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Performance of air sparging systems: a review of case studies

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Abstract

Fluor Daniel GTI (now IT Corporation) has compiled a database of 49 completed in-situ air sparging case studies. Air sparging is a commonly used remediation technology which volatilizes and enhances aerobic biodegradation of contamination in groundwater and saturated zone soil. The air sparging database was compiled to address questions regarding the effectiveness and permanence of air sparging, and to provide predictive indicators of air sparging success to aid in optimization of existing and future air sparging systems. In each case study, groundwater concentrations were compared before sparging was initiated, just before sparging was terminated, and in the months following shutdown of the sparging system. The case studies included both chlorinated solvents and petroleum hydrocarbon contamination, and covered a wide range of soil conditions and sparge system parameters. In many cases, air sparging achieved a substantial and permanent decrease in groundwater concentrations. Successful systems were achieved with both chlorinated and petroleum contamination, both sandy and silty soils, and both continuous and pulsed flow sparging. In other cases, however, a significant rebound of groundwater concentrations was observed after sparging was terminated. Rebound sometimes required 6 to 12 months to develop fully. Rebound was more frequently observed at sites contaminated with petroleum hydrocarbons than with chlorinated solvents. Petroleum-contaminated sites were more likely to rebound when initial groundwater contamination levels were high enough to suggest the presence of LNAPL or a smear zone of residual LNAPL. Rebound at petroleum sites appeared to be minimized by a high density of sparge wells addressing the entire source area and a high sparge air injection rate. In some cases, rebound appeared to be related to a rising water table.

Keywords: Air sparging; Rebound; In situ remediation

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1. Introduction

In situ air sparging is a commonly used remediation technology which was developed in the late 1980s as a method for treating dissolved volatile organic compounds (VOCs) in groundwater. Air sparging involves the injection of air under pressure into saturated zone soils. The injected air displaces water and creates air-filled porosity in the saturated soils, volatilizes and removes dissolved and adsorbed phase VOCs, and transfers oxygen into the groundwater. As a result, both physical removal and aerobic biodegradation of contamination in groundwater and saturated zone soil are enhanced. Air sparging has been used to remediate both chlorinated solvents and petroleum hydrocarbons [1–5].

Air sparging offers a means of remediating soils and groundwater without the need for active groundwater pumping, and in some cases, air sparging has been shown to produce significant and permanent reductions in groundwater contaminant concentrations. As a result there has been a steady increase in application of air sparging, and hundreds of systems are currently in operation. However, dissolved groundwater concentrations sometimes fall dramatically during sparging, but then ‘‘rebound’’ nearly to original levels once the sparge system is turned off.

The efficacy of air sparging is determined principally by the degree of contact between the injected air and the contaminated soil and groundwater. It is generally agreed that the injected air forms channels through the saturated soil matrix [5–7]. When there is a high density of uniformly distributed air channels and/or significant mixing between channels, then air sparging is expected to be effective. Air sparging is less likely to be effective when the density of air channels is low or non-uniformly distributed and when there is little or no mixing of the water between the air channels.

In this paper, the results of 49 sparging case studies are compiled to shed light on how well and under what conditions air sparging achieves permanent reduction in groundwater contaminant concentrations. This work is based on an expansion of the sparging case study database reported earlier [8].

2. Review of case studies

Tables 1 and 2 summarize 44 air sparging sites designed to address source area contamination (eight chlorinated and 36 petroleum hydrocarbon sites, respectively) for which groundwater contaminant concentration data were available before sparging began, just before sparging was terminated, and after shutdown of the sparging system. Table 3 summarizes five sites where air sparging barriers were installed to treat downgradient contamination, again addressing both chlorinated solvents and petroleum hydrocarbon contamination. In all of these tables, sites are listed generally in order of best to poorest sparge system performance. The case studies in these tables cover a wide range of geography, soil conditions, and sparge system parameters. Systems were located in 18 states, the District of Columbia and Italy. Soils range from silt to coarse sand and gravel, with both native and backfilled material as the sparged matrix. Sparge well spacings range from 12 to 80 ft, and flow rate per sparge well from 3 to 35 scfm.

Some systems inject sparge air continuously, others intermittently (pulsed operation). In one case, ''in-well'' sparging is performed by inserting a sparge pipe to the bottom of existing monitoring wells. Well systems range from 1 to 63 wells and include both horizontal and vertical wells. Duration of sparging system operation ranges from a few months to more than 4 years.

In each case study, groundwater concentrations are compared before sparging was initiated, just before sparging was terminated, and in the months following shutdown of the sparging system. Post-shutdown monitoring data are available for only a few months in most cases, but at some sites, more than a year of post-shutdown data have been taken. The contaminant reduction, expressed as a percentage, is defined at the point when sparging was turned off:

$$\text{Reduction} = 100\%\left(1 - \frac{C_f}{C_o}\right) \tag{1}$$

where C_o is the dissolved concentration at start of sparging and C_f is the dissolved concentration at end of spargingand.

At the end of the post-shutdown monitoring period:

$$\text{Reduction} = 100\%\left(1 - \frac{C_r}{C_o}\right) \tag{2}$$

where C_r is the dissolved concentration after post-sparging monitoring.

Rebound is defined as

$$\text{Rebound} = \frac{\log(C_r/C_f)}{\log(C_o/C_f)} \tag{3}$$

As defined in Eq. (3), rebound is the log of the concentration increase after sparging ends, divided by the log of the concentration decrease during sparging. In other words, rebound is the orders of magnitude of concentration increase after the system is shut down divided by the orders of magnitude of concentration reduction while the system is operating. It is the authors' experience that when rebound is less than 0.2 (less than one order of magnitude of post-shutdown increase for each five orders of magnitude of initial decrease) the reduction in groundwater concentrations is perceived as permanent, while a value greater than 0.5 (more than one order of magnitude increase for each two orders of magnitude of initial decrease) generally is perceived as substantial rebound.

Overall, of the 44 source area air sparging systems summarized, the following average permanent reductions (i.e. after post-shutdown monitoring, as defined by Eq. (2)) in dissolved contaminant concentrations were observed:

- 21 systems (47%) achieved an average permanent reduction greater than 95%;
- 26 systems (59%) achieved an average permanent reduction greater than 90%;
- 31 systems (70%) achieved an average permanent reduction greater than 80%.

However, in many cases, the average reduction was high, but a single monitoring well either failed to show sufficient contaminant attenuation or else rebounded after the system was shut down, resulting in the need for further action. Another approach to assessment of sparge system performance, then, is the permanent reduction achieved in

Table 1
Air sparging case histories at sites with chlorinated solvent contamination

Site specifics	Duration (months)		Contaminant	Dissolved concentrations at most contaminated wells (μg/l)			Rebound[c]	Comments
	Sparge	Post-closure		At start	At shutdown (% reduction)[a]	Post-closure (% reduction)[b]		
Most successful systems								
(1) Dry cleaner (DE), 15 sparge wells, ≈ 40 ft spacing,	7.5	2	PCE, TCE, DCE	41,000	704 (98.3%)	1250 (97.2%)	0.14	Well within presumed zone of sparging influence.
10 scfm/well, continuous flow				6700	115 (98.3%)	249 (96.3%)	0.19	Well located 20 ft from nearest sparge well. Soil is permeable sand.
(2) Industrial (MA), two sparge wells, 25 ft spacing,	8	1	1,1,1-TCA, TCE, 1,1-DCE	7190	129 (98.2%)	339 (95.3%)	0.24	Both wells within the presumed zone of sparging influence.
4 scfm/well, pulsed (6 h cycle)				2133	87 (95.9%)	dry (–)	–	Ozone injected with sparge air during last 3 months of sparging. Soil is very tight silty sand.
(3) Industrial (IN), 11 sparge wells, ≈ 50 ft spacing,	18	4	1,1,1-TCA, TCE, DCE, DCA	542	17 (96.9%)	15 (97.2%)	−0.04	Well 30 ft downgradient of sparge system.
15 scfm/well, continuous flow				272	64 (76.5%)	29 (89.3%)	−0.50	Well 25 ft from nearest sparge well. Soil is sand and gravel.
(4) Industrial (WI), three sparge wells, ≈ 80 ft spacing,	15	4	TCE	670	10 (98.5%)	4 (99.4%)	−0.25	Both wells are 25 ft from the nearest sparge well. Sandy soil.
10 scfm/well, pulsed (4 h cycle)				17	1 (94.1%)	2 (88.2%)	0.18	Pulsing began 7 months after start of operation.
(5) Industrial (NY), two sparge wells, 28 ft spacing,	26	6	1,1,1-TCA, TCE	45,550	6 (99.99%)	3031 (93.35%)	0.697	All wells are 11 to 19 ft from the nearest sparge well. Fine/medium sandy soil.

7.5 scfm/well, continuous → pulsed				26,360	168 (99.36%)	147 (99.44%)	−0.03	Post-sparging soil samples all below detection limits.
(6) Industrial (AK), four sparge wells, 45–60 ft spacing,	14	9	1,1,1-TCA, PCE	71,960	<1 ($>99.99\%$)	52.5 (99.93%)	0.35	Shut down for winters due to extreme climate.
10 scfm/well, continuous flow; seasonal operation				6520	28.3 (99.57%)	85.5 (98.69%)	0.20	
Qualified successes								
(7) Industrial (CA), 16 sparge wells, ≈ 50 ft spacing,	3.5	7.5	1,1,1-TCA, 1,1-DCE	9860	<5 ($>99.95\%$)	1725 (82.5%)	–	Well 30 ft from nearest sparge well.
12 scfm/well, pulsed (daily cycle)				6700	33 (99.5%)	51 (99.2%)	0.08	Well 35 ft downgradient from sparge system. Water table rose 20 ft in the last 3 years, now falling. Soil is well graded fine sand.
(8) Industrial (MA), three sparge wells, 80–150 ft spacing,	7	1.5	1,1,1-TCA, 1,1-DCE, PCE	247	22 (91.1%)	15 (93.9%)	−0.16	Well located 35 ft from nearest sparge well. (Sparge wells were placed in non-contiguous hot spots.)
18 scfm/well, continuous flow				22.4	4.4 (80.0%)	14.8 (33.9%)	0.75	Well placed 5 ft from nearest sparge well, operated only 2 months. Sandy soil.

[a] $100(1-C_f/C_o)$ where C_o is concentration at start of sparging and C_f is concentration at termination of sparging.
[b] $100(1-C_r/C_o)$ where C_o is concentration at start of sparging and C_r is concentration at end of post-shutdown monitoring period.
[c] $[\log(C_r/C_f)]/[\log(C_o/C_f)]$ with C_o, C_f and C_r as defined in notes (a) and (b) above.

Table 2
Air sparging case histories at sites with petroleum contamination

Site specifics	Duration (months)		Contaminant	Dissolved concentrations at most contaminated wells (μg/l)			Rebound[c]	Comments
	Sparge	Post-closure		At start	At shutdown (% reduction)[a]	Post-closure (% reduction)[b]		
Most successful systems								
(9) Service Sta. (NY), seven sparge wells, 12 ft spacing,	15	1	BTEX	18,500	< 0.5 (> 99.997%)	< 0.5 (> 99.997%)	–	
13 scfm/well, continuous flow				650	< 0.5 (> 99.92%)	< 0.5 (> 99.92%)	–	
(10) Service Sta. (NH), three sparge wells, 20 ft spacing, 3 scfm/well, continuous flow	47	20	BTEX	24,000	10 (99.96%)	12 (99.95%)	0.02	Well is less than 10 ft from the nearest sparge well.
(11) Service Sta. (FL), six sparge wells, 40 to 60 ft spacing, 6 scfm/well, continuous flow	4	7	BTEX	13,068	< 0.5 (> 99.996%)	< 0.5 (> 99.996%)	–	Well located within 10 ft of nearest sparge well. 60 ft depth to water; product is not believed to have reached the water table, so plume is purely dissolved phase. Sandy soil.
(12) Service Sta. (FL), five sparge wells, 35 ft spacing,	4	6	BTEX	3413	< 2 (> 99.94%)	< 2 (> 99.94%)	–	Sandy soil.
8 scfm/well, pulsed (daily cycle)			MTBE	230	< 5 (> 97.8%)	< 5 (> 97.8%)	–	

(13) Service Sta. (MA), one sparge well,	11	12	BTEX	25,200	< 5 (> 99.98%)	< 5 (> 99.98%)	–	Both wells are within 20 ft of the sparge well.
35 scfm, continuous flow				3334	1770 (46.9%)	14 (99.5%)	−4.29	Soil is uniform sand.
(14) Fuel station (NM), nine sparge wells, 40 to 50 ft spacing,	19	13	BTEX	64	nd	nd	–	Well is 100 ft downgradient of sparge system. Soil is gravelly sand.
6 to 10 scfm/well, continuous flow			MTBE	1600	27 (98.3%)	8 (99.5%)	−0.3	
(15) Service Sta. (NY), horizontal wells, 10 ft spacing,	17	10	BTEX	14,000	480 (96.6%)	8 (99.94%)	−1.2	Sparge laterals placed in bottom of the excavated tank pit. Nutrients added to soil before
90 scfm total, continuous flow				24.0	1.0 (95.8%)	1.4 (94.2%)	0.08	returning to tank pit. Soil is fine sand.
(16) Service Sta. (CA), nine sparge wells, 10 to 20 ft spacing,	23	5	BTEX	2760	43 (98.4%)	158 (94.3%)	0.31	Both wells are within 10 ft of the nearest sparge well.
5 scfm/well, pulsed (12 h cycle)				1071	10 (99.1%)	4 (99.6%)	−0.19	Some of source area believed to be under a building and, hence, not addressed by the sparge system. This could explain rebound in one monitoring well. Soil is sandy.
(17) Service Sta. (MA), four sparge wells, 25 to 35 ft spacing,	13	8	BTEX	25,000	3400 (86.4%)	1100 (95.6%)	−0.57	Both wells are within 10 ft of the nearest sparge well.
5 scfm/well, continuous flow				2200	83 (96.2%)	300 (86.3%)	0.39	Soil is medium to fine sand and silt.

Table 2 (continued)

Site specifics	Duration (months)		Contaminant	Dissolved concentrations at most contaminated wells (μg/l)			Rebound[c]	Comments
	Sparge	Post-closure		At start	At shutdown (% reduction)[a]	Post-closure (% reduction)[b]		
Most successful systems								
(18) Service Sta. (ME),	14.5	6.5	Gasoline	92,000	3500 (96.2%)	3590 (96.1%)	0.007	All wells are within 10 ft of the
seven sparge wells,				49,000	910 (98.1%)	301 (99.4%)	−0.28	nearest sparge well.
25 to 35 ft spacing,				71,000	340 (99.5%)	103 (99.9%)	−0.22	Soil is fine sand and silt.
5 to 10 scfm/well,				210,000	28 (99.99%)	80 (99.96%)	0.12	
continuous flow								
			BTEX	22,600	550 (97.6%)	604 (97.3%)	0.025	
				97,300	172 (99.8%)	20 (99.98%)	−0.034	
				50,600	6 (99.99%)	2 (99.99%)	−0.12	
				198,000	< 20 (> 99.99%)	30 (99.98%)	–	
			MTBE	7200	860 (88%)	nd (> 99%)	–	
				62,000	16 (99.97%)	29 (99.95%)	0.072	
				8700	980 (89%)	115 (98.7%)	−0.98	
				18,000	48 (99.7%)	38 (99.8%)	−0.039	
(19) Service Station (CA), five sparge wells,	12	2	Benzene	8700	4 (99.95%)	7 (99.92%)	0.09	Significant downtime (> 50%) during remediation.
20 ft spacing, 6 scfm/well,			BTEX	16,500	7 (99.96%)	59 (99.64%)	0.29	Site is closed.
pulsed (30 min cycle)			TPH-G	34,000	68 (99.8%)	720 (97.88%)	0.38	
(20) AST Source (AK),	37	17	BTEX	1970	< 1 (> 99.95%)	7 (99.65%)	0.26	Pulsing began after 27 months much
28 sparge wells, 40–60 ft spacing,				1730	< 1 (> 99.94%)	7 (99.6%)	0.26	of original source area excavated.
5–10 scfm/well, continuous → pulsed			TPH	3600	< 100 (> 97.22%)	< 100 (> 97.22%)	–	
(6 h cycle)				2700	< 100 (> 96.3%)	< 100 (> 96.3%)	–	

(21) Service Station (CA), six sparge wells, 20 ft spacing, pulsed (16 h cycle)	6	6	BTEX	24	< 1 (99.98%)	< 1 (> 99.98%)	–	Sandy soil under silty sand; water table is in the silt; leading to pancaking.
				448	540 (−20.54%)	10 (97.77%)	−21	
			TPH	240	< 100 (> 99.33%)	< 100 (> 99.33%)	–	Sparge air seemed to make it through silt, leading
				2200	2800 (−27.27%)	< 100 (> 98.68%)	−3.3	to 13,000 lb excess TPH recovery.
(22) Service Station (KY), four sparge wells, 40 ft spacing pulsed	10	2	Benzene	12,000	190 (98.42%)	28 (99.77%)	−0.46	Five to ten feet of clay underlain by sands.
			BTEX	43,000	190 (99.56%)	28 (99.93%)	−0.35	
(23) Service Station (NY), five sparge wells, 15–35 ft spacing	20	3	BTEX	34,450	6464 (81.24%)	76 (99.78%)	−2.6	Sand and silt.
				14,990	3400 (77.32%)	570 (96.20%)	−1.2	
Qualified successes								
(24) Fueling Sta. (NH), seven sparge wells, 20 to 25 ft spacing,	20	9	BTEX	37,110	4355 (88.3%)	149 (99.6%)	−1.6	Both wells are within 15 ft of the nearest sparge well.
5 scfm/well, pulsed (12 h cycle)				36,410	13.910 (61.8%)	3176 (91.3%)	−1.5	Soil is fine to medium sand.
(25) Service Sta. (NY), 14 sparge wells, 20 to 25 ft spacing,	13	1	BTEX	3270	< 5 (99.8%)	< 5 (99.8%)	–	Well is 17 ft from the nearest sparge well (two similarly contaminated wells within the sparging zone of influence also
8 scfm/well, continuous flow				964	16 (98.3%)	212 (78.0%)	0.63	reached and stayed at < 5 μg/l BTEX). Well is less than 10 ft from the nearest sparge well. Soil is fine to medium sand.

Table 2 (continued)

Site specifics	Duration (months)		Contaminant	Dissolved concentrations at most contaminated wells (μg/l)			Rebound[c]	Comments
	Sparge	Post-closure		At start	At shutdown (% reduction)[a]	Post-closure (% reduction)[b]		
Qualified successes								
(26) UST Site (FL), one sparge well, 10 scfm, pulsed (1–2 h cycle)	2	9	TPH	5322	110 (97.9%)	827 (84.5%)	0.52	Well is within 10 ft of the sparge well. Release is a mixture of gasoline and diesel, believed to be of limited areal extent (perhaps 20 ft^2). Soil is sandy.
(27) UST Site (CA), six sparge wells, 35 to 45 ft spacing,	16	7	TPH	10,000	1000 (90.0%)	690 (93.1%)	−0.16	Well is 15 ft from the nearest sparge well. Soil is sandy, with evidence of low permeability lenses.
5 scfm/well, pulsed (12 h cycle)			Benzene	280	30 (89.3%)	79 (71.8%)	0.43	
(28) Service Sta. (MA), 13 sparge wells, 15 to 20 ft spacing,	7	1	BTEX	3900	140 (96.4%)	2070 (46.9%)	0.80	Both wells are at the edge of the sparge system, within 10 ft of the nearest sparge well. Soil is fine sand and silt.
5 scfm/well, pulsed (12 h cycle)				1300	220 (83.1%)	35 (97.3%)	−1.0	
(29) Service Sta. (MA), two sparge wells, 36 ft spacing,	5.5	6.5	BTEX	51,000	230 (99.95%)	2600 (94.9%)	0.45	Well is 22 ft from the nearest sparge well.
20 scfm/well, pulsed (6 h cycle)				82,000	4700 (72%)	2400 (86%)	−0.52	Well is 35 ft from the nearest sparge well.
(30) Service Sta. (DE), eight sparge wells, 23–26 ft spacing,	25	5	BTEX	24,920	1320 (94.70%)	1882 (92.45%)	0.12	Most wells showed good results; a well 19 ft from the system showed poor results.
6–13 scfm/well, continuous flow				16,910	801 (95.26%)	494 (97.08%)	−0.16	

(31) Fueling Sta. (NY),	15	1	BTEX	725	125 (82.76%)	186 (74.34%)	0.23	Not enough post-shutdown data to properly assess.
10 sparge wells,								
30 ft spacing,								
2.5 scfm/well,				141	12.8 (90.92%)	10.9 (92.27%)	−0.07	
continuous flow								
(32) Service Sta. (WV),	12	2.5	BTEX	1307	< 1 (> 99.92%)	50 (96.17%)	0.55	Additional spill occurred during cleanup.
five sparge wells,				710	6.9 (99.03%)	5.9 (99.17%)	−0.03	
40–55 ft spacing,								
10 scfm/well,			TPH	18,800	1390 (92.61%)	940 (95.0%)	−0.15	Another well saw only 45–70% reduction.
pulsed (8 h cycle)				4290	< 100 (> 97.67%)	180 (95.8%)	0.16	
(33) Service Sta. (DC),	18	13	BTEX	14,100	117 (99.17%)	66 (99.53%)	−0.12	Started with LNAPL in some wells.
six sparge wells,								
20 ft spacing,								
10 scfm/well,				13,300	4720 (64.51%)	5450 (59.02%)	0.14	
continuous → pulsed								
(2–4 week cycle)								
(34) Bulk Terminal	8	1	TPH	24,530		862 (96.5%)		Remediation effectiveness measured
(Italy), 63 sparge wells,				9700		442 (95.4%)		using pre- and post-sparging composited
75 ft spacing,				1260		118 (90.6%)		soil samples.
15 scfm/well,				(ppb in soil)		(ppb in soil)		Marine bacteria added in area with
continuous flow								separate phase.
Least successful systems								
(35) Service Sta. (CT),	21	10	BTEX	Separate phase	7310	9470	–	Both wells are at the edge of the sparge system, within 15 ft of the nearest sparge well.
five sparge wells,								
50 ft spacing,								
5 scfm/well,				Separate phase	2365	1508	–	System was turned off due to mechanical problems and has been restarted. Soil is fine sand.
continuous flow								

Table 2 (continued)

Site specifics	Duration (months)		Contaminant	Dissolved concentrations at most contaminated wells (μg/l)			Rebound[c]	Comments
	Sparge	Post-closure		At start	At shutdown (% reduction)[a]	Post-closure (% reduction)[b]		
Least successful systems								
(36) Service Sta. (WA), three sparge wells, 30 ft spacing,	20	2	BTEX	12,400	6 (99.95%)	1054 (91.5%)	0.68	Sparge wells placed in tank pit gravel, which is surrounded by tight silt/clay soil.
4 scfm/well, pulsed (28 day cycle)				5561	4 (99.93%)	1566 (71.8%)	0.83	No sparge wells placed outside the tank pit. Monitoring wells are within the tank pit.
(37) Service Sta. (NJ), three sparge wells, 20 ft spacing,	19	25	BTEX	31,000	2610 (91.6%)	9340 (69.9%)	0.52	Excavated soil returned to tank pit, one sparge well placed within the tank pit (the other sparge wells were to address dissolved migration and a separate source).
5 scfm/well, pulsed (14 day cycle)				27,000	592 (97.8%)	7960 (70.5%)	0.68	Soil surrounding tank pit is a tight silty sand.
(38) Service Sta. (NY), four sparge wells, 35 to 55 ft spacing,	12	19	BTEX	53,200	7 (99.99%)	23,150 (56.5%)	0.91	Well is 30 ft from nearest sparge well.
13 scfm/well, pulsed (daily cycle)				7830	42 (99.5%)	778 (90.0%)	0.56	Well is collocated with one of the sparge wells. System did not address entire source area. Soil is medium sand.
(39) Service Sta. (CT), two sparge wells, 40 ft spacing,	17	14	BTEX	119,000	4750 (96.0%)	8110 (93.2%)	0.17	Both wells are within 20 ft of the nearest sparge well.
3.5 scfm/well, pulsed (daily cycle)				76,000	2252 (97.0%)	26,120 (65.6%)	0.70	Pilot system only, so not all of the source area was addressed (full scale system never implemented). Soil is medium to fine sand.

(40) Service Sta. (MA), two sparge wells, 36 ft spacing,	5.5	6.5	BTEX	21,000	4100 (80.5%)	4700 (77.6%)	0.08	Well is 26 ft from the nearest sparge well.
20 scfm/well, pulsed (6 h cycle)				7400	230 (96.9%)	2600 (64.9%)	0.70	Well is less than 20 ft from the nearest sparge well. Release is a mixture of gasoline and diesel.
(41) Fueling Sta. (MD), five sparge wells, 55 to 85 ft spacing,	24	5	BTEX	29,900	6730 (77.5%)	13,560 (54.6%)	0.47	Well is at the edge of the sparge system, 20 ft from the nearest sparge well.
5 to 15 scfm/well, pulsed (14 day cycle)				13,560	<4 (>99.98%)	2320 (89.8%)	–	Well is at the edge of the sparge system, 20 ft from the nearest sparge well. Soil is fine to medium sand.
(42) Residence (ME), three sparge wells, 30 ft spacing,	31	3	Fuel oil	490	44 (91%)	113 (77%)	0.39	Well is 7 ft from the closest sparge well.
4 scfm/well, continuous flow				490	547 (-12%)	376 (23%)	–	Well is 50 ft from the closest sparge well. Soil is fine to coarse sand.
(43) Service Sta. (NH), three sparge wells,	17	–	BTEX	5905	2749 (53.4%)	–	–	''In-well'' sparging to enhance bioremediation, as a polish for groundwater pumping with SVE.
8 to 15 ft spacing, continuous flow				2800	124 (95.6%)	–	–	Monitoring wells are about 20 ft cross-gradient from the sparge wells. Soil is fine to medium sand.
(44) Service Sta. (NC),	15	16	BTEX	29,000	8000 (72.41%)	21,080 (27.31%)	0.75	Fresh gasoline; beach sand two periods of down time.
one sparge well, 12–15 scfm, continuous flow				1700	4400 (-159%)	19,900 (-1071%)		

[a] $100(1-C_f/C_o)$ where C_o is concentration at start of sparging and C_f is concentration at termination of sparging.
[b] $100(1-C_r/C_o)$ where C_o is concentration at start of sparging and C_r is concentration at end of post-shutdown monitoring period.
[c] $[\log(C_r/C_f)]/[\log(C_o/C_f)]$ with C_o, C_f and C_r as defined in notes (a) and (b) above.

Table 3
Air sparging barrier case histories

Site specifics	Duration (months)		Contaminant	Dissolved concentrations at most contaminated wells (μg/l)			Rebound[c]	Comments
	Sparge	Post-closure		At start	At shutdown (% reduction)[a]	Post-closure (% reduction)[b]		
(45) Industrial (NY), six sparge wells, 40 ft spacing, 7 scfm/well, continuous → pulsed	33	15	TCA, TCE	10,800	5.2 (99.95%)	3 (99.97%)	−0.07	Barrier system started with four sparge wells; two wells added and pulsing started after 18 months.
				6610	14.7 (99.78%)	73 (98.90%)	0.262	
				1020	2.2 (99.78%)	15 (98.53%)	0.313	
(46) Industrial (WI), five sparge wells, ≈ 80 ft spacing,	10	4	TCE, PCE	280	1 (99.6%)	16 (94.3%)	0.49	Both wells are within 40 ft of the nearest sparge well. Began pulsing after 3 months of operation. Sandy soil.
10 scfm/well, pulsed (4 h cycle)				150	16 (89.3%)	6 (96.0%)	−0.44	
(47) Service Sta. (MA), six sparge wells, 30 to 40 ft spacing,	21	–	Benzene	1230	7 (99.4%)	–	–	Well is 70 ft downgradient of the sparge barrier. System operation continues. Soil is fine to medium sand.
5 scfm/well, continuous flow			MTBE	215	115 (46.5%)	–	–	
(48) Service Sta. (MA), five parge wells, 13 ft spacing, 2.5 scfm/well, continuous flow	18	9	BTEX	478	< 5 (> 99.0%)	< 5 (> 99.0%)	–	Well is 18 ft upgradient from the sparge barrier. Source area was excavated. Soil is fine to medium sand and silt.
(49) Service Sta. (NH), five sparge wells, 20 ft spacing, 3 scfm/well, pulsed (24 h cycle)	36	20	BTEX	13,123	3260 (75.2%)	14,666	1.1	Well is 30 ft downgradient from barrier system. The source is an upgradient gasoline release which remains unaddressed.

[a] $100(1 - C_f/C_o)$ where C_o is concentration at start of sparging and C_f is concentration at termination of sparging.
[b] $100(1 - C_r/C_o)$ where C_o is concentration at start of sparging and C_r is concentration at end of post-shutdown monitoring period.
[c] $[\log(C_r/C_f)]/[\log(C_o/C_f)]$ with C_o, C_f and C_r as defined in notes (a) and (b) above.

the least responsive monitoring well. Using this criterion, the following summarizes the minimum permanent reductions in dissolved contaminant concentrations:

- 16 systems (36%) achieved a minimum permanent reduction greater than 95%;
- 21 systems (47%) achieved a minimum permanent reduction greater than 90%;
- 27 systems (61%) achieved a minimum permanent reduction greater than 80%.

In general, systems which produced permanent reductions averaging greater than 90% with all monitoring wells showing a permanent reduction of at least 80% were considered to be successful. The least successful systems produced average permanent reductions less than 80% and/or had more than one well displaying significant rebound (the ''in-well'' sparging system was among the least successful). The grey area in between (''qualified successes'') includes sites where permanent reductions between 80% and 90% were sufficient to effect site closure, or where the substantial reductions achieved (in excess of 90%) were still insufficient to meet stringent remediation goals.

3. Analysis

The 49 sites which comprise this data base are a limited number considering the range of site, soil, contaminant and sparge system conditions represented. Furthermore, the data available for analysis are only those necessary to meet regulatory requirements. These are not controlled experiments, and so extrapolation of the results must be done with caution. Nevertheless, examination of the characteristics and behavior of the sparging study sites in Tables 1 and 2 reveals some trends and observations which can be useful in designing and predicting the performance of air sparging systems.

3.1. Poor performance was generally characterized by initially reduced concentrations followed by substantial rebound

Sparging usually resulted in an initial reduction in dissolved concentrations, however, the maximum rebound at the most successful sites (sites 1–6, 9–23) averaged a negligible 0.08, compared with 0.68 (more than two orders of magnitude of rebound for every three orders of magnitude of initial remediation) at the least successful sites (sites 35–44). Furthermore, all but one of the less successful petroleum sites had a rebound number greater than 0.68 in at least one well, while only one of the most successful sites had a well with maximum rebound greater than 0.4. Rebound was variable at the qualified successes (sites 7–8, 24–34).

3.2. Sparging at chlorinated solvent sites is generally more successful than at petroleum sites

All of the chlorinated sites in Table 1 meet the criteria for success (sites 1–6) or qualified success (sites 7–8), as outlined above, but about one-quarter of the petroleum sites (sites 35–44) were unsuccessful. On the other hand, when sparging was successful at petroleum sites, the permanent reductions in groundwater concentrations were much greater than at chlorinated sites. For example, successful petroleum sites 9–14 had average permanent reductions ranging from 99.1% to 99.96%. The maximum average permanent reduction observed at a chlorinated site (site 6) was 99.3%, and next highest (site 1) was 96.6%. The greater permanent reductions at successful petroleum sites may be reflective of the multiple remediation pathways (bioremediation and volatilization) available for hydrocarbons.

3.3. More successful systems at petroleum sites had a higher sparge well density covering the entire source area

The successful systems (sites 9–34) consisted of an average of 7.2 wells spaced an average of 28.6 ft apart (corresponding to an assumed radius of sparging influence of about 16 ft). In contrast, the less successful systems (sites 35–44) consisted of only 3.4 wells on average spaced 40.1 ft apart (an assumed radius of influence averaging 23 ft). In addition, several of the less successful systems (for example, sites 36–39) did not address the entire source area, either because of physical constraints or because the focus was exclusively on the tank pit.

3.4. Performance was generally better in systems treating dissolved phase plumes than in systems treating adsorbed contaminants

When released product at petroleum sites did not contact the groundwater (i.e., there was no smear zone of adsorbed product), then remediation by sparging was more effective and permanent, even with less aggressive sparge systems. For example, at sites 11 and 14, where the released product did not extend downward through the entirety of the 60-ft deep vadose zone, remediation of the underlying groundwater was rapid despite well spacing in excess of 40 ft at both sites, and a sparging duration of only 4 months at site 11. Similarly, the barrier systems in Table 3 which treated low level dissolved plumes (sites 46–48) were all successful at removing BTEX and chlorinated VOCs, despite large well spacings in some cases (80 ft at site 46, 30 to 40 ft at site 47). In contrast, among systems addressing smear zones at petroleum sites, those with higher initial dissolved contaminant concentrations (often reflective of a greater prevalence of adsorbed product) did more poorly than those with lower concentrations. The average initial BTEX concentration at the most contaminated well at the successful sites (sites 9–34, excluding sites 18 and 29, which had very high initial concentrations) was 14,600 $\mu g/l$, about a third of the average initial concentration (37,700 $\mu g/l$) at the least successful sites (sites 35–44). Likewise, the barrier system in Table 3 which treated a smear zone emanating from an upgradient source (site 49) produced only modest reductions in BTEX concentrations, which rebounded fully following termination of the system.

These observations are consistent with the generally good performance observed at chlorinated solvent sites. The contamination at the chlorinated sites probably partitioned into groundwater more than at the petroleum sites. The soils at all of the sites in Table 1 were sandy with low organic carbon, and the chlorinated solvents released do not contain a low solubility, high molecular weight fraction (as do most petroleum products). Furthermore, the extent of the releases was more modest at the chlorinated sites (had the releases been much more substantial, evidence of mobile DNAPL would have been observed and sparging would not have been considered). Therefore, the chlorinated solvent sites in Table 1 are essentially dissolved plumes. As discussed above, good contaminant reductions with limited rebound was typically observed after remediation of these sites, despite well spacings as great as 80 ft in some cases.

It is possible that residual LNAPL in the smear zone is serving as a reservoir for BTEX, resulting in the observed rebound. Boersma has described two case histories in which chlorinated solvents were the target contaminants [9]. The first site was a single well 30-day pilot test at a sandy site with dissolved chlorinated concentrations of 2 to 3 ppm. Dissolved concentrations decreased by one-half to one order of magnitude, with little rebound 6 months after system shutdown. The conditions and results are consistent with those at the chlorinated sites in Table 1. At the second site, the source of the chlorinated solvents was a petroleum LNAPL in which the solvents were initially dissolved. Sparging had a smaller and less permanent impact on dissolved concentrations at this site.

3.5. When rebound occurred, it sometimes happened many months after sparge system shutdown

For example, sites 7, 37 and 38 all showed only moderate rebound 2 to 4 months following shutdown, but in some source area wells concentrations jumped by another order of magnitude or more within 7.5 to 16 months after shutdown.

3.6. Changes in water table levels appeared to be associated with increased rebound

Rising water tables can bring groundwater in contact with fresh sources of contamination. This appeared to be the case at site 7, where the water table rose by 20 ft over the course of the remediation and post-remediation monitoring. No rebound was observed in any monitoring well following termination of sparging, but 7.5 months after sparging was concluded the concentrations increased suddenly by three orders of magnitude in one well. Sites 25 and 40 also experienced substantial rebound in some wells following a post-shutdown water table rise.

3.7. Sparging duration could not be correlated with performance

The successful sparge systems operated for an average of 16 months, which was not significantly different than the average times for qualified successes (12 months) or unsuccessful systems (16 months). The remediation times in successful systems ranged from a few months to 4 years. While extent of remediation is certainly a function of remediation time, it would appear that other factors are masking the effects of remediation time in this limited database.

4. Conclusions

Based on available case study and experimental information, the following approach to air sparging can be recommended.

• Of the 44 air sparging source area remediation systems, 21 (48%) produced permanent reductions greater than 90% averaged over all monitoring wells, with no monitoring well showing a permanent reduction of less than 80%. An additional 13 sites (29%) had averaged permanent reductions somewhat less than 90%, but this was still sufficient to effect site closure. The performance at the remaining 10 sites (23%) was unsatisfactory.

• Sparging appears to clean up chlorinated solvent and downgradient BTEX plumes more easily than petroleum hydrocarbon source areas. Sparge well depth and well spacing can be greater when treating a chlorinated or downgradient dissolved BTEX plume than when treating a petroleum hydrocarbon source area.

• The source area at petroleum sites where a smear zone is present should be addressed using a high density of sparge wells, closely spaced (<20 ft and preferably <15 ft), placed in such a way as to address the entire source area.

• The higher the initial dissolved concentrations at petroleum sites, the more aggressive the sparge system will have to be to achieve acceptable results.

• Pulsing improves sparge system performance by increasing mixing and radius of influence, but continuous flow sparging can also yield good results.

• ‘‘In-well’’ sparging, in which a sparge pipe is inserted to the bottom of existing monitoring wells, was not effective.

• A sparge pilot test must be performed before each sparge system is installed. The most important information the sparge pilot test provides is an indication of whether sparged air can be captured in the vadose zone. Secondarily, the sparge test provides an indication of radius of influence and pressure/flow requirements for blower sizing.

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