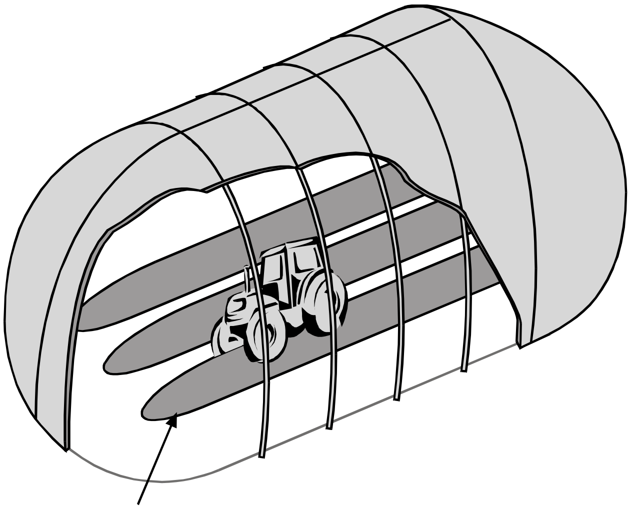
Composting is a controlled biological process in which microorganisms convert perchlorate to less harmful byproducts. Under anaerobic, thermophilic conditions (54 to 65 °C), soil contaminated with perchlorate is composted. Heat produced by microorganisms during degradation of the contaminants in the waste increases the temperature of the compost pile (FRTR, 2005; Roote, 2001). Additional information about perchlorate transformation and biodegradation, including microbial degradation pathways, is presented above under bioreactors.

Technology Description

Contaminated soil is excavated and mixed with bulking agents and organic amendments such as wood chips, hay, manure, and vegetative (e.g., potato) wastes. Selection of proper amendment is necessary to ensure adequate porosity and provide a balance of carbon and nitrogen to promote thermophilic, microbial activity. Monitoring of moisture content and temperature are important for achieving maximum degradation efficiency (FRTR, 2005; Cox et al., 2000a).

Composting has been performed using three types of process designs: aerated static pile composting (compost is formed into piles and aerated with blowers or vacuum pumps), mechanically agitated in-vessel composting (compost is placed in a reactor vessel where it is mixed and aerated), and windrow composting (compost is placed in long piles known as windrows and periodically mixed with mobile equipment). Figure 3.4-1 shows a simplified version of windrow composting (FRTR, 2005).

Figure 3.4-1. Composting for Perchlorate Treatment (FRTR, 2005)



Perchlorate-Contaminated Media Treated

- Soil

Type, Number, and Scale of Identified Projects

One full-scale and three pilot-scale demonstrations of anaerobic composting for treatment of perchlorate in soil have been identified.

Summary of Performance Data

Table 3.4-1 summarizes available performance data for treatment of perchlorate-contaminated soil using composting. As discussed above, cleanup goals varied by site and type of project. When provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end use, and other factors.

In the one full-scale project, measurements in six sampling locations indicated reduction of perchlorate concentrations in soil from 500 mg/kg to less than 270 mg/kg. In the three pilot-scale projects, final concentrations of perchlorate ranged from 0.1 to 23 mg/kg (Cox et al., 2000a; Cox et al., 2000c; EPA, 2004c; EPA, 2004o; Roote, 2001).

Table 3.4-1. Composting Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Naval Weapons Industrial Reserve Plant, McGregor, TX; Composting; Full-scale; Soil; Completed	Soil at this site is contaminated with perchlorate, and was transported to an onsite treatment cell. This engineered treatment cell was lined with a 30-mil high-density polyethylene (HDPE) liner. The cell was approximately six feet deep with a 500x30 feet bottom. Perchlorate-contaminated soil was placed approximately 2.5 feet deep in the cell. Prior to placing soil in the treatment cell, it was mixed with citric acid (carbon source), nitrate- and phosphate-fertilizers (micronutrients), and soda-ash (buffer). Soil was saturated as it was placed in the treatment cell. Approximately 2 inches of water was maintained above the soil to foster anaerobic conditions. The cell was covered with a 6-mil HDPE liner.	Period of Performance: October 1999 – April 2000 Influent perchlorate concentration in soil was 500 mg/kg. Perchlorate concentrations in the treated soil sampled at six different locations was less than 270 mg/kg.	Roote, Diane (Ground-Water Remediation Technologies Analysis Center [GWRTAC]). 2001. "Technology Status Report – Perchlorate Treatment Technologies, 1st Edition." May.
Aerojet General Corp. Superfund Site, Rancho Cordova, CA; Composting; Soil; Pilot-scale; Completed	This is a Superfund site containing perchlorate-contaminated soils. A pilot test of anaerobic composting was used to treat soil from the former perchlorate burn area. Approximately 20 cubic yards of soil was treated. Manure was initially placed on top of perchlorate hot spots. Compost was later tilled into soil to enhance perchlorate destruction 2 to 3 inches below the surface.	Period of Performance: June 2001 – October 2002 Maximum initial concentration of perchlorate in soil was 4,200 mg/kg. Average concentrations of perchlorate following seven days of treatment ranged from 0.1 to 23 mg/kg.	1. Cox, E., Edwards, E., Neville, S., and Girard, M. 2000a. Aerojet Bioremediation of Soil from Former Burn Area by Anaerobic Composting. Available at: http://www.perchlorateinfo.com/perchlorate-case-01.html. Downloaded July 2004. 2. California Environmental Protection Agency (Cal EPA). 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Edwards Air Force Base (AFB), CA; Composting; Pilot-scale; Soil; Completed	Anaerobic composting was tested at pilot-scale at this site. The study was conducted in 55-gallon drums. Horse stable compost was used as the electron donor to facilitate perchlorate reduction.	Period of Performance: Not available Initial concentration of perchlorate was 57 mg/kg. Perchlorate in the treated soil was less than the remedial goal of 7.8 mg/kg.	The Interstate Technology Regulatory Council (ITRC). 2005. Overview: Perchlorate Overview. Draft. March.
UTC Site, San Jose, CA; Composting; Pilot-scale; Soil; Completed	Soil at this site was contaminated with perchlorate. Anaerobic composting was tested at pilot scale to study its suitability for perchlorate treatment. The compost pile was 5 ft. high with a 7 feet diameter at the bottom. A plastic liner was placed underneath the pile, and soil berms were constructed around the circumference of the pile to prevent migration of leachate, if any. A plastic sheet was used to cover the top of the compost pile.	Period of Performance: Not available Average initial concentration of perchlorate was 170 mg/kg. Final concentration in composted soil after 38 days was less than 0.64 mg/kg.	1. Cox, E., Edwards, E., Neville, S., and Girard, M. 2000c. Rocket Manufacturing Site Soil Bioremediation by Anaerobic Composting. Available at: http://www.perchlorateinfo.com/perchlorate-case-52.html. Downloaded July 2004. 2. EPA. 2004o. Record of telephone conversation between Sashi Vissa (Tetra Tech EM Inc.) and Kevin Mayer (US EPA Region 9). September 24.

Summary of Cost Data

Costs for composting are generally compared favorably with costs for other aboveground soil treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Case Study: Aerojet General Corp. Superfund Site, Rancho Cordova, CA

The Aerojet General Corp. Superfund site is located in Rancho Cordova (Sacramento County), California. This site was formerly used for manufacturing rocket fuel. Soil at this site was 1 to 18 inches deep over fractured bedrock and consisted of low permeability silty clay soil contaminated with perchlorate at concentrations of up to 4,200 mg/kg. Anaerobic composting was applied to treat soil from the former perchlorate burn area at the site. Compost was then tilled 2 to 3 inches into the soil to enhance perchlorate degradation. Approximately 20 cubic yards of soil was treated during this pilot-scale demonstration. Perchlorate concentrations in treated soil ranged from 0.1 to 23 mg/kg after a seven-day treatment period (Cal EPA, 2004; Cox et al., 2000a; EPA, 2004c).

3.5 In Situ Bioremediation

Summary

In situ bioremediation (ISB) is a technology used frequently to treat perchlorate in contaminated groundwater and soil. It uses microorganisms capable of reducing perchlorate to chloride and oxygen under anaerobic conditions. This process requires supply of electron donor and an appropriate substrate to support microbial growth. ISB has reduced perchlorate concentrations to less than 4 µg/L in groundwater.

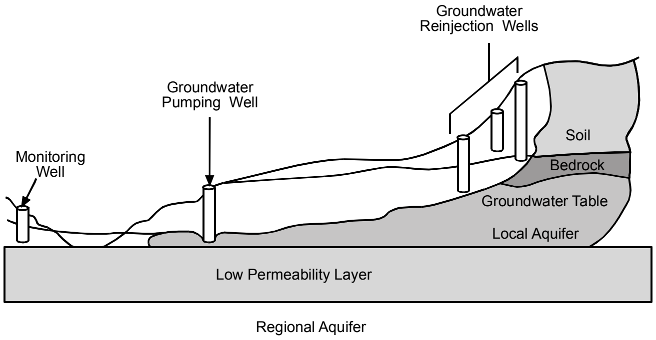
Technology Principles

In situ bioremediation (ISB) is a controlled biological process in which microorganisms convert perchlorate to chloride and oxygen. Bioremediation reduces perchlorate via enzymatic degradation by select species of bacteria under anaerobic conditions. This requires an adequate supply of nutrients to support microbial growth (Urbansky and Schock, 1999; Rosen, 2003). According to Urbansky and Schock (1999) certain bacteria have a natural tendency to degrade perchlorate into chloride and oxygen under anaerobic conditions. These bacteria include: *Ideonella dechloratans, Proteobacteria, Vibrio dechloraticans Cuzensove* B-1168, and *Wolinella succinogenes* HAP-1 (Urbansky and Schock, 1999). Other bacteria capable of reducing perchlorate have been identified in the genera *Dechloromonas* and *Dechlorosoma* (ITRC, 2005; Coates et al., 1999; Coates et al., 2000). Additional information about perchlorate transformation and biodegradation, including microbial degradation pathways, is presented above under bioreactors (see Section 3.2).

Technology Description

ISB of perchlorate typically involves enhancement techniques. Biological degradation of perchlorate requires select species of microorganisms, mostly bacteria, and sufficient amounts of amendments in the form of nutrients and electron donors (Urbansky and Schock, 1999; and Owsianiak et al., 2003). Some commonly used electron donors include organic acids such as acetate, citrate, and lactate; sugars such as glucose; alcohols such as ethanol; and protein-rich substances such as casamino acids and whey (ITRC, 2005). Similarly, vegetable oils and vegetable oil emulsions can also serve as electron donors with additional benefit of a slow-release substrate with extended longevity in the subsurface (Borden et al., 2004a; Henry et al., 2003). For enhanced ISB, the electron donor and nutrient material are injected into the contaminated zone. Number and spacing of injection points depend on several factors including extent of contaminant plume, design of the injection field (e.g., re-circulation, barrier, or grid), subsurface lithology, and type of material injected. The injected substances cause the perchlorate-reductive reactions to occur within the contaminated media (Owsianiak et al., 2003; Koenigsberg and Willett, 2004). As shown in Figure 3.5-1, another technique for bioremediation of perchlorate-contaminated groundwater involves extraction and aboveground treatment of contaminated water, followed by amendment with soluble electron-donor substrate (e.g., lactate, acetate, or ethanol). The amended water is then reinjected into the aquifer (Rosen, 2003). Reactions leading to biological degradation of perchlorate by in situ bioremediation are under investigation. Ongoing research indicates that perchlorate is reduced in a three-step process. First, perchlorate ion is reduced to ClO_3^-, then to ClO_2^-, and subsequently to Cl^-, and O_2. The reactions discussed above are catalyzed by the enzymes perchlorate reductase and chlorite dismutase (Beisel et al., 2004; NAVFAC, 2000; Polk et al., 2001).

Figure 3.5-1. In Situ Bioremediation (ISB) for Perchlorate Treatment (FRTR, 2005)



Perchlorate-Contaminated Media Treated

- Groundwater
- Soil

Type, Number, and Scale of Identified Projects

One full-scale and 10 pilot-scale demonstrations of ISB for treatment of perchlorate have been identified. Six of the 10 pilot-scale projects addressed treatment of groundwater, while the remaining four projects addressed treatment of soil.

Summary of Performance Data

Table 3.5-1 summarizes available performance data for treatment of perchlorate-contaminated groundwater and soil using ISB. As discussed above, cleanup goals varied by site and type of project. Where provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end-use, and other factors.

For the six pilot-scale groundwater projects, final concentrations ranged from 4 µg/L to 22 µg/L. For the four pilot-scale soil applications, final concentration of perchlorate ranged from 40 to 500 µg/kg (Rosen, 2003; Koenigsberg and Willett, 2004; Owsianik et al., 2003; Lieberman et al., 2004).

Factors Affecting ISB Performance

- **Type of Amendments** – Selection of an appropriate amendment is essential to provide adequate amounts of carbon and nitrogen required for microbial growth (ITRC, 2002; FRTR, 2005).

- **pH** – Solubilities and availabilities of many constituents that can affect biological activity in the soil depend on pH conditions (FRTR, 2005).

- **Hydrogeology** – Injection of amendments into the contaminated zone may be slow and difficult on a heterogeneous subsurface (FRTR, 2005).

Potential Limitations

ISB completely destroys perchlorate – yielding chloride and oxygen as end products (ITRC, 2002). However, water treated by this technology may not be acceptable for drinking purposes because of the presence of bacteria enhanced by the biotreatment process. Moreover, in some instances, the resulting strong reducing conditions in the aquifer have mobilized metals, including iron and manganese, and generated methane (EPA, 2005b). Proper care is necessary to ensure the adequate supply of nutrient amendments required for growth of bacterial population (FRTR, 2005).

Summary of Cost Data

Costs for ISB generally compare favorably with costs for groundwater treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Case Study: Aerojet General Corp. Superfund Site, Rancho Cordova, CA (Cox et al., 2000b; Cox and Scott, 2003; EPA, 2004c)

The Aerojet General Corp. Superfund site is located in Rancho Cordova, California. Phase I of a pilot project using in situ bioremediation was performed from 2000 through 2001 to assess the potential to jointly bioremediate perchlorate and trichloroethene (TCE), and to control migration of an 800 foot (ft) wide plume. The target aquifer was located at 100 ft below ground surface (bgs). The demonstration was designed as a closed loop with a recirculation rate of 5 to 10 gallons per minute (gpm) and a residence time of 21 days. One nutrient delivery and one extraction well were used, with two monitoring wells located between the delivery and extraction wells. Proprietary dehalorespiring bacteria (KB-1) were added in Phase I for TCE removal. Various electron donors were tried for perchlorate destruction, including calcium magnesium acetate, sodium acetate, and sodium lactate. Phase I showed that perchlorate could be reduced from 12,000,000 µg/L to levels below detection limits within 15 feet of the electron donor injection well. Information was not provided about the effectiveness of treatment for TCE during Phase I.

Phase II of the project was conducted from late 2001 through 2002 to determine the feasibility of a single pass active groundwater biobarrier for perchlorate destruction. Ethanol was added to the extracted groundwater as an electron donor. Phase II showed that perchlorate at 8,000 µg/L was reduced to less than 4 µg/L within 35 feet of the electron donor delivery system. The 72-day Phase II study showed that a combined perchlorate/TCE plume could be remediated with a single pass biobarrier with only a partial degradation of TCE.

A more recent demonstration used horizontal flow treatment wells in a deep area, screened from 48 to 63 ft bgs and at 80 to 100 ft bgs (separated by pneumatic packers). This zone was used to cut off 200 ft of plume width. The work plan for this treatment system was approved in April 2004. However, data about this project are not yet available.

Table 3-5.1. In Situ Bioremediation (ISB) Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Whittaker Ordnance Site, Whittaker, CA; In Situ Bioremediation; Full-scale; Groundwater Groundwater – interbedded clay units with silty-sand layers aquifer; perched groundwater at 35 to 50 feet (ft) below ground surface (bgs) Test area size 3,200 ft^2; perched aquifer thickness of 4.5 ft	Two types of enhancement techniques were used to stimulate ISB. First, hydrogen release compound (HRC®) (660 pounds) was applied using direct push technology. Second, an in situ reactive zone (IRZ) was created using corn syrup addition. Specific design and operation conditions were not provided for HRC addition. For IRZ, design and operation for a field demonstration included delivery in pressurized, manual batches (at approximately 30 pounds per square inch [psi]), using three permanent injection points, and a strategy of reduced dosage and frequency of dosing. Six injection events were performed over a one year period (October 2001, November 2001, January 2002, March 2002, May 2002, and November 2002). An expanded full-scale system was used to address the majority of perched groundwater from the burn trench and leach field. Design criteria included a 20 ft radius of influence using wellhead pressure of 30 psi. This used a 47 point grid configuration within a dual-level (shallow and deep) aquifer and a down-gradient portion for migration control. Delivery point installation spacing ranged from 30 to 120 ft.	Period of Performance: Not available Initial concentration of perchlorate in groundwater was more than 200,000 µg/L; other contaminants were noted to include hexavalent chromium (Cr^{+6}), Freon-113, and trichloroethene (TCE) (concentrations not provided). ISB using HRC reduced perchlorate concentrations by more than 88% (from >7,000 µg/L) within 80 days of treatment. The IRZ induced anaerobic conditions within 30 days of first dosing, based on data from the field demonstration for dissolved oxygen (DO) and oxidation reduction potential (ORP). Perchlorate concentrations decreased in groundwater samples to 22 µg/L within 18 ft of the feed source, with an average 94.3% reduction in perchlorate reported in three monitoring points over a 12 month active remediation period.	1. Owsianiak, Lisa Marie, Lenzo, Frank and Molnaa, Barry (ARCADIS), and Kelleher, Brian (Kelleher & Associates). 2003. "In Situ Removal of Perchlorate from Perched Groundwater by Inducing Enhanced Anaerobic Conditions." Presented at the Seventh International In Situ and On-Site Bioremediation Symposium. June 2 – 5. 2. Koenigsberg, Stephen S. and Willett, Anna. 2004. "Enhanced In Situ Bioremediation of Perchlorate in Groundwater with Hydrogen Release Compound (HRC®)." Presented at National Ground Water Association (NGWA) Conference on MTBE and Perchlorate. June 4.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
AMPAC Facility, NV (Pepcon Facility); In Situ Bioremediation; Groundwater; Pilot-scale; Completed December 2002 – May 2003 (injection) Test area approximately 200 by 150 feet	Groundwater recirculation and citric acid addition. Recirculation design consisted of a single groundwater extraction well and a single reinjection well. Citric acid (quantity/concentration not provided) was injected daily over 41 days for one hour each day to the extracted water prior to reinjection. Ethanol was used as the original carbon source, but citric acid was substituted to reduce biofouling. Chlorine dioxide was also used to control biofouling. The system operated at 5 to 7 gallons per minute (gpm).	Period of Performance: December 2002 – May 2003 Prior to injection of citric acid, perchlorate concentrations were as high as 530,000 µg/L. Soon after addition of citric acid, perchlorate concentrations were less than 100 µg/L, and rapidly decreased to less than 10 µg/L. Perchlorate concentrations appeared to reach an asympototic level of approximately 4 µg/L after one month of treatment and remained at that level following cessation of citric acid addition (based on one month of post-treatment data). Over this 6 month monitoring period, concentrations of nitrate were reduced from 45 mg/L to less than 1 mg/L, chlorate from 60 mg/L to less than 1 mg/L, dissolved oxygen from 8 mg/L to less than 1 mg/L, and sulfate was reduced from 350 mg/L to less than 100 mg/L.	1. Rosen, Jamey (GeoSyntec). 2003. "Successful In Situ Bioremediation of Perchlorate in Groundwater." Poster presented at the SERDP Technical Symposium and Workshop, Washington, DC. November 30 – December 2. 2. EPA Region 9. 2005i. E-mail message regarding perchlorate treatment. From Larry Bowerman (EPA Region 9) to John Quander. June 24.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Aerojet General Corp. Superfund Site, Rancho Cordova, CA; In Situ Bioremediation; Groundwater; Pilot-scale; Completed Site is underlain by an alluvial aquifer consisting of interbedded silts, sands, and gravel, with the water table at 20 ft bgs.	Phase I of the pilot project was performed from 2000 through 2001 to assess the potential to jointly bioremediate perchlorate and TCE and to control migration of an 800-ft wide plume. The target aquifer was located at 100 ft bgs. The demonstration was designed as a closed loop with a recirculation rate of 5 to 10 gpm and a residence time of 21 days. One nutrient delivery and one extraction well were used, with two monitoring wells located between the delivery and extraction wells. Proprietary dehalorespiring bacteria (KB-1) were added in Phase I for TCE removal. Various electron donors were tried for perchlorate destruction, including calcium magnesium acetate, sodium acetate, and sodium lactate. Phase II of the project was conducted from late 2001 through 2002. The purpose of Phase II was to demonstrate the feasibility of a single pass active groundwater biobarrier for perchlorate destruction. Ethanol was added to the extracted groundwater as an electron donor. A more recent demonstration used horizontal flow treatment wells in a deep area, screened from 48 to 63 ft bgs and at 80 to 100 ft bgs (separated by pneumatic packers). This zone was used to cut off 200 ft of plume width. Work plan for this treatment system was approved in April 2004. However, data about this project are not yet available.	Period of Performance: 2000 – Ongoing Groundwater chemistry consists of perchlorate at 12,000,000 µg/L, nitrate at 5,000 µg/L, sulfate at 10,000 µg/L, oxygen at 4 mg/L, redox at +200 mV, and pH = 6.8 Phase I showed that perchlorate could be reduced from 12,000,000 µg/L to levels below detection limits within 15 feet of the electron donor injection well. Phase II showed that perchlorate at 8,000 µg/L was reduced to less than 4 µg/L within 35 feet of the electron donor delivery system. The 72-day Phase II study showed that a combined perchlorate/TCE plume could be remediated with a single pass biobarrier with only a partial degradation of TCE. No results are yet available for the horizontal flow treatment system demonstration.	1. Cox, Evan E. and Neville, Scott. 2003. "In Situ Bioremediation of Perchlorate: Comparison of Results from Multiple Field Demonstrations." Presented at In Situ and On-Site Bioremediation-The Seventh International Symposium. June 2 – 5. 2. Cox, E., Edwards, E., Neville, S., and Girard, M. 2000b. Aerojet In Situ Bioremediation Field Demonstration. Available at http://perchlorateinfo.com/perchlorate-case-04.html. Downloaded July 26. 3. EPA. 2004c. E-mail message regarding perchlorate treatment. From Charles Berrey (EPA Region 9) to Sashi Vissa (Tetra Tech EM Inc.). September 13.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Explosive Device Manufacturing Facility (Waste Storage Pad Area), CA; In Situ Bioremediation; Soil; Pilot-Scale; Completed	The Waste Storage Pad Area had a clay retaining layer between the vadose zone and the saturated zone. Corn syrup and ethanol were simultaneously evaluated as substrates during a demonstration of the IRZ technology. These substrates were used to "flood" the vadose zone and drive it anaerobic. The demonstration consisted of one injection event, followed by monitoring for 250 days following the injection.	Period of Performance: 2002 – 2004 Perchlorate contour maps from September 2002, June 2003, and February 2004 show substantial reduction in the area of elevated perchlorate concentrations, with the maximum concentrations reduced from greater than 5,000 µg/kg to 500 µg/kg over that period.	Liles, David S. and Owsianiak, Lisa (ARCADIS). 2004. "Pilot-Scale Biological Treatment of Perchlorate, Trichloroethylene, and Hexavalent Chromium as Co-Contaminants." Poster Presentation at the SERDP Technical Symposium and Workshop, Washington, DC. November 30 – December 2.
Former Munitions Manufacturing Facility, Los Angeles County, CA; In Situ Bioremediation; Soil; Pilot-Scale; Completed	Gaseous Electron Donor Injection Technology (GEDIT) was demonstrated at this site under the Environmental Security Technology Certification Program (ESTCP) Project No. CU-0511. This process involves injection of electron donors as a gas into the vadose zone to stimulate anaerobic biodegradation of perchlorate. Several operational conditions were evaluated during this demonstration, including electron donor type (hydrogen, ethanol, ethyl acetate, butyl acetate, and butyraldehyde), delivery method (continuous vs. pulsed injection), soil moisture, and nutrients.	Period of Performance: Not available Demonstration results showed that moisture content was a key parameter that affected biodegradation and transport, and that ethyl acetate was a good choice of electron donor to meet biodegradation, transport, economic, and regulatory requirements. In one demonstration using ethanol as the electron donor, the concentration of perchlorate decreased from approximately 25 mg/kg in the control to less than 1 mg/kg when moisture content was increased.	Evans, Patrick J. (CDM). 2004. "Perchlorate Remediation by Gaseous Electron Donor Injection Technology (GEDIT)." Poster Presentation at the SERDP Technical Symposium and Workshop, Washington, DC. November 30 – December 2.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Longhorn Army Ammunition Plant Superfund site, Karnack, TX (Site 17); In Situ Bioremediation; Soil; Pilot-scale; Completed	Site 17 at the Longhorn Army Ammunition Plant (LHAAP) was an open burning and detonation ground. Soil was contaminated with perchlorate and explosives, and groundwater was contaminated with perchlorate and chlorinated solvents. The surface application and mobilization of nutrient amendments (SAMNA) was used to stimulate microbial degradation of perchlorate and other contaminants in a 1-acre area.	Period of Performance: Not available Initial concentrations in the soil of perchlorate were >200 mg/kg and TNT were >1,000 mg/kg. Eight months following SAMNA application, >70% of vadose zone soils were remediated to concentrations <40 µg/kg. Also, the perchlorate and chlorinated solvents concentrations in groundwater showed a decreasing trend.	1. O'Niell, Walter L. (Planteco Environmental Consultants, Athens, Georgia), Nzengung, Valentine A., Das, K.C., Kastner, James, and Dowd, John (University of Georgia, Athens, Georgia). 2003. Feasibility of In Situ Bioremediation of Perchlorate-Contaminated Soils. Presented at the Seventh International In Situ and On-Site Bioremediation Symposium. June 2 – 5. 2. Interstate Technology Regulatory Council (ITRC). 2005. Overview: Perchlorate Overview. Draft. March.
Longhorn Army Ammunition Plant, Karnack, TX (Site 43-X); In Situ Bioremediation; Soil; Pilot-scale; Completed	Site 43-X at LHAAP included a pyrotechnic/rocket storage shed, and had soil contaminated with perchlorate. The surface application and mobilization of nutrient amendments was used to stimulate microbial degradation of perchlorate and explosives without leaching contaminants to groundwater in a 110 square foot area.	Period of Performance: Not available The consultant reported that the site was completely restored and closed out in 10 months following SAMNA application. The ITRC reported a decrease in concentration from 6,700 µg/kg to <40 µg/kg in the top 30 inches.	1. O'Neill, Walter (PLANTECO Environmental Consultants, LLC). 2004. "In Situ Bioremediation of Perchlorate and Explosives in Vadose Zone Source Areas." Poster presented at the SERDP Technical Symposium and Workshop, Washington, DC. November 30 – December 2. 2. ITRC. 2005. Overview: Perchlorate Overview. Draft. March.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
National Industrial Reserve Ordnance Plant (NIROP), Magna, UT; In Situ Bioremediation; Pilot-scale; Groundwater; Ongoing	This project involves an active in situ biobarrier where groundwater is captured, amended with an optimized concentration (based on stoichiometric needs) of electron donors and recharged to the aquifer. This promotes in situ perchlorate reduction and thus controls perchlorate migration. This approach allows for addition of a controlled and optimized amount of electron donor and therefore has minimal adverse impact on secondary groundwater quality.	Period of Performance: Not available Technology performance data not provided.	ITRC. 2005. Overview: Perchlorate Overview. Draft. March.
The Indian Head Division Naval Surface Warfare Center (IHD), Indian Head, MD; In Situ Bioremediation; Pilot-scale; Groundwater Groundwater plume was several hundred feet long and 50 ft wide, with a pH <5.0; groundwater was located at 6-16 ft bgs	A pilot study was performed at the Hog-out facility at IHDIV (Mattowoman Creek side) which used a control plot and a test plot (each 10 ft by 12 ft). Groundwater was recirculated and amended with lactate and a buffer.	Period of Performance: Not available – January 2003 Initial concentration of perchlorate in groundwater was 430,000 µg/L. After 105 days operation, perchlorate was reduced to less than 4 µg/L in the test area. The pH was at 6.5.	1. Hatzinger, P.B., Engbring, D.E., Giovanelli, M.R., Diebold, J.B., Yates, C.A., and Cramer, R.J. 2003. “Field evaluation of in situ perchlorate bioremediation at the Indian Head Division, Naval Surface Warfare Center.” Presented at In Situ and On-Site Bioremediation – The Seventh International Symposium. June 2 – 5. 2. Diebold, J. B., Hatzinger, P.B., Engbring, D.E., Giovanelli, M.R., Yates C.A., and Cramer, R.J. 2004. “Field Evaluation of In Situ Perchlorate Bioremediation at the Naval Surface Warfare Center – Indian Head Division.” Presented at NGWA Conference on MTBE and Perchlorate. June 3 – 4.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Rialto-Colton, CA; In Situ Bioremediation; Groundwater; Pilot-scale; Ongoing	This was a demonstration project about use of discrete-point horizontal wells for vapor sparging of an electron donor.	Period of Performance: Not available Technology performance data not provided.	1. Jenkins, David V. (Kleinfelder, Inc.) and Nutall, Eric H. 2004. "Innovative Engineering Strategies for Perchlorate Cleanup." Poster Presentation at the SERDP Technical Symposium and Workshop, Washington, DC. November 30 – December 2. 2. EPA. 2004p. E-mail message regarding perchlorate treatment. From Wayne Praskins (EPA Region 9) to Sashi Vissa. December 8.
Rocket Manufacturing Site, MD; In Situ Bioremediation (injection of emulsified edible oil substrate [EOS®]); Groundwater; Pilot-scale; Ongoing	This project is investigating an innovative approach for distributing and immobilizing a water-miscible emulsified vegetable oil product (EOS®) with a controlled droplet size as the biodegradable organic substrate in a perchlorate-contaminated aquifer. The emulsion was prepared using food-grade soybean oil and emulsifiers and then distributed throughout the treatment zone (i.e., a 60-ft long biobarrier impacting a 10 ft zone from 8 to 18 ft bgs) using temporary injection points. Approximately 850 pounds of EOS® were injected. A portion of the oil is trapped within the soil pores leaving a residual oil phase to support long-term anaerobic biodegradation of the perchlorate. Treatment occurs as contaminated groundwater moves through the barrier whose width is engineered to provide adequate contact time for biodegradation to occur.	Period of Performance: Not available – Ongoing Initial concentration of perchlorate in groundwater was approximately 10,000 µg/L. Groundwater flow velocity up to 75 ft/yr carried contaminated groundwater through the barrier. Perchlorate concentrations in the treatment zone were reduced to below 4 µg/L within 4 days of EOS® injection. Similar perchlorate reductions were seen in groundwater up to 20 feet from the barrier within 35 days. The treated zone downgradient remained perchlorate-free for over 18 months with no additional injection of substrate.	Lieberman, M.T., C. Zawtocki, R.C. Borden, and Gary M. Birk 2004. "Treatment of Perchlorate and Trichloroethane in Groundwater Using Edible Oil Substrate (EOS®)." *Proceedings of the National Ground Water Association Conference on MTBE and Perchlorate: Assessment, Remediation and Public Policy, Costa Mesa, CA*. June 3 – 4. (Funded by ESTCP)

3.6 Permeable Reactive Barrier

Summary

A permeable reactive barrier (PRB) is an in situ technology used to treat perchlorate-contaminated groundwater at full scale. Some of the commonly used reactive materials for barriers include soybean and other edible oils, woodchips, pecan shells, cotton seed, chitin, limestone, and other composting materials. Many of these materials can provide both electron donors and the necessary nutrients for microbial growth. Soluble electron donors such as lactate, acetate, and citrate may be added to the barrier materials to further stimulate biodegradation of perchlorate to chloride and oxygen.

Technology Principles

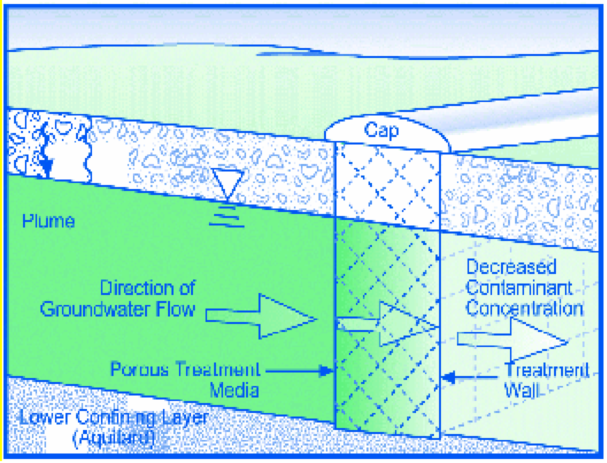
A permeable reactive barrier (PRB) is an in situ treatment zone of reactive material that degrades or immobilizes contaminants as groundwater flows through it. PRBs are installed as permanent, semi-permanent, or temporary units across the flow path of a contaminant plume. Contaminants in groundwater that flow through a PRB are degraded chemically or biologically (FRTR, 2005). The barriers are made of reactive material that targets specific contaminants. Examples of reactive materials used in PRBs include soybean and other edible oils, woodchips, pecan shells, cotton seed, chitin, limestone, and other composting materials (EPA, 2005f). When applied as a biological treatment method, the reactive material may promote growth of indigenous microorganisms or may have to be supplied with microorganisms capable of biodegrading the target contaminants (AFCEE, 2002b; EPA, 2005b). To treat groundwater contaminated with perchlorate, the reactive barrier may be inoculated with anaerobic bacteria that can convert perchlorate into chloride and oxygen (AFCEE, 2002b). Additional information about perchlorate transformation or biodegradation, including microbial degradation pathways, is presented in Section 3.2 under bioreactors.

Technology Description

PRBs are installed in one of two basic configurations – funnel-and-gate or continuous trench. A funnel-and-gate system consists of a gate containing the reactive media (microbes or chemicals) and a funnel formed by solid walls that direct the flow of the groundwater. The trench system consists of one or more trenches excavated across the contaminant plume and filled with reactive material (AFCEE, 2002b).

For treatment of perchlorate-contaminated groundwater, the PRB system is backfilled with reactive material that includes an electron donor to stimulate reduction of perchlorate and organic substrates to nourish the microorganisms (AFCEE, 2002b; Craig and Jacobs, 2004; Beisel et al., 2004). Figure 3.6-1 shows a conceptual design of a PRB system (AFCEE, 2002b).

Figure 3.6-1. Permeable Reactive Barrier (PRB) for Perchlorate Treatment (EPA OSWER, 2002)



Perchlorate-Contaminated Media Treated

- Groundwater

Type, Number, and Scale of Identified Projects

Two full-scale projects and one pilot-scale project have been identified that used PRBs for treatment of perchlorate in groundwater.

Summary of Performance Data

Table 3.6-1 summarizes available performance data for treatment of perchlorate-contaminated groundwater using PRBs. As discussed above, cleanup goals varied by site and type of project. Where provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end-use, and other factors.

Perchlorate concentrations in one of the full-scale projects was reduced from 13,000 µg/L to below detection limit of 0.45 µg/L. The other full-scale project reduced perchlorate concentrations from 120 µg/L to 20µg/L. The pilot-scale project reduced perchlorate concentrations from 10,000 µg/L to below 4 µg/L (Beisel et al., 2004; Borden et al., 2004b; Cal EPA, 2004; Craig and Jacobs, 2004; EPA, 2005f).

Factors Affecting PRB Performance

- **Type of Barrier Material** – Selection of appropriate barrier material is essential to provide adequate amounts of carbon and nitrogen required for microbial growth (FRTR, 2005; AFCEE, 2002b).
- **Hydrogeology** – Design, installation, and operation of PRBs depends on site hydrogeology (FRTR, 2005).

Potential Limitations

Proper installation of PRBs requires access to depths of the contaminated groundwater and barriers formed by trenches that surface excavation or trenching equipment may not be able to reach (FRTR, 2005). Thus it may render impractical the treatment of deeper contaminated groundwater using mechanically constructed trench designs. However, PRBs formed using injectable substrates can be established at greater depths. Regardless, PRBs may lose their reactive capacity over time, requiring replacement, renourishment, or re-injection of the reactive material or substrate. Additional maintenance may be required to unclog the barrier fouled biologically or clogged with chemical precipitates (AFCEE, 2002b; EPA, 2005f).

Summary of Cost Data

Costs for in situ bioremediation, including PRB configurations, are generally considered smaller than average costs for groundwater treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Case Study: Naval Weapons Industrial Reserve Plant, McGregor, TX

The Naval Weapons Industrial Reserve Plant (NWIRP), in McGregor, TX, has groundwater contaminated with perchlorate and trichloroethene (TCE). The contaminant plumes are located in the upper portions of an unconfined 5- to 35-foot (ft) thick bedrock aquifer exhibiting decreased limestone fracturing and weathering with increased depth. Groundwater depth varies seasonally from 2 to 10 ft below ground surface (bgs), with a flow velocity of 0.13 to 3.0 ft/day. Full-scale permeable reactive barriers (PRBs) were installed at Area S at NWIRP in late 2002, following a pilot study, to address a perchlorate plume migrating off site. Seven PRBs were installed in segments, with each trench ranging from 100 to 750 ft long, and covering a total length of 3,500 ft in 3 zones. The seven trenches were installed on 1,000 ft centers in a gallery fashion, and each was backfilled with a mixture of gravel (70%), mushroom compost (20%), and soybean oil-soaked woodchips (10%). Approximately 4,200 tons of material was used to backfill the trenches.

Groundwater entering the trench located closest to the source area contained an average perchlorate concentration of 13,000 µg/L. Perchlorate concentrations in groundwater exiting the trench were reduced to below detection limit. The information sources used for this paper did not provide the perchlorate detection limit for this project. The first three months of performance monitoring indicated that the treatment envelope of a single trench had traveled a distance of 400 ft down-gradient, and that the concentration of perchlorate in a monitoring well at the down-gradient location was reduced by 99% from a pre-treatment concentration of 1,000 µg/L (Beisel et al., 2004; Craig and Jacobs, 2004; EPA, 2004f).

Table 3-6.1. Permeable Reactive Barrier (PRB) Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Los Almos National Laboratory, Mortandad Canyon, NM; Permeable Reactive Barrier; Full-scale; Groundwater; Ongoing	Four-layered PRB consisting of gravel-sized scoria, apatite, pecan shells and cotton seed with an admixture of gravel (biobarrier), and limestone.	Period of Performance: Not available – Ongoing Influent concentration was approximately 120 µg/L and was reduced to 20 µg/L in the effluent	California Environmental Protection Agency (Cal EPA). 2004. "Perchlorate Contamination Treatment Alternatives: Draft." January.
Naval Weapons Industrial Reserve Plant (NWIRP), McGregor, TX; Permeable Reactive Barrier; Full-scale; Groundwater; Ongoing The contaminant plumes are located in the upper portions of an unconfined 5- to 35-foot (ft) thick bedrock aquifer exhibiting decreased limestone fracturing and weathering with increased depth. Groundwater depth varies seasonally from 2 to 10 ft bgs, with a flow velocity of 0.13 to 3.0 ft/day.	Groundwater at this site is contaminated with perchlorate and trichloroethene (TCE). Full-scale PRBs were installed at Area S at NWIRP in late 2002, following a pilot study, to address a perchlorate plume migrating off site. Seven PRBs were installed in segments, with each trench ranging from 100 to 750 ft long, and covering a total length of 3,500 ft in 3 zones. The seven trenches were installed on 1,000 ft centers in series, and each was backfilled with a mixture of gravel (70%), mushroom compost (20%), and soybean oil-soaked woodchips (10%). Approximately 4,200 tons of material was used to backfill the trenches.	Period of Performance: Not available – Ongoing Groundwater entering the trench located closest to the source area contained an average perchlorate concentration of 13,000 µg/L. Perchlorate concentrations in groundwater exiting the trench was reduced to below detection limit (detection limit is 0.45 µg/L). The first three months of performance monitoring indicated that the treatment envelope of a single trench had traveled a distance of 400 ft down-gradient, and that the concentration of perchlorate in a monitoring well at the down-gradient location was reduced by 99% from a pre-treatment concentration of 1,000 µg/L.	1. Beisel, Thomas H., Craig, Mark, and Perlmutter, Mike. 2004. "Ex-Situ Treatment of Perchlorate Contaminated Groundwater." Presented at National Ground Water Association (NGWA) Conference on MTBE and Perchlorate. June 3 – 4. 2. Craig, Mark (Naval Facilities Engineering Command [NAVFAC]) and Jacobs, Alan (EnSafe). 2004. "Biological PRB Used for Perchlorate Degradation in Groundwater." In: Technology News Trends, Issue 10. February. 3. EPA. 2004f. E-mail message regarding perchlorate treatment. From Bob Sturdivant (EPA Region 6) to Sashi Vissa (Tetra Tech EM Inc.). September 28.

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Rocket Manufacturing Site, MD; Permeable Reactive Barrier; Pilot-scale; Groundwater; Ongoing	Groundwater at this site is contaminated with perchlorate and 1,1,1-Trichloroethane (TCA). A pilot-scale, 60-ft long permeable reactive biobarrier was installed perpendicular to the groundwater flow. Approximately 850 pounds of emulsified edible oil substrate (edible oil substrate [EOS®]) was injected into a 10-ft thick zone. The EOS® serves as a nutrient source for microbial growth and an electron donor to support anaerobic degradation of the contaminants.	Period of Performance: Not available – Ongoing Initial concentration of perchlorate in groundwater was approximately 10,000 µg/L. Perchlorate in treated groundwater was reduced to below 4 µg/L within 4 days of EOS® injection. Treatment resulted in an uncontaminated zone downgradient of the PRB for over 1.5 years without re-injection of EOS® barrier material.	1. Borden, Robert, Lieberman, Tony, and Zawtocki, Christie. 2004. "Anaerobic Biodegradation of Perchlorate and TCA in an EOS® Permeable Reactive Barrier." Poster presented at the SERDP Technical Symposium and Workshop, Washington, DC. November 30 – December 2. 2. Lieberman, M.T., C. Zawtocki, R.C. Borden, and Gary M. Birk. 2004. "Treatment of Perchlorate and Trichloroethane in Groundwater Using Edible Oil Substrate (EOS®)." *Proceedings of the National Ground Water Association Conference on MTBE and Perchlorate: Assessment, Remediation and Public Policy, Costa Mesa, CA*. June 3-4. (Funded by Environmental Security Technology Certification Program [ESTCP]) 3. EPA. 2005f. E-mail message with comments on perchlorate issue paper. From Tony M. Lieberman (Solutions-IES) to Josh Barber (EPA-FFRRO). March 28.

3.7 Phytotechnology

Summary

Phytotechnology is an emerging technology for perchlorate remediation. It involves use of plants to remove contaminants by natural processes occurring within the plant body. Selection of the best plant species is critical to achieving the treatment goals. Research is currently under way to identify the mechanism involved in perchlorate removal by phytotechnology. A few bench-scale studies have indicated the suitability of certain plant species for remediation of perchlorate-contaminated media.

Technology Principles

Phytotechnology is a process that uses plants to remove contaminants from media including groundwater, surface water, and soil. Phytotechnology includes various mechanisms such as rhizosphere biodegradation, phytovolatilization, phytostabilization, and phytoextraction (FRTR, 2005). Rhizodegradation or rhizosphere degradation proceeds via activities of microorganisms present in the soil surrounding the roots. The natural substances released by plant roots provide nutrient material to the microbial population, which in turn degrade the contaminants present in soil. The mechanism of remediation of perchlorate-contaminated media by phytotechnology is not yet established. However, studies conducted at bench scale have indicated possible suitability of certain plant species for perchlorate removal (Motzer, 2001; Schnoor et al., 2004; Susarla et al., 1999).

Technology Description

Phytotechnology uses plants to remediate contaminated media. The enzymes and natural chemicals produced in the plant's root system provide nutrient material to microorganisms growing in the soil around the roots. These microorganisms may biologically reduce perchlorate present in the soil and groundwater (FRTR, 2005; Motzer, 2001). The mechanism of perchlorate removal by phytotechnology is not well known. Research is being conducted to delineate the remediation process. The sources used for this report suggest that species such as willow, hybrid poplar, cottonwood, and water lily are possibly suited for phytoremediation of perchlorate (Motzer, 2001; Schnoor et al., 2004; Susarla et al., 1999). Figure 3.7-1 shows a simplified model of a phytotechnology system (EPA OSWER, 2002).

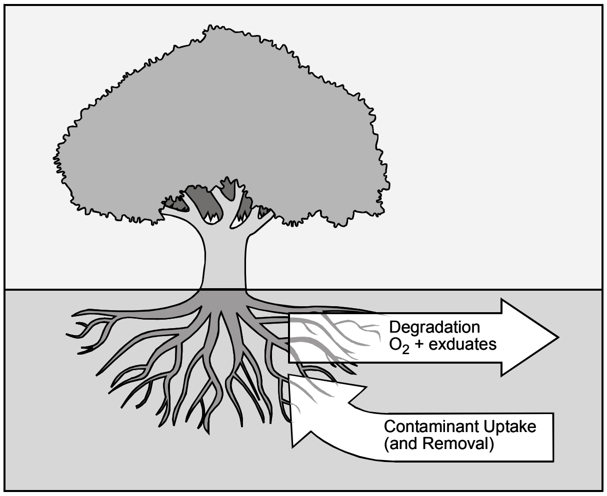
Perchlorate-Contaminated Media Treated

- Groundwater

Type, Number, and Scale of Identified Projects

One pilot-scale application of phytotechnology has been identified from the sources used for this paper.

Figure 3.7-1. Phytotechnology for Perchlorate Treatment (EPA OSWER, 2002)



Summary of Performance Data

Table 3.7-1 summarizes available performance data for this technology. Initial perchlorate concentration was 34 mg/L. After a year, the concentration of perchlorate in treated groundwater had decreased to 23 mg/L. As discussed above, cleanup goals varied by site and type of project. When provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end-use, and other factors (Schnoor et al., 2004).

Table 3.7-1. Phytotechnology Performance Summary for Perchlorate Treatment Project

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Longhorn Army Ammunition Plant (LHAAP), TX; Phytotechnology; Groundwater; Field Demonstration; Ongoing	LHAAP has groundwater that is contaminated with perchlorate. A field demonstration of phytotechnology using 425 hybrid poplars was performed, with the trees planted in March 2003 on a 0.7 acre demonstration site.	Period of Performance: March 2003 – Ongoing In this demonstration, concentrations of perchlorate were reduced from 34 mg/L to 23 mg/L, as of March 2004. According to the site researcher, the mass of perchlorate taken up by the poplar trees and/or degraded within in the rhizosphere was 0.114 ± 0.016 kg/d. Between April 2003 and September 2004, 52 kg of perchlorate was removed from the groundwater by the hybrid poplar trees and/or the microbes that grow in the root zone.	1. Schnoor, J.L. et al. 2004. Demonstration Project of Phytoremediation and Rhizodegradation of Perchlorate in Groundwater at the Longhorn Army Ammunition Plant, the University of Iowa, Department of Civil and Environmental Engineering. 2. EPA, 2005a. E-mail message regarding perchlorate treatment. From J.L. Schnoor (University of Iowa) to Ellen Rubin (EPA Office of Superfund Remediation and Technology Innovation). February 10, 2005

Factors Affecting Phytotechnology Performance

- **Plant Species** – Perchlorate might exert a toxic effect on certain species. Therefore, selecting a plant species suitable for achieving treatment goals is important (FRTR, 2005).

- **Concentration of Contaminant** – Presence of excess amounts of perchlorate may fatally affect plants. Therefore, the tolerability limit of the selected plant species should be determined before implementing the remediation process (FRTR, 2005; Susarla, et al., 1999).

Potential Limitations

Phytotechnology applies a natural process occurring in select plant species to help remove contamination from the media of concern. High concentrations of contaminants can impede plant growth and the remediation process (FRTR, 2005). Climatic changes can significantly impact plant growth, thus requiring variation in the treatment period. Prior research is necessary to determine the suitability of specific plant species for remediating the contaminants of concern (FRTR, 2005).

Summary of Cost Data

Costs for phytotechnology generally compare favorably with costs for aboveground treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

3.8 Membrane Technologies

Technologies involving use of semi-permeable or permeable membranes for perchlorate removal are referred to as membrane technologies. Electrodialysis and reverse osmosis are examples of membrane technologies used for removal of perchlorate from groundwater, surface water, and wastewater. They are discussed below.

3.8.1 Electrodialysis

Summary

Electrodialysis is an ex situ technology that applies an electric current to remove perchlorate. Perchlorate-contaminated water is exposed to an electric current as it passes through a semi-permeable membrane. This separates perchlorate ions from contaminated groundwater and surface water. The technology produces alternate channels of nearly deionized water (the diluate or dialyzate) and salty water (the concentrate). The diluate is used, and the concentrate undergoes further treatment prior to disposal.

Technology Principles

Electrodialysis is a membrane technique that uses electric current to remove perchlorate (Roquebert et al., 2000). In this technology, electric current is applied to perchlorate-contaminated water as it passes through channels of alternating permeable membranes selective of anions and cations. The electric current dissociates perchlorate salts into cations and anions. Ammonium perchlorate and potassium perchlorate are two common forms of perchlorate contamination. Perchlorate ions, being negatively-charged (anion), accumulate at the cationic-selective membrane and are eventually collected as concentrate or salty water. Similarly, positive ions accumulate at the anionic-selective membrane. This method produces two types of water – salty water and relatively deionized water. The deionized water is used while the salty water is disposed of or further treated by an appropriate method prior to disposal (Urbansky and Schock, 1999). One source for this paper reported the benefit of occasionally reversing polarity of electrodes to prevent membrane fouling (Roquebert et al., 2000).

Technology Description

Electrodialysis is a physical method for removing perchlorate. Perchlorate-contaminated water is exposed to an electric current as it passes through a semi-permeable membrane. This separates perchlorate ions from contaminated groundwater and surface water. The technology produces alternate channels of nearly deionized water (the diluate or dialyzate) and salty water (the concentrate). The diluate is used, and the concentrate is subject to further treatment prior to disposal (Roquebert et al., 2000; Urbansky and Schock, 1999).

Perchlorate-Contaminated Media Treated

- Groundwater
- Drinking Water

Type, Number, and Scale of Identified Projects

Data sources used for this issue paper have provided information about two pilot-scale demonstrations of electrodialysis for perchlorate removal from groundwater.

Summary of Performance Data

Table 3.8-1 summarizes available performance data for this technology. As discussed above, cleanup goals varied by site and type of project. When provided, actual technology performance data are presented relative to cleanup goals. Treatment technologies often operate to achieve specified goals that vary by site, end-use, and other factors.

Influent perchlorate concentrations ranged from 15 µg/L to 130 µg/L. Concentration of perchlorate in effluent water ranged from 11 µg/L to 17 µg/L. Information sources used for this paper did not provide performance data for the second project presented in Table 3.8-1.

Table 3.8-1. Electrodialysis Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Bacchus Works, Alliant Techsytems, Inc., Salt Lake County, UT; Electrodialysis; Pilot-scale; Groundwater; Completed	A pilot-scale electrodialysis system was tested at this site for the removal of perchlorate from groundwater. The treatment system consisted of alternating semi-permeable and permeable membranes exposed to an electric field. The flow rate was maintained at approximately 7.4 gallons per minute (gpm).	Period of Performance: June 1999 – September 1999 Initial perchlorate concentration in groundwater ranged from 15 µg/L to 130 µg/L. Perchlorate concentrations in the effluent ranged from 11 µg/L to 17 µg/L.	Roquebert, Vincent, Booth, Stephen, Cushing, Robert S., Crozes, Gil, Hansen, Ed. 2000. "Electrodialysis reversal (EDR) and ion exchange as polishing treatment for perchlorate treatment." *Proceedings of the Conference on Membranes in Drinking and Industrial Water Production*. Volume 1, pp. 481 – 487. October.
Barton Well Field, Salt Lake County, UT; Electrodialysis; Pilot-scale; Groundwater; Ongoing	A pilot-scale electrodialysis reversal (EDR) system is currently being tested at this site for removal of perchlorate from groundwater. The EDR system consists of a four-hydraulic stage EDR membrane stacked with two electric stages. The treatment capacity is approximately 18,000 to 20,000 gallons per day (gpd).	Period of Performance: December 2004 – Ongoing (Proposed duration is 20 weeks) Performance data are currently not available for this project.	Carollo Engineers, Inc. 2005. E-mail communication between Sashi Vissa (Tetra Tech EM Inc.) and Brandon Heidelberger (Carollo Engineers, Inc.). January 4.

A case study presented at the end of this section describes use of electrodialysis to remove perchlorate from groundwater at the Bacchus Works, Alliant Techsytems, Inc., Salt Lake County, UT (Carollo Engineers., Inc., 2005; Roquebert et al., 2000).

Factors Affecting Electrodialysis Performance

The sources used for this paper did not provide any information on the factors affecting electrodialysis performance.

Potential Limitations

Reduced effectiveness of electrodialysis for perchlorate removal may result from membrane fouling and low selectivity of the semi-permeable membrane for perchlorate. The concentrate resulting from this method may require large quantities of water for further treatment prior to disposal (Urbansky and Schock, 1999). The sources used for this paper did not provide information about treatment and disposal of concentrate.

Summary of Cost Data

Cost for electrodialysis (categorized as separation processes) generally compares unfavorably with costs for aboveground treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Case Study: Bacchus Works, Alliant Techsytems, Inc., Salt Lake County, UT

Groundwater at this site is contaminated with perchlorate, 1,1,1-trichloroethane (TCA), trichlorethene (TCE), 1,1-dichlorothene (DCE), and Freon 113. A pilot-scale electrodialysis system was tested at this site for removal of perchlorate from groundwater. The treatment system consisted of alternating semi-permeable and permeable membranes exposed to an electric field. The flow rate was maintained at approximately 7.4 gallons per minute (gpm). This pilot system operated from June to September 1999. Initial perchlorate concentration in groundwater ranged from 15 µg/L to 130 µg/L. Perchlorate concentrations in the effluent ranged from 11µg/L to 17 µg/L. (Carollo Engineers, Inc., 2005; Roquebert et al., 2000).

3.8.2 Reverse Osmosis

Summary

Reverse osmosis is a physical separation method based on the principle of osmosis. In this technology, high pressure is applied to reverse the osmosis process and force water molecules to pass through the semi-permeable membrane out of the perchlorate-contaminated water. As a result, two channels of water are formed in the reverse osmosis system. One is treated water from the freshwater side of the system and the other is concentrate or salty water containing perchlorate, which is subject to further treatment prior to disposal.

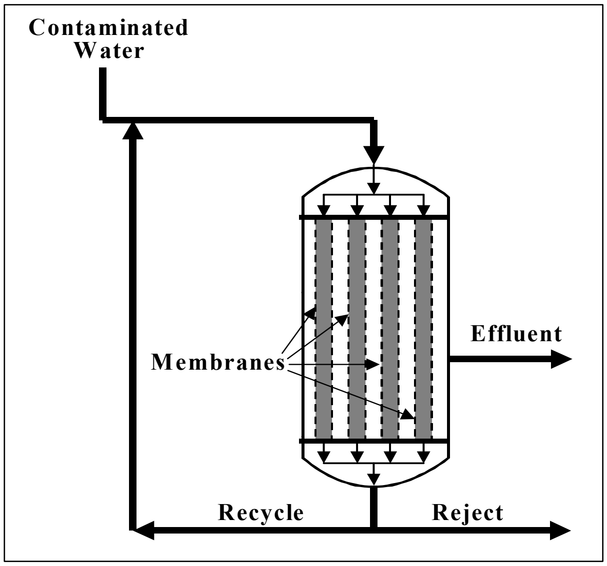
Technology Principles

Reverse osmosis is another membrane technique used for perchlorate removal (Burt et al.; Urbansky, 1998). Osmosis can be defined as the movement of water molecules from a region of lower solute concentration to a region of higher solute concentration through a semi-permeable membrane (Urbansky and Schock, 1999). In this case, the solute is a perchlorate salt. The reverse osmosis system consists of a chamber in which perchlorate-contaminated water is placed on one side of the semi-permeable membrane and fresh water is placed on the other side of the membrane. Pressure is applied at the inlet to force water molecules against the concentration gradient from the contaminated water into the fresh water section of the reverse osmosis system. This results in separation of perchlorate ions from contaminated water. Treated water can be used. The water containing perchlorate and other contaminants is further treated prior to disposal (Burt et al.).

Technology Description

Reverse osmosis is a physical separation method based on the principle of osmosis. In this technology, high pressure is applied to reverse the osmosis process and force water molecules to pass through the semi-permeable membrane out of the perchlorate-contaminated water (Urbansky and Schock, 1999; Burt et al.). Figure 3.8-1 shows a conceptual design of a reverse osmosis system (EPA OSWER, 2002).

Figure 3.8-1. Reverse Osmosis for Perchlorate Removal (EPA OSWER, 2002)



Perchlorate-Contaminated Media Treated

- Groundwater
- Drinking Water

Type, Number, and Scale of Identified Projects

Data sources used for this issue paper provided information about one bench-scale project for perchlorate removal by reverse osmosis. A pilot-scale study is planned for the Redlands Plume site, CA.

Summary of Performance Data

Table 3.8-2 presents performance data for the bench-scale study. Results of the bench-scale project indicate that the influent perchlorate concentrations ranged from 125 µg/L to 2,000 µg/L. Perchlorate concentration in the effluent water ranged from 5 µg/L to 80 µg/L (Burt et al.).

Factors Affecting Reverse Osmosis Performance

- **Organic Matter** – Presence of large amounts of organic matter and microorganisms can foul and thus damage the membrane (Urbansky and Schock, 1999).
- **Co-contaminants** – Presence of alkaline earth metals can enhance membrane fouling (Urbansky and Schock, 1999).

Potential Limitations

Reverse osmosis is normally suitable for point-of-use or small systems. Post-treatment including application of sodium chloride or sodium bicarbonate is required to make water palatable and prevent fouling of the distribution system (Urbansky, 1998).

Summary of Cost Data

Costs for reverse osmosis (categorized as separation processes) generally compare unfavorably with costs for aboveground treatment technologies, according to the FRTR. http://www.frtr.gov/matrix2/section3/table3_2.html

Table 3.8-2. Reverse Osmosis Performance Summaries for Perchlorate Treatment Projects

Location, Technology, Type of Media, Scale, and Status	Technology Design and Operation	Technology Performance Summary	Source
Clarkson University; Reverse Osmosis; Bench-scale; Groundwater; Completed	The reverse osmosis system was tested at bench scale for perchlorate removal. The reverse osmosis chamber consisted of a membrane impermeable to ions. The chamber is filled with fresh water on one side of the membrane and perchlorate-contaminated water on the other side. Pressure was applied in the range of 20 to 90 pounds per square inch (psi) to facilitate movement of water molecules through the membrane against the concentration gradient. This results in separation of perchlorate and other contaminants from contaminated water.	Period of Performance: Not available Initial perchlorate concentration in groundwater ranged from 125 µg/L to 2,000 µg/L. Perchlorate concentrations in the effluent ranged from 5 µg/L to 80 µg/L.	Burt, Michelle, Cooper, Michael, Hickey, Kevin, Kenyon Kevin, and St. Onge, Deanna. Clarkson University. “Task 3: Perchlorate Treatment for Domestic Water Systems.”

3.9 Recent or Planned Treatment Technology Research

EPA, DoD, and others are actively pursuing a wide variety of research projects on perchlorate treatment and other related subjects. Much of the treatment technology research is looking at various aspects of bioremediation for perchlorate – both ex situ and in situ. Recent or planned research on treatment technologies for perchlorate-contaminated soil or groundwater includes the following:

EPA (EPA, 2004m)

Atlantic Research Corporation (Gainesville, VA) – In situ anaerobic bioremediation of the deep groundwater. The objective of the field pilot study is to determine if subsurface conditions can be adjusted to create an in situ, anaerobic, bioremediation system capable of reducing perchlorate and VOCs (PCE and 1,1,1-TCA and associated daughter compounds). VOCs and perchlorate-reducing bacteria will be stimulated by distribution of carbon-based substrate(s) – such as acetate and chlorinated solvent/edible oils solution – into groundwater.

ATK Tactical Systems, LLC (Elkton, MD) – Pilot study using edible oil barriers (slow-release organic substrates) for treatment (enhanced anaerobic biodegradation) of perchlorate and chlorinated solvent in shallow groundwater.

Atlantic Research Corp. (Camden, Arkansas) – Environmental Alliance Inc. and GeoSyntec consultants – Bioremediation activities for ex situ and in situ pilot test to evaluate accelerated anaerobic reduction of perchlorate in soil and groundwater. Based on data collected during a pilot test, ex situ anaerobic composting has proven efficient and effective for treating perchlorate-impacted soil. Laboratory data collected to date suggest that the passive reactive barrier generated through injection of insoluble substrate (i.e., recycled cooking oil) successfully treats perchlorate-impacted groundwater and contains the most concentrated perchlorate plume.

Environmental Security Technology Certification Program (ESTCP) (EPA, 2004m)

- Fiscal Year (FY) 04 New Start – Permeable Mulch Biowall for Enhanced Bioremediation of Perchlorate in Groundwater at a DoD Facility (CU-0427)

- FY04 New Start – Evaluation of Potential for Monitored Natural Attenuation of Perchlorate in Groundwater (CU-0428)

- FY04 New Start – Field Comparison of Biofouling Control Measures for In Situ Bioremediation of Groundwater (CU-0429)

- FY04 New Start – In Situ Bioremediation of Perchlorate in Vadose Zone Source Areas (CU-0435)

- Ongoing – Laboratory study to determine suitability of constructed wetland systems to treat perchlorate-contaminated water (CU-1235). Two identical mesocosms were constructed. Graceful Cattails (*Typha laxmanil*) was transplanted to the substrate medium, and the medium was fed with water containing 100 µg/L, 1,000 µg/L, and 10,000 µg/L perchlorate. Effluent concentrations were not available in the sources used for this paper (Jackson, 2004)

- Ongoing – During a Strategic Environmental Research and Development Program (SERDP)-funded project (CU-1163), a mathematical model was developed to describe biodegradation kinetics of perchlorate. This model will be used during ESTCP Project CU-0425 to describe perchlorate biodegradation during in situ treatment using a horizontal flow treatment well (HFTW) system (Hatzinger, 2004)

- Completed – Investigation of feasibility of in situ bioremediation by using laboratory microcosms and continuous flow reactors. Results indicated that acetate addition caused degradation of perchlorate (Medina, 2004)

Environmental Security Technology Certification Program (ESTCP) Solicitation for Technologies for Treatment of Perchlorate-Contaminated Groundwater

In October 2004, ESTCP issued a request for "pre-proposal white papers" for technologies to treat perchlorate-contaminated groundwater. The U.S. Department of Defense (DoD), through ESTCP, will be funding demonstration projects for treating perchlorate in drinking water to evaluate alternative technologies that can apply to large-scale treatments of perchlorate-contaminated drinking water. The due date for these pre-proposals was November 18, 2004. Additional information about this solicitation is available at http://www.estcp.org/opportunities/solicitations/.

Miscellaneous

- Phoenix-Goodyear Wastewater Treatment Plant study on perchlorate – this study is looking at the ability of biological waste water, sewage, or septic systems to treat perchlorate (Geomatrix Consultants, 2003).

- A report is pending from USACE (Omaha Office) regarding effects of various soil types on perchlorate detection (EPA, 2004b).

- DoD and Cal EPA have finalized a procedure for prioritizing perchlorate sampling efforts at DoD facilities throughout California. The procedure document provides guidance to California and DoD officials on the steps each party will take to identify and prioritize areas on military sites where perchlorate has likely been released in proximity to drinking water sources. (DoD Office of the Assistant Secretary of Defense (Public Affairs) News Release No. 979-04, October 1, 2004. http://www.dod.mil/releases/2004/nr20041001-1343.html)

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Appendix A

Selected Perchlorate Web Sites

Appendix A

Selected Perchlorate Web Sites

Organization	Web Address
EPA Office of Superfund Remediation and Technology Innovation	www.cluin.org/perchlorate
U.S. Department of Defense	https://www.denix.osd.mil/denix/Public/Library/Water/Perchlorate/perchlorate.html
EPA Federal Facilities Restoration and Reuse Office	http://www.epa.gov/fedfac/documents/perchlorate.htm
EPA Office of Groundwater and Drinking Water	www.epa.gov/safewater/ccl/perchlorate/perchlorate.html
EPA Office of Research and Development: National Center for Environmental Assessment	http://cfpub.epa.gov/ncea/cfm/perch.cfm?ActType=default
American Water Works Association Research	www.awwarf.com/, search under projects and topics
Air Force Center for Environmental Excellence	www.afcee.brooks.af.mil/products/techtrans/perchloratetreatment/default.asp
Interstate Technology and Regulatory Council	http://www.itrcweb.org/teampublic_Perchlorate.asp
Perchlorate Info.com	www.perchlorateinfo.com/perchlorate.html
Santa Clara Valley Water District	www.valleywater.org

Appendix B

Federal Facilities Forum Members

Appendix B

Federal Facilities Forum Members

Office Location	Contacts
EPA - Region 1 1 Congress Street Boston, MA 02114-2023	Christine A.P. Williams (HBT)* (617) 918-1384 Fax: (617) 918- 1291 Jane Dolan (617) 918-1272
EPA - Region 2 290 Broadway New York, NY 10007-1866	Paul Ingrisano (212) 637-4337
EPA - Region 3 1650 Arch Street Philadelphia, PA 19103-2029	Stacie Driscoll (C) (3HS13) (215) 814-3368 Fax: (215) 814-3051 Steve Hirsh (C) (3HS13) (215) 814-3352 Fax: (215) 814-3051 Mary T. Cooke (215) 814-5129
EPA - Region 4 61 Forsyth Street Atlanta, GA 30303-8960	Jim Barksdale (404) 562-8537 Fax: (404) 562-8518 Robert Pope (404) 562-8506 Lila Koroma-Llamas (404) 562-9969 Fax: (404) 562-8158
EPA - Region 5 77 W. Jackson Boulevard Chicago, IL 60604	David Seely (312) 886-7058 Gene Jablonowski (312) 886-4591
EPA - Region 6 1445 Ross Avenue Dallas, TX 75202	Chris Villarreal (6SF-AP) (214) 665-6758 Fax: (214) 665-6660 Mike Overbay (6PD-NB) (214) 665-6482 Fax: (214) 665-6660
EPA - Region 7 901 North 5th Street Kansas City, KS 66101	Scott Marquess (SUPR/FFSE) (913) 551-7131 Fax: (913) 551-7063

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EPA - Region 8 999 18th Street Denver, CO 80202-2413	Jim Kiefer (8EPR-F)* (303) 312-6907 Fax: (303) 312-6067
EPA - Region 9 75 Hawthorne Street San Francisco, CA 94105	Lida Tan (415) 972-3018 Fax: (415) 744-1917 Glenn Kistner (415) 972-3004
EPA - Region 10 1200 Sixth Avenue Seattle, WA 98101	Harry Craig (000)* (Portland, OR Office: 811 SW 6th Ave. Portland, OR 97204) (503) 326-3689 Fax: (503) 326-3399
EPA Headquarters Ariel Rios Building 1200 Pennsylvania Avenue Washington, DC 20460	Joshua Barber (5106G) EPA/FFRRO (703) 603-0265 Tracey Seymour (5106G) EPA/FFRRO (703) 603-8712 (703) 603-0043 John Quander (5102G)** EPA/OSRTI (703) 603-7198

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