COST AND PERFORMANCE REPORT

Enhanced Bioremediation
of Contaminated Groundwater:

Balfour Road Site
Brentwood, California

Fourth Plain Service Station Site
Vancouver, Washington

Steve's Standard and Golden Belt 66 Site
Great Bend, Kansas

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EPA

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Office of Solid Waste and Emergency Response
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SITE INFORMATION

This report summarizes data on the cost and performance of enhanced bioremediation using Oxygen Release Compound (ORC®) to treat groundwater contaminated with gasoline-range petroleum hydrocarbons at the following three sites:

- Balfour Road, Brentwood, California
- Fourth Plain Service Station, Vancouver, Washington
- Steve's Standard and Golden Belt 66, Great Bend, Kansas

Table 1 summarizes information about the sites, including location, operations, year contamination was detected, source of contamination, and regulatory agency that oversees the cleanup.

This report describes remedial activities involving the use of ORC at three sites at which groundwater is contaminated with gasoline-range petroleum hydrocarbons. It provides information about the cost and performance of ORC®, methods used to apply ORC® to groundwater, and lessons learned.

Table 1: Summary of Site Information [2, 3, 4]

Site	Location	Operations	Year Contamination Detected	Source of Contamination	Regulatory Agency
Balfour Road	Brentwood, California	Supply Pipeline	1990	Pipeline Leak	California Regional Water Quality Control Board
Fourth Plain	Vancouver, Washington	Retail Station	1993	Pinhole Leak below Product Dispenser	Washington Department of Ecology
Steve's Standard	Great Bend, Kansas	Retail Stations	1994	Leak in Piping and Underground Storage Tanks	Kansas Department of Health and the Environment

Background [2, 3, 4]

History: Contamination at each site resulted from leaks in underground petroleum storage tanks and supply pipelines at or near retail dispensing locations. Refined petroleum product was released to the subsurface soil and groundwater at each site for unknown periods of time, until being detected in the 1990's.

At Balfour Road, pipeline leaks were discovered in a gasoline supply pipeline in 1990. From 1990 to 1995, groundwater was extracted at the site through an excavation trench and treated. Once the majority of the free product was recovered, the trench system was no longer a cost effective solution. Enhanced bioremediation of the groundwater using ORC® was implemented in December 1995.

At Fourth Plain, a release of gasoline-range petroleum hydrocarbons beneath a product dispenser was discovered in May 1993. At that time, the source was repaired and contaminated soils were excavated. Groundwater monitoring began in 1993, and a feasibility study and technology evaluation were conducted in 1995. That study included a pilot test of soil vapor

SITE INFORMATION (CONTINUED)

extraction (SVE) conducted in March 1995. Groundwater pumping constant discharge and recovery tests also were conducted in March 1995. Enhanced bioremediation of the groundwater using ORC® was implemented in July 1996.

At Steve's Standard, leaks in piping and underground storage tanks were discovered in 1994. Steve's Standard is a combination of two sites, Steve's Standard and Golden Belt 66. The two sites are adjacent to one another; remediation of the contamination plume in the groundwater beneath the sites has been considered as a single project for this report (referred to as Steve's Standard for this report). At Steve's Standard, enhanced bioremediation of the groundwater using ORC® was implemented in July 1996.

Regulatory Context: The three sites were cleaned up under their respective state voluntary cleanup programs. Oversight was performed by the respective state agency (see Table 1), without involvement of EPA.

Information on cleanup goals for the three sites is discussed under the Treatment System Performance section of this report.

Remedy Selection: Enhanced bioremediation using ORC® was selected by the lead contractors for each of the sites on the basis of results of an evaluation that compared enhanced bioremediation using ORC®, air sparging and SVE (AS/SVE), and groundwater extraction (pump-and-treat). Enhanced bioremediation using ORC® was selected because it was expected to reduce the mass of contaminants in the aquifer by more than 50 percent in only six months, thereby reducing risk to human health and the environment from exposure to contaminated groundwater, and because it required a smaller capital investment and lower operating expenses than the two alternative technologies. Regenesis indicated that enhanced biodegradation using ORC® was not expected to treat the groundwater to the federal maximum contaminant levels (MCL), but that the treatment would reduce substantially the dissolved-phase mass of contaminants present in the aquifer, as well as reduce sources characterized as moderate smear zones. Direct injection of ORC® into the source or a line of wells on the perimeter of the plume are the primary methods used to achieve the stated goals.

Period of Operation:

Balfour Road:	December 1995 to present (report covers the period through October 1997)
Fourth Plain:	July 1996 to present (report covers the period through October 1997)
Steve's Standard:	July 1996 to present (report covers the period through October 1997)

MATRIX DESCRIPTION

Matrix Identification

Type of Matrix Treated: Groundwater

Contaminant Characterization [2, 3, 4]

Primary Contaminant Groups: Benzene, toluene, ethylbenzene, and xylenes (BTEX) and total petroleum hydrocarbons (TPH)

At the three sites, benzene, total BTEX, and TPH were detected at concentrations in groundwater ranging from 0.43 milligrams per liter (mg/L) to 5.1 mg/L, 13.2 to 14 mg/L, and 10 to 120 mg/L, respectively. Table 2 presents the maximum concentrations of benzene, total BTEX, and TPH detected in groundwater at Balfour Road, Fourth Plain, and Steve's Standard before application of ORC®.

MATRIX DESCRIPTION (CONTINUED)

Matrix Characteristics Affecting Cost or Performance [2, 3, 4]

Table 3 summarizes the matrix characteristics that affect the cost or performance of the technology and the values measured. At each site, contamination occurred in a shallow unconfined aquifer that consisted of a sandy and clayey mixture and ranged in thickness from 7 to 18 feet. As shown on Table 3, Fourth Plain had a relatively high groundwater velocity. According to Regenesis, the vendor of ORC®, higher groundwater velocity aids in dispersing oxygen from an application of ORC® more quickly over a wider area and in mixing the oxygen with contaminants.

Table 2: Maximum Initial Concentrations Detected Prior to Application of ORC® [2, 3, 4]

Contaminants	Site		
	Balfour Road	Fourth Plain	Steve's Standard
Benzene (mg/L)	0.43	1.0	5.1
Total BTEX (mg/L)	Not available	14.0	13.2
Total Petroleum Hydrocarbons (mg/L)	10	120	30

Table 3: Matrix Characteristics Affecting Cost or Performance [2, 3, 4]

Parameters	Site			Method of Measurement
	Balfour Road	Fourth Plain	Steve's Standard	
Thickness of Aquifer (ft)	18	12 - 15	7 - 10	Visual inspection of core samples
Conductivity (centimeters per second [cm/sec])	0.001*	0.08	0.02	Slug or constant discharge and recovery test
Groundwater velocity (ft/day)	0.00076**	1 - 10	0.025**	Calculation using Darcy's Law
Hydraulic Gradient (ft/ft)	0.0009	0.003 - 0.03	0.0015	Water level indicator and site survey

* estimated as 0.001cm/sec for silty clay
** calculated using estimate of porosity, 0.3

MATRIX DESCRIPTION (CONTINUED)

Table 3 (continued): Matrix Characteristics Affecting Cost or Performance [2, 3, 4]

Parameters	Site			Method of Measurement
	Balfour Road	Fourth Plain	Steve's Standards	
Depth to Groundwater (feet below ground surface [ft bgs])	15 - 22	13-21	7-9	Water level indicator
Soil Type or Classification	Aquifer is a heterogeneous combination of silty clays on top of clayey silts, with sand lenses and fingers (CL-ML 80-95%)	Aquifer primarily consists of sands and gravels, with silty and clayey zones (Sand/ gravel/silt 65/25/10)	Aquifer consists of loose, medium- to coarse-grain sand, overlain by silty clay soil	Visual inspection of core samples
pH	Not provided	6.2-7.4	6.8-7.2	-
Porosity	20-30% (estimated based on soil type)	20-30%	~25-30%	-
Seasonal water table fluctuation	Not provided	1-2 ft	~4 ft	Time series data from water level indicator

DESCRIPTION OF TREATMENT SYSTEM

Primary Treatment Technology

Enhanced bioremediation

Supplemental Treatment Technology

None

System Description and Operation [1, 2, 3, 4]

Enhanced bioremediation was performed at the three sites, using in situ bioremediation and application of ORC®. ORC® is a proprietary formulation based on magnesium peroxide and is available from Regenesis Bioremediation Products, Inc (Regenesis). The following information on ORC® was provided by Regenesis. When it comes in contact with groundwater, ORC® slowly releases oxygen to the groundwater and is converted to a magnesium hydroxide byproduct. Regenesis has indicated that, when hydrated, ORC® can release oxygen for up to a year or longer (often typically 6 months) depending on contaminant flux and that the rate of release is a function of the molecular matrix Regenesis produces during synthesis and is not achieved by a coating process.

When ORC® is used, the level of dissolved oxygen (DO) measured in the groundwater is raised above background levels, and the rate of natural bioremediation is increased. The level of DO varies according to several factors, including:

DESCRIPTION OF TREATMENT SYSTEM (CONTINUED)

- The dosage of ORC® applied to the groundwater.
- The amount of DO consumed during biological degradation of hydrocarbons.
- The amount of time that has elapsed since ORC® was applied to the groundwater.

According to Regenesis, the quantity of ORC® required for a site is based on several factors including the estimated mass of contaminant at the site (dissolved-phase concentration) and the specific, properties of the aquifer such as parasity and thickness. Regenesis indicates that a key factor in estimating the quantity of ORC® required is the stoichiometric quantity of oxygen required to degrade the contaminants. For example, fully degrading one pound of benzene to carbon dioxide and water would require 3 pounds of oxygen. Given that ORC® releases 10 percent of its mass as oxygen, 30 pounds of ORC® would be required to fully degrade one pound of benzene. Oxygen typically is released from ORC® over a four- to eight-month period, resulting in a sustained increase in the amount of dissolved oxygen available to promote aerobic biodegradation of groundwater contamination.

Application of ORC® [2, 3, 4]

A different method of applying ORC® to the groundwater was used at each site, as identified below:

- Balfour Road: wells containing filter socks
- Fourth Plain: borings containing slurry
- Steve's Standard: direct push injection

Descriptions of the systems used at the three sites to apply ORC® to the groundwater and to monitor the concentrations of contaminants and DO in the groundwater are presented below.

Balfour Road - At the Balfour Road site, filter socks containing ORC® and an inert carrier matrix (silica sand) were applied to the groundwater through a system of 10 wells in two barriers, one line of four and another of six wells installed downgradient of the source areas. The barrier of four wells was installed closer to the source than the second barrier. Both barriers were arranged in a line perpendicular to the direction of groundwater flow. Approximately 200 pounds of ORC® were applied to the groundwater at this site. The mass of contaminants in the aquifer was not available for this site, and therefore the amount of ORC applied at Balfour Road was estimated based on the concentrations of contaminants and properties of the aquifer. Monitoring wells (MW) were placed 42 feet upgradient and downgradient of each battery of wells. Monthly monitoring of DO, benzene, and TPH was conducted.

MW SB-43A was installed to monitor groundwater downgradient of the battery of ORC® wells nearest to the source of contamination, and MW SB-37A was installed to monitor groundwater downgradient from the battery of wells farther downstream from the source of contamination.

Fourth Plain - At the Fourth Plain site, a fence of 15 boreholes (borings) at 10-foot spacing was drilled near the upgradient edge of the anaerobic core of the contaminant plume. The borings were drilled to about 25 feet bgs and each was filled from about 10 ft bgs to 25 ft bgs with a slurry containing approximately 70 pounds of ORC®. The oxygen released by the ORC® was transported to the anaerobic core of the contaminant plume by the natural flow of groundwater at the site. The site initially was estimated to have approximately 33 pounds of dissolved-phase contaminant (BTEX) in the groundwater; on the basis of the 30 to 1 ratio for ORC® to dissolved-phase contaminant discussed earlier in this report, approximately 1,000 pounds of ORC® would be required to treat the groundwater at the site. The 15 borings drilled at the site contained a total of approximately 1,000 pounds of ORC® (70 lbs x 15 wells). MWs were located on site and

DESCRIPTION OF TREATMENT SYSTEM (CONTINUED)

approximately 90 to 120 feet downgradient of the site. The MWs were monitored monthly for DO, BTEX, TPH, and pH.

Steve's Standard - At this site, a total of 2,325 pounds of ORC® slurry was injected into the groundwater with a Geoprobe™ (direct-push technology). Slurry was injected at approximately 118 points at the site, at an injection pressure ranging from 50 to 100 pounds per square inch (psi), on a rectangular grid pattern. Similarly to Balfour Road, the mass of contaminants in the aquifer was not available for this site, and therefore the amount of ORC applied at Steve's Standard was estimated based on the dissolved-phase concentrations of contaminants and properties of the aquifer.

Approximately 50 MWs provided monitoring of the performance of the system at Steve's Standard. The site was monitored periodically fora variety of parameters, including BTEX, TPH, and DO. MWs were located throughout the site and were used to measure the concentrations of contaminants within source areas (for example, MW-10 at Steve's Standard and OB-06 at Golden Belt 66) and at locations downgradient of the source areas (for example, MW-8 and MW-15).

Operating Parameters Affecting Treatment Cost or Performance

Operating parameters that affect cost or performance include the number of points at which ORC® is introduced (ORC® source points), the screened intervals of source points, the spacing of the source points (if using socks and wells), the dosage of ORC®, and background and operating concentrations of DO. Table 4 presents the major operating parameters that affect cost and performance for the technology and the values measured for each of those parameters.

Table 4: Operating Parameters Affecting Cost or Performance [2, 3, 4]

Parameter	Value		
	Balfour Road	Fourth Plain	Steve's Standard
Method of Application	Wells filled with ORC® filter socks	Borings filled with slurry	Geoprobe™ injection of slurry
Number of Source Points	10 wells	15 borings	118 injection points
Screened Interval (ft below ground surface)	10 - 25 and 30 - 33	10 - 25	10 - 25*
Source Point Spacing (ft)	20	10	5 - 10
Dosage of ORC® (lbs/well)	20	70	20
Dosage of ORC® (total lbs applied)	200	1,000	2,325
Background Dissolved Oxygen Concentration (mg/L)	<1	1 - 4	0-2

* There is no screened interval for a Geoprobe™ direct-push technology; the value given represents the depth below the surface of the water table at which ORC® was injected at a pressure ranging from 50 to 100 pounds per square inch.

TREATMENT SYSTEM PERFORMANCE

Cleanup Goals [2, 10, 12]

The three sites were remediated under their respective state voluntary cleanup programs. The following is a discussion on how the remediation objectives were established for each site.

The cleanup goals identified for the Balfour Road site were groundwater drinking-water standards; however, no specific numerical standards were provided by Santa Fe Pipeline Partners. Federal groundwater drinking standards at 40 Code of Federal Regulations (CFR) 141.61 include an MCL for benzene of 0.005 mg/L.

The cleanup goals for the Fourth Plain site identified by Environmental Partners, Inc. were:

- Benzene, 0.005 mg/L
- Total BTEX, 0.095 mg/L
- TPH, 1.0 mg/L

The Fourth Plain site was remediated under the state of Washington's Independent Remedial Action Program (IRAP) that allows site owners to manage site cleanups independently. Under the IRAP, managed by the Washington State Department of Ecology, the state does not provide oversight or direction to site owners on the appropriateness of their remedial approaches. Instead, under the program, the state provides a letter requiring "no further action" when a site owner provides to the state sufficient evidence that cleanup levels have been met and that the site no longer represents a threat to human health and the environment.

Because the aquifer at the site was a source of potable water, as defined by the state of Washington, and because a surface-water body was immediately down-gradient from the site, the cleanup level identified for benzene was the MTCA cleanup level of 0.005 mg/L. The cleanup level for TPH was established for aesthetic reasons; no risk-based cleanup level was identified for TPH.

No cleanup levels were established for the Steve's Standard site. Remediation of the Steve's Standard site was conducted as a pilot test by the Kansas Department of Health and the Environment (KDHE) to determine whether ORC® could be used as a cost-effective method of remediating groundwater contaminated with hydrocarbons. As such, it was intended to evaluate the effectiveness of ORC® rather than to achieve a specified cleanup goal for the groundwater. The application also was intended to identify design parameters needed to optimize an ORC® application while attracting only minimal attention in the neighboring community. It was funded partially by the State.

Treatment Performance Data

Performance data collected for these three sites are summarized in Tables 5 through 8. Table 5 identifies the number of MWs, locations of MWs, frequency of sampling, and method of analysis for each site. Tables 6, 7, and 8 summarize analytical data for benzene, total BTEX, TPH, and DO for selected MWs at each of the three sites. Figures 1 and 2 present graphically the data shown on Table 6 for Balfour Road.

None of the sites reported any exceptions to the quality assurance and quality control plans.

TREATMENT SYSTEM PERFORMANCE (CONTINUED)

Table 5: Performance Data Sampling [1, 2, 3]

Sampling Information	Balfour Road	Fourth Plain	Steve's Standard
Number of MWs	4 (on site)	10 (on site)	Approximately 50
Locations of MWs	One Well up- and one down-gradient of each of the two barriers of ORC® wells	Up- and downgradient of the ORC® barrier of borings	Throughout the application area and on the perimeter of the property
Frequency of Sampling	Monthly	Quarterly	Week, month, two-month (doubling period between sampling events)
Method of Analysis	YSI 55 (DO) 8015/8020 (organics)	Hach AccuVac (DO) Hydrocarbon Methods	Hach AccuVac (DO) Method 8260 (BTEX) OA-1 (TPH)

Table 6: Summary of Treatment Performance Data for the Balfour Road Site (mg/L) [2]

Date	Well SB-37A		Well SB-43A	
	Benzene	DO	Benzene	DO
December 1995*	NR	0.77	NR	NR
January 1996	0.43	1.75	0.080	1.29
February 1996	0.41	0.87	0.093	1.30
March 1996	0.25	3.40	0.0035	3.32
April 1996	0.11	1.19	0.0028	1.92
May 1996	0.19	1.69	0.0014	2.47

* = ORC® socks placed in wells
NR = Not reported

TREATMENT SYSTEM PERFORMANCE (CONTINUED)

Figure 1. Summary of Monitoring Data. SB-37A, Balfour Road [2]*

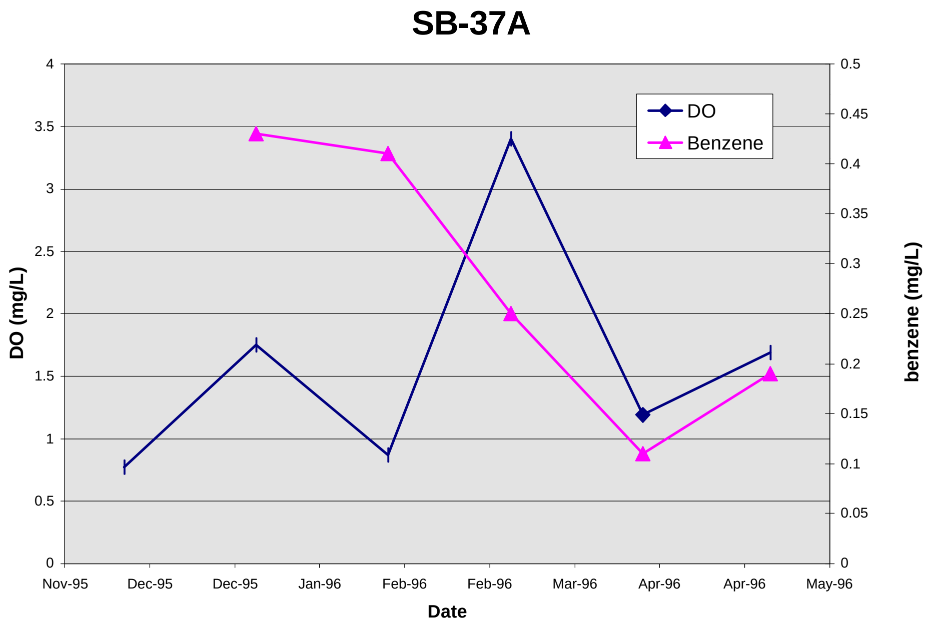
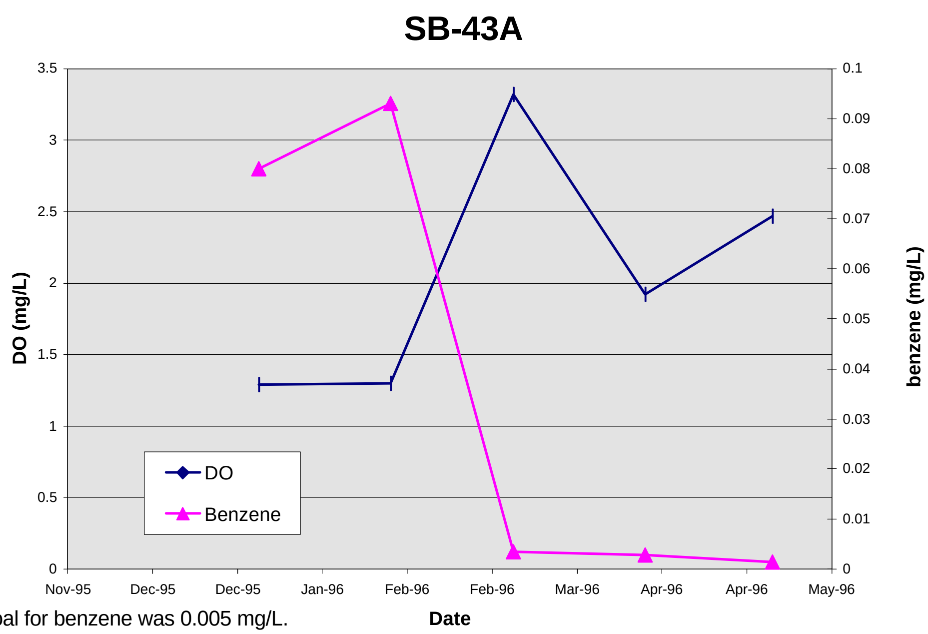


Figure 2. Summary of Monitoring Data. SB-43A, Balfour Road [2]*



* Cleanup goal for benzene was 0.005 mg/L.

TREATMENT SYSTEM PERFORMANCE (CONTINUED)

Table 7: Summary of Treatment Performance Measured using a Geometric Mean for Fourth Plain Site (mg/L) [17]*

Date	Benzene	Total BTEX	TPH/GRO
July 1996 **	0.053	0.976	11.10
October 1996	0.029	0.481	6.90
January 1997	0.032	0.850	6.16

* = Calculated based on data from 6 monitoring wells.

Table 8: Summary of Treatment Performance Measured using a Geometric Mean for Steve's Standard Site* (mg/L) [4, 20]

Date	Benzene	Total BTEX	TPH/GRO
July 1996**	0.18	0.66	4.1
November 1996	0.04	0.14	2.5
February 1997	0.03	0.06	2.6
August 1997	0.11	0.27	2.6
November 1997	0.11	0.30	2.5

* = Based on 17 monitoring wells
** = ORC® injected
NS = Not Sampled

Performance Data Assessment

This section presents a discussion of the data on concentrations of contaminants for each of the three sites. Where possible, the geometric mean of wells at each site was evaluated to provide an indication of the trend in contaminant concentrations at the site.

Balfour Road. Table 6 and Figures 1 and 2 show the results of monitoring from December 1995 to May 1996 for benzene and dissolved oxygen at two MWs at Balfour Road located downgradient of the barrier of the ORC® wells. Figures 1 and 2 show that, as of May 1996, concentrations of benzene were reduced by more than 50 percent in six months. In well MW SB-43A, closest to the source of contamination, concentrations of benzene were reduced from 0.080 mg/L to 0.0014 mg/L, which is below the cleanup goal of 0.005 mg/L. In the well, concentrations of DO varied from 1.29 to 3.32 mg/L. In well MW-SB-37A, farther from the source of contamination, concentrations of benzene were reduced 56 percent from 0.43 mg/L to 0.19 mg/L. In that well, concentrations of DO varied from 0.77 to 3.40 mg/L.

Fourth Plain. At the Fourth Plain site, concentrations of contaminants were reported in six MWs located throughout the plume (MW-4, 6, 7, 9, 11, 14). During baseline monitoring of the groundwater at the site (July 1996), wells in this area were shown to have the highest

TREATMENT SYSTEM PERFORMANCE (CONTINUED)

concentrations of benzene, total BTEX, and TPH-G, and the lowest concentrations of DO. Table 7 shows the geometric mean concentrations of benzene, total BTEX, and TPH-G measured in these wells in July 1996, October 1996, and January 1997, covering approximately 180 days after the application of ORC®. Over that 180-day period, the geometric mean concentrations of benzene, total BTEX, and TPH-G decreased by 45, 51, and 38 percent after 90 days, and 38, 12, and 44 percent after 180 days, respectively.

Background concentrations of DO at the Fourth Plain site ranged from 1 to 4 mg/L, as shown in Table 5. Before application of ORC®, the anoxic core of the plume extended over an area of approximately 1 acre, with a concentration of DO in that area of less than 0.3 mg/L. The anoxic core of the plume had the highest levels of BTEX and TPH; MW-7 was located within the anoxic core area. The concentrations of DO in the area increased to levels ranging from 2.6 to 4.9 mg/L during the first 90 days after application of ORC® and continued to rise to a maximum of 7.8 mg/L, reached 180 days after application of ORC®.

Steve's Standard. Table 8 summarizes the results for a geometric mean of 18 of the MWs at this site. The monitoring data cover approximately a 16-month period after the application of ORC®. A photo-ionization detector (PID) analysis conducted in early 1997 identified a continuing source of hydrocarbons in the subsurface at this site. [20] The PID data were used to develop a plot of hydrocarbon concentrations in the subsurface which indicated a continuing source near the OB-6 boring. Over the first seven months after application of ORC (July 1996 - February 1997), concentrations of benzene, BTEX, and TPH-G were reduced; over the next nine months, concentrations appeared to stabilize or rise slightly. During the first seven months, concentrations for benzene, total BTEX, and TPH-G were reduced 83, 91, and 36 percent, respectively, while overall from July 1996 - November 1997, concentrations were reduced 39, 55, and 39 percent, respectively.

The concentration of DO throughout the site ranged from 0 to 6 mg/L over the period from July 1996 to February 1997. By February 1997, the concentration of DO was measured as 0 mg/L for 80 percent of the MWs.

The vendor supporting the KDHE (Terranext) concluded the following about the effectiveness of ORC at the Steve's Standard site:

- the use of ORC stimulated aerobic biodegradation of petroleum constituents to almost non-detect levels in areas around the petroleum release source areas
- total BTEX levels in wells hydraulically downgradient of the source areas have continued to decrease
- total BTEX levels in source areas increased, thus indicating that the total mass of BTEX in these areas is greater than was estimated during the design of ORC injection

Estimate of Mass of Contaminants Degraded

In 1997, Regenesis commissioned Principia Mathematica, a groundwater modeling firm, to model two of the sites (Fourth Plain and Steve's Standard) to estimate the mass of contaminants degraded in the aquifers. As mentioned in the previous discussion of performance data, a photo ionization detector identified a continuing source below Steve's Standard. This complicates the interpretation of modeling results for Steve's Standard; therefore, only modeling results for Fourth Plain are presented below. Table 9 presents a summary of the modeling results, including assumptions applied in the modeling, and mass of contaminants degraded. Approximately 280 pounds of TPH were degraded in six months at this site.

Table 10 shows a comparison of the mass of ORC® dosage applied at Fourth Plain with the mass of BTEX degraded. Approximately 30 lbs of ORC® were applied for each pound of BTEX degraded.

TREATMENT SYSTEM PERFORMANCE (CONTINUED)

Table 9: Summary of Modeling Results for Estimating Mass of Contaminants Degraded [13]

Estimated Quantity	Fourth Plain
Area (ft^2) (see assumptions)	20,400
Mass of Benzene Degraded (lbs)	1.8
Mass of Total BTEX Degraded (lbs)	32.2
Mass of GRO-TPH Degraded (lbs)	281.5
Assumptions: • Area defined by 10 mg/L isopleth • Porosity = 0.3 and density of water = 28.3 kg/ft^3 • Affected thickness of aquifer = 10 feet	

Note: Calculations are based on a logarithmic Kriging analysis fitting a surface to the available data points and saving the fitted surface to a finite difference grid. Volumes used in the analysis are a function of the areal extent of the 10 mg/L concentration isopleths times a 10 -foot-thick contaminated zone with a porosity of 0.3. In addition, volumes presented here assume a low groundwater velocity over a short period, resulting in only one volume of throughput. (It is likely that, because groundwater velocity at Fourth Plain is higher than at Steve's Standard, the volume used in this analysis for Fourth Plain was underestimated.)

Table 10: Ratio of ORC® Dosage to Mass of BTEX Degraded [2, 3, 4, 13, 18]

Parameter	Fourth Plain
Mass of ORC® Dosage (lbs)	1,000
Estimated Mass of BTEX Before Application (lb)	33
Mass of Total BTEX Degraded (lbs)	32.2
Ratio of ORC® Dosage to Mass of BTEX Degraded	31.1

Recent Activities [10, 11, 12]

As of October 1997, the cleanup goals described above had not been met at either the Balfour Road or Fourth Plain sites; however the geometric mean concentration and mass of benzene, total BTEX, and TPH had been reduced by approximately 50 percent in the aquifers in only 6 months for roughly $50,000 per site. In addition, at the Steve's Standard site, the concentration and mass of benzene, total BTEX, and TPH had been reduced in portions of the aquifer. Recent activities at the three sites are discussed below.

Balfour Road SFPP divided the site into two areas, referred to as north of Balfour Road and south of Balfour Road, for requesting closure letters from the state. For the area north of Balfour Road, a single ORC® source well contained benzene at 0.15 mg/L. There has been no reapplication of ORC® since the original application (December 1995). The vendor of the treatment indicated that it is likely that there will be a second application of ORC® in the affected well and that the site will request from the state a letter for no further action at that time. According to the vendor, for the area south of Balfour Road, SFPP conducted further

Treatment System Performance (continued)

activities in the summer of 1997 to characterize the levels of contamination in the soil and groundwater at the site. The results of these activities revealed additional contamination in a utility trench located along the boundary of the area. The contamination had not been detected previously. SFPP had not yet identified an appropriate remedial action for the areas south of Balfour Road.

Fourth Plain As shown above, the concentrations of benzene, total BTEX, and TPH had not met the cleanup levels for the site after six months of treatment. Environmental Partners Inc. stated its belief that the application of an additional 200 pounds of ORC® per quarter for a period of 1.25 years (1,000 pounds of ORC® total) would help achieve the cleanup goal. The cost of the additional effort was estimated to be an additional $50,000. The references available do not provide information about whether the additional treatment was being performed.

Steve's Standard Jacobs Engineering Group indicated that the dissolved-phase plume was reduced in volume following application of ORC®, but that elevated concentrations of hydrocarbons remained at one location at the site. In September 1997, 1,500 pounds of ORC® were injected into the aquifer, at a cost of $25,000; samples of groundwater were collected from the location in November 1997 to evaluate the concentrations of hydrocarbons remaining after that latest application of ORC®. As shown in Table 9, concentrations had not changed much from August to November 1997.

Cost of the Treatment System

Procurement Process [2, 3, 4]

At each site, the site owner chose a prime contractor to be responsible for site management. That contractor entered into subcontracts with other firms, such as Regenesis, to help with design and construction of treatment systems for enhanced bioremediation, including the use of ORC®. No information is available that indicates whether the prime contractors or subcontractors were selected through a competitive bidding process.

Costs for the Treatment System [2, 3, 4]

Table 11 summarizes the actual costs of enhanced bioremediation, including use of ORC®, at the three sites. All cost data were solicited and collected from the contractor that performed the work. Total costs for the three sites varied by a factor of 2.5, with costs at Fourth Plain the lowest ($37,300), and those at Steve's Standard the highest ($96,187). Steve's Standard covered three times the area, including two service stations (As discussed earlier, Steve's Standard referred to in this report comprises both the Steve's Standard and Golden Belt 66 sites). The costs of individual elements of the projects are presented in Table 12.

The costs for installation of wells at Balfour Road were high, compared with those at the other two sites (where borings and direct push technology were used). According to SFPP, Balfour Road used a more expensive method of application of ORC® to facilitate use of air sparging as a contingency if application of ORC® did not meet goals of the project (the ORC® wells could be converted to sparging wells). The costs of site work and installation of wells at Fourth Plain are less than those for the other two sites because the site operator used some MWs that had been installed for site characterization in the ORC® application system.

COST OF THE TREATMENT SYSTEM (CONTINUED)

Vendor Input on Costs [19]

The primary costs of using ORC® are those for the installation of ORC® source points, the amount of ORC® applied, and the amount and type of monitoring required. Contaminant mass, hydrogeology of the aquifer, and groundwater flow rate are the most significant parameters that affect those costs because they determine the spacing of the source points, the number of source points required, and the amount of ORC® to be applied. Monitoring costs will depend on the regulatory requirements and are beyond the direct control of the vendor.

Table 11: Summary of Cost Data [2, 3, 4]

Cleanup Activity	Balfour Road	Fourth Plain	Steve's Standard**
Treatment Activities ($)			
Site Work and Well Installation	25,488	7,200	37,126
ORC®	6,520	9,900	23,599
Operations	1,500	18,600	6,046
Monitoring[a]	-	-	26,668
Treatment Subtotal	33,508	35,700	93,439
After Treatment Activities ($)			
Decontamination	4,900	500	2,748
Site Restoration	1,000	500	-
Demobilization and Disposal	2,200	600	-
After Treatment Subtotal	8,100	1,600	2,748
TOTAL COST	$41,608	$37,300	$96,182

[a] For Balfour Road and Fourth Plain, this cost was not provided separately from operating costs.
** Steve's Standard comprises two adjacent facilities.

SITE CONTACTS

Table 12 presents the contacts for each of the three sites.

Table 12: Site Contacts

Balfour Road	
Site Management/Design: Mark Sandon Santa Fe Pipeline Partners L.P. 1100 Towne & Country Road Orange, CA 92868 (714) 560-4867	**State Contact:** Joel Weiss California Regional Water Quality Control Board Central Valley Region (916) 255-3077
Construction: Levine-Fricke 2001 Douglas Boulevard Roseville, CA 95661 (916) 786-0320	**Design (Additional):** Craig Sandefur Regenesis Bioremediation Products, Inc. 27130A Paseo Espada, Suite 1407 San Juan Capistrano, CA 92675 (714) 443-3136
Fourth Plain	
Site Management: Joseph L. Glassman Environmental Insurance Management, Inc. 512 North Oakland Street Arlington, VA 22203	**State Contact:** Carol Fleshes Washington Department of Ecology NW Region, Mail Stop PV11 Olympia, WA 98504-8711 (206) 649-7000
Construction/Design: Thomas Morin Environmental Partners Inc. 10940 NE 33rd Place, Suite 110 Bellevue, WA 98004 (206) 889-4747	**Design (Additional):** Steve Koenigsberg Regenesis Bioremediation Products, Inc. 27130A Paseo Espada, Suite 1407 San Juan Capistrano, CA 92675 (714) 443-3136
Steve's Standard	
Site Management: Roger Lamb Jacobs Engineering Group Inc. 8208 Melrose Drive, Suite 210 Lenexa, KS 66214 (913) 492-9218	**State Contact:** Emily McGuire Kansas Department of Health and Environment Bureau of Environmental Remediation Forbes Field, Building 740 Topeka, KS 66620 (913) 296-7005
Construction: Roger Lamb Jacobs Engineering Group Inc. 8208 Melrose Drive, Suite 210 Lenexa, KS 66214 (913) 492-9218	**Design:** Craig Sandefur and David Peterson Regenesis Bioremediation Products, Inc. 27130A Paseo Espada, Suite 1407 San Juan Capistrano, CA 92675 (714) 443-3136

OBSERVATIONS AND LESSONS LEARNED

Cost Observations and Lessons Learned

- Actual costs for enhanced bioremediation using ORC® at the three sites ranged from $37,300 to $96,187, with costs at two of the three sites less than $50,000. The relatively high cost at Steve's Standard is attributed to the large area treated for two service stations. The costs included activities directly attributed to treatment, such as site work, installation of wells, application of ORC®, operations, and monitoring, and activities performed after treatment, such as decontamination, site restoration, and demobilization and disposal.

- The factors that most affected costs at the three sites included the amount of ORC® applied, (e.g., 200 lbs at Balfour Road; 1,000 lbs at Fourth Plain; 2,325 lbs at Steve's Standard) the number of ORC® source points, (e.g., 10 wells at Balfour Road; 15 borings at Fourth Plain; 118 injection points at Steve's Standard), and the type of equipment used to apply ORC® (for example, the wells used at Balfour Road were relatively more expensive than equipment used at the other two sites).

- The firms responsible for site management and construction compared the cost of remediating the sites by enhanced bioremediation using ORC® with the costs of other technologies such as an AS/SVE system. For example, at the Balfour Road site, the installation and startup costs alone for an AS/SVE system were estimated to cost $181,077 compared to $33,508 for a complete ORC application. At the Steve's Standard site, the site management firm estimated that installation and operation of an AS/SVE system would have cost $250,000, including $36,000 for operations. The firm indicated that pilot tests showed that AS/SVE would have been effective at the site, but that it would not have been practical to install such a system because of limited space available for equipment and the close proximity of residential housing. [12]

- At the Balfour Road site, use of ORC® was estimated by SFPP to have saved the site owner approximately $100,000 over the cost of AS/SVE. [2]

Performance Observations and Lessons Learned

- At the Balfour Road site, the overall cleanup goal was not met during the six-month operation period of the ORC® application. However, benzene concentrations in the well closest to the source of contamination were reduced by 98 percent to 0.0014 mg/L (below the cleanup goal of 0.005 mg/L). Benzene concentrations in a well farther from the source were reduced by 56 percent, but concentrationd remained above the cleanup goal.

- The six-month application of ORC® at the Fourth Plain site resulted in a 40 percent reduction in the mean benzene concentration, a 45 percent reduction in the mean TPH/GRO concentration, and a 13 percent reduction in the mean BTEX concentration. However, the final concentrations of all three parameters remained above the cleanup goals.

- The application at the Steve's Standard site was conducted by the state as a pilot test; there were no specific cleanup goals for the application. The geometric mean concentrations for benzene, total BTEX, and TPH-G were reduced by nearly 40 percent at this site during the first seven months of operation. However, there was a continuing source of contamination at this site, and this limited the effectiveness of the technology application.

Observations and Lessons Learned (continued)

- Modeling was used to estimate the mass of contaminant degraded in the aquifer at the Fourth Plain site. The total mass of total BTEX and TPH degraded was 32.2 and 282 lbs, respectively. This corresponds to a ratio of dose of ORC® to mass of total BTEX degraded of 31:1. The ratio identified for the Fourth Plain site is very close to the ratio of dose of ORC® to mass of total BTEX degraded of 31.1. The ratio identified for the Fourth Plain site is very close to the ratio of 30:1 estimated on the basis of soichiometric relationships.

- Remediation at all three sites was conducted in relatively shallow unconfined aquifers (less than 20 feet deep) contaminated with gasoline-range petroleum hydrocarbons. At Fourth Plain, the mass of contaminants in the aquifer was estimated to be 30 lbs before treatment with ORC®. The mass of contaminants in the aquifer before treatment was not provided for either the Balfour Road or the Steve's Standard site. For those sites, Regenesis determined the amount of ORC® to apply to the groundwater on the basis of concentrations of contaminants and hydrogeological data. The amount of ORC® applied to the aquifers at the three sites differed by a factor of 10, ranging from 200 lbs at Balfour Road to 2,325 lbs at Steve's Standard.

- The levels of DO measured in the aquifers at the three sites generally were higher after application of ORC® than before its application. The levels of DO typically ranged from 2 to 8 mg/L within six months after application of ORC®.

Other Observations and Lessons Learned

Regenesis has stated that it developed ORC® to reduce the mass of petroleum hydrocarbons in groundwater over a shorter period of time and for a lower cost than can be achieved by conventional technologies, and provided the following additional observations about the use of ORC®:

- Costs for ORC® are less than those for other technologies such as AS/SVE or pump-and-treat. ORC® requires less capital investment in equipment than the other technologies and can be deployed relatively quickly. Use of ORC® will substantially reduce the mass of contaminants in an aquifer, and will control levels of contamination in source areas, reducing risk to human health and the environment from exposure to contaminants in an aquifer and increasing levels of DO in an aquifer. ORC® typically will reduce concentrations of contaminants in an aquifer by at least 50 percent in six months, but is likely not the best remedy for a site that must be remediated to meet MCLs. In addition, ORC may be used to remediate relatively less-contaminated areas of an aquifer (polishing).

- Compared with other technologies, such as pump-and-treat or AS/SVE, ORC® is a passive technology, the implementation of which does not require an extensive design.

- ORC® may be used not only as a treatment barrier to reduce concentrations of contaminants in dissolved hydrocarbon plumes migrating off site but also as a source control technology when injected directly into a source.

- The effectiveness of ORC® over the long term remains unknown. Monitoring over two-year periods and multiple applications will be useful in obtaining the data needed to determine the technology's ability to achieve cleanup goals.

- Further research on the applicability of ORC® in more complex hydrogeological environments is necessary. The three sites presented in this report all had relatively shallow, unconfined aquifers.

- ORC® provides a quick response technology for elevating concentrations of DO and increasing aerobic degradation processes in groundwater over a wide area.

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Preparation Of The Analysis

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