COST AND PERFORMANCE REPORT

Phytoremediation at the
Magic Marker and Fort Dix Sites, New Jersey

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Background Information

Two demonstrations of phytoremediation were performed to evaluate the use of phytoremediation to treat soil contaminated with lead. The first was performed at the former Magic Marker site in Trenton, New Jersey and the second was performed at Fort Dix in New Jersey. The phytoextraction process that was demonstrated is owned by Edenspace (formerly Phytotech Inc.).

Magic Marker SITE Demonstration (1,2)

The seven-acre Magic Marker site located in Trenton, New Jersey is an urban area "Brownfield". The site was used for lead-acid battery manufacturing from 1947 to 1979, and then by the Magic Marker facility up until its closure in 1987. Previous investigations identified lead in surface soils at the site above the New Jersey Department of Environmental Protection (NJDEP) residential regulatory limit of 400 milligrams per kilogram (mg/kg).

A demonstration under the EPA Superfund Innovative Technology Evaluation (SITE) program was performed to determine if the phytoextraction technology could be effective in reducing lead contamination from surface soils. The demonstration was conducted between May 1997 and November 1998.

Fort Dix Demonstration(2,3)

The soil from the Small Arms Firing Range (SAFR) 24 at Fort Dix, New Jersey was determined to be contaminated with lead, including spent bullets and bullet fragments. A joint demonstration with the U.S. Department of Defense RangeSafe Technology Demonstration Initiative (RTDI) and the SITE Program was performed to evaluate use of physical treatment (soil washing) followed by phytoremediation to treat lead in soil at the site. The SITE program participated in the demonstration by measuring, collecting, and analyzing recirculated leachate water derived from excess precipitation and irrigation. The phytoremediation demonstration was performed between April and October 2000 to determine if this technology could further reduce lead concentrations in soil following soil washing.

Technology Description and System Design

The technology and system designs for the Magic Marker and Fort Dix phytoremediation demonstrations are discussed below.

Magic Marker SITE Demonstration Design

Locations within the Magic Marker site were selected for the Treatment Plot and the no treatment Control Plot used for the demonstration. The Treatment Plot was established by tilling and preparing an area measuring 77 feet by 50 feet. The Control Plot was a 40 foot by 30 foot area of soil. The Treatment and Control Plots were separated by approximately 80 feet to minimize the potential for cross contamination as a result of tilling, planting, irrigating, adding of nutrients and amendments, and harvesting.

A total of three crops were planted and harvested over two growing seasons. The first two crops, grown and harvested during the spring and summer of 1997, consisted of Indian Mustard (*Brassica juncea*) plants. A third crop of sunflowers (*Helianthus annus*) was grown and harvested in the summer of 1998. Between the end of the 1997 harvest and beginning of the 1998 growing season, both the Treatment Plot and Control Plot were covered with heavy gauge plastic to prevent infiltration of rain and snow melt into the soil during the winter months.

Between 26 to 28 plant tissue samples were collected and analyzed for each of the three harvested crops to determine whether the plants were able to bioaccumulate a significant quantity of lead into above-ground tissue. Pre-treatment ("baseline") soil samples and post-treatment ("final") soil samples were collected from the Treatment Plot from a total of 140 locations in the top six inches of soil. These surface soil samples were used to estimate the amount of lead removed from the soil and to identify any spatial variations in the treatment. Additional soil samples were collected at the 6-12 inch and 12-18 inch intervals.

Fort Dix Demonstration Design

The phytoremediation demonstration was conducted in a 1.25-acre *ex situ* lined treatment cell, equipped with a drainage system. Excess water from irrigation and precipitation was collected in a lined catchment basin and recirculated through the irrigation system, as needed. The demonstration included three cropping cycles planted during the 2000 growing season: (1) Indian Mustard (*Brassica juncea*) on April 26, 2000, (2) Sunflower (*Helianthus annus*) on June 8, 2000, and (3) a mixture of rye (*Secale cereale*) and barley (*Hordeum vulgare*) on August 29, 2000. Initial and final surface and subsurface soil samples were collected on a stratified grid pattern at forty four (44) surface (0 to 6 inches below existing soil surface) and twelve (12) subsurface (6- to 12-inch depth interval) locations to determine the lateral and vertical extent of soil lead concentration. Leachate samples were collected to assess the quantity and fate of the lead in the leachate from phytoextraction.

Technology Performance

Magic Marker SITE Demonstration:

The specific objectives of the SITE demonstration were to: (1) demonstrate, with a 90% level of confidence, that the average concentration of lead accumulated in the above-ground plant tissue from each crop harvested from the Treatment Plot would be > 200 mg/kg on a dry weight basis, and (2) demonstrate a minimum 15% reduction in dry weight soil lead concentration, at sample locations within a treatment plot where the baseline concentrations exceeded the state residential regulatory standard of 400 mg/kg.

Table 1 presents a summary of crop growth and plant tissue data, including lead concentrations by plant tissue type, uptake and biomass data, and climatic and chronological information on the plantings. As shown in this table, phytoextraction achieved the demonstration objective of an average concentration of lead accumulated in the above-ground plant tissue from each crop of >200 mg/kg. The average accumulation of lead in above-ground plant tissue for crops 1, 2, and 3 was 830 mg/kg, 2,300 mg/kg, and 400 mg/kg, respectively.

Table 1. Crop Growth and Plant Tissue Data Summary - Magic Marker Site

Tissue Sampling Date	CROP 1 *Brassica juncea* 07/27/97	CROP 2 *Brassica juncea* 09/18/97	CROP 3 *Helianthus annus* 08/26/98
Crop Growth Data			
Growing Period	June 7 - July 27	July 28 - Sept. 18	June 20 - August 26
Growing Period Length	50 days	52 days	67 days
Climate Temperature [1]	71/ F	70/F	74/ F
Regional Precipitation [2]	3.1 inches	4.9 inches	2.6 inches
Amendment Dosage [3]	"Initial"	"Optimized"	"Optimized"
Plant Tissue Data			
Above-Ground Tissue Lead Concentration [4]	830 mg/kg	2,300 mg/kg	400 mg/kg
Root Tissue Lead Concentration [4]	- - -	89 mg/kg	290 mg/kg
Above-Ground Tissue Mass (wet) [5]	86.5 kg	164 kg	141 kg
Above-Ground Tissue Mass (dry) [5]	10.5 kg	12.2 kg	34.4 kg
Total Lead Extracted from Soil (Above-Ground Tissue Conc. X Above-Ground Tissue Mass)[6]	8.7 grams	28.0 grams	14.0 grams

[1] Estimated average temperature based on NOAA historical data for the state of New Jersey - Region 2. The following approximate average temperatures were used: June '97 - 67EF, July '97 - 75EF, August '97 - 71EF, September '97 - 66EF, June '98 - 69EF, July '98 - 75EF, and August '98 - 74EF.

[2] Estimated average precipitation based on NOAA historical data for the State of New Jersey - Region 2. The following approximate average precipitation values were used: June '98 - 4.2", July '98 - 2.2", and August '98 - 2.5".

[3] Per the developer, the amendment mixture and dosage was changed after Crop 1. For Crops 2 and 3, an additional component was added to the amendment mixture and the concentration of one component was increased (Note: the amendments and ratios used are proprietary).

[4] The test methods used were SW-846 3050/6010. All values have been corrected for moisture content to determine concentration on a dry weight basis; and have been rounded to two significant digits.

[5] Values are rounded to three significant digits. A total of 5 samples were collected for Crops 1 and 2, and 10 samples were collected for Crop 3. Each sample represented one yd^2 of harvested plants. Wet mass values are the average sample weight times the treatment plot area (190 yd^2). Dry mass values were then determined using moisture content data.

[6] Values are rounded to two significant digits.

--- = No sample collected

Lead mass removal was estimated by multiplying the average total dry mass of each crop harvested by the average lead uptake (on a dry weight basis) for that crop. While plant uptake met the objectives of the demonstration, the overall mass of lead removed from the soil was relatively low due to low plant biomass from all three crops. The estimated mass of lead removed for the three crops totaled approximately 51 grams, over half of which was removed by the second crop of B. *juncea* plants. In addition, the phytoextraction process concentrated lead in the above-ground plant tissue relative to the below-ground plant tissue.

Table 2 presents a summary of baseline and final concentrations in the Treatment and Control Plots, along with the results of statistical analyses of the data. An analysis of the baseline and final soil lead concentration data from the Treatment Plot showed that, at locations where baseline soil lead concentrations were greater than 400 mg/kg, the average lead concentration reduction in the top six inches of soil was 17 percent, at 0.1 level of significance (LOS). This met the demonstration objective of a minimum 15% reduction in dry weight soil lead concentration, at sample locations within a treatment plot where the baseline concentrations exceeded the state residential regulatory standard of 400 mg/kg. In the Treatment Plot, apparent reductions in the soil lead concentrations at the 6-12 inch and 12-18 inch depths, respectively showed no significant changes (i.e., decrease or increase) at a 0.1 LOS. In comparison to the Treatment Plot, over the same course of time, in the Control Plot at all locations, the average lead concentration in the top six inches of soil demonstrated no statistically significant change in concentration at a 0.1 LOS.

Table 2. Summary Statistics for Lead in Treatment and Control Plot Soils - Magic Marker Site

Parameter	TREATMENT 0-6" Sample Interval[1]		CONTROL 0-6" Sample Interval	
	Baseline	Final	Baseline	Final
Number of Sample Locations	102	102	21	21
Average Concentration (mg/kg)	1,812	791	1,009	724
Minimum Concentration (mg/kg)	408	76	123	173
Maximum Concentration (mg/kg)	57,114	8,453	3,126	2,164
Standard Deviation	5,649	1,074	718	489
Coefficient of Variance	3.1	1.4	0.7	0.7

Table 2. Summary Statistics for Lead in Treatment and Control Plot Soils - Magic Marker Site (continued)

Parameter	TREATMENT 0-6" Sample Interval[1]		CONTROL 0-6" Sample Interval	
90% Lower Confidence Level	892	616	751	548
90% Upper Confidence Level	2,733	966	1,266	899
Validated Minimum Reduction in Lead at locations where baseline concentrations > 400 mg/kg (treatment plot) and for all locations (control plot)	---	17%	---	0%

1 The calculations apply to sample locations having baseline lead concentrations > 400 mg/kg.

Fort Dix Demonstration

The specific goals of the demonstration were to achieve either: (1) the NJDEP industrial total lead concentration goal of 600 mg/kg or the residential goal of 400 mg/kg, or (2) a TCLP lead concentration of 5 milligrams per liter (mg/L). An additional objective of the demonstration was to investigate the potential for solubilized lead to migrate or leach below the plant root zone. Table 3 summarizes the lead concentrations from initial and final soil sampling.

Table 3. Average Initial and Final Lead Concentrations of the Surface, Subsurface, and Total Soil Samples from the Fort Dix Study

Parameter	Mean Lead Concentration ± 80% CI (mg/kg)		
	Surface (0-6")	Subsurface (6-12")	Total (0-12")
Initial	525 ± 15	506 ± 55	516 ± 35
Final	182 ± 20	398 ± 114	290 ± 67
Delta of Mean	343	108	226

Analysis of the 44 baseline (pre-treatment) soil samples for lead concentration varied widely (219 to 13,514 mg/kg). According to the vendor, the variability was unexpected because the soil was previously washed and homogenized before being placed into the lined cell. As a result, Edenspace performed an outlier analysis to derive a statistically valid representation of the true starting concentration. Upon exclusion of the identified outliers, the initial average lead concentrations of the surface soil (0-6"), subsurface soil (6-12"), and combined surface and subsurface soil (0-12"), were 525±15 mg/kg, 506±55 mg/kg, and 516±35 mg/kg (as determined by the average surface and subsurface concentrations), respectively.

Final soil lead concentrations (post-treatment) from the 44 surface samples varied widely, from 81 to 9,590 mg/kg. Upon exclusion of four identified outliers, lead concentrations averaged 182±20 mg/kg. Compared to the initial result, this final average lead concentration of the surface samples is 343 mg/kg lower and meets the 400 mg/kg target concentration for this demonstration (i.e., the mean + 80% CI is less than 400 mg/kg). Final lead concentrations from the 12 subsurface soil samples also varied widely, from 93 to 1,130 mg/kg. As no outliers were identified in this dataset, the soil lead concentrations of the subsurface samples averaged 398±114 mg/kg, and possessed a median lead concentration of 306 mg/kg.

Compared to the initial result, this final average lead concentration is 108 mg/kg lower but the mean + 80% CI value remains above the 400 mg/kg target concentration for this demonstration. The overall final average lead concentration of the demonstration cell (including surface and subsurface lead concentrations) is 290±67 mg/kg. Compared to the initial result, this final average lead concentration is 226 mg/kg lower, meeting the 400 mg/kg target concentration for this demonstration.

The average lead concentrations within the harvested biomass of the first crop (*B. juncea*), the second crop (*H. annus*) and the third crop (*S. cereale* and *H. vulgare)* were 1,437 ± 573 mg/kg, 1,675 ± 527 mg/kg, and 4,395 mg/kg, respectively. An estimate of the biomass recovered during the growing season (all three crops) is 9 tons (dry weight basis). Based on the volume of soil treated and the average uptake in the plant biomass, up to 20 mg/kg of the soil lead reduction can be attributed to phytoextraction.

The results of leachate sampling was used to determine the amount of leached lead (i.e., the amount of lead that had not been phytoextracted). At the completion of the demonstration, five 21,000-gallon storage tanks were filled with drainage water with a sixth tank containing about 5,000 gallons of water. The average lead concentration from these five tanks is 160 mg/L, which equates to a total of approximately 66.7 kg of lead removed from the entire 1,606 m^3 volume of soil within the demonstration cell. With a total soil mass of approximately 2,250,000 kg (assuming a bulk density of 1.47 g/cm^3), the amount of lead in the remaining drainage water corresponded to a maximum 30 mg/kg decrease in the overall soil lead concentration.

Technology Cost

No specific costs were provided for these demonstrations. Edenspace provided the following costs for phytoremediation of a 1-acre (43,560 ft^2) area containing 43,560-ft^3 (1,613 cubic yards) of contaminated soil, based on their experience in applying the technology at both *in situ* (unlined) and *ex situ* (lined) sites.

Site Mobilization

Site grading	$6,000
Liner system	$44,000
Drainage pipes	5,000
Water collection basin	$4,000
Initial Soil Sampling	$3,000
Install/Test Irrigation System	$10,000
Single Crop	$30,000
Final Sampling	$3,500
Final Report	10,000
Biomass Disposal as hazardous waste (single crop)	$5,000
Truck Water for Irrigation (single crop)	$12,000
Provide Electricity (single crop)	$3,000
Water Management (season)	$10,000

Edenspace provided unit cost information for three examples configuring the tasks associated with phytoremediation as shown in the table below. The costs are average estimated costs for each example and show that the cost varies based on system design and operation. Example C has the highest comparative cost per cubic yard (CY) of soil due primarily to the use of a liner and a high biomass disposal cost. Examples A and B have lower costs as a liner is not used.

Examples	Tasks	Unit Cost ($)	Average Cost ($/CY)
A	Single crop	30,000	23.87
	Final sampling	3,500	
	Low biomass disposal cost	5,000	
B	Three crops	90,000	70.37
	Irrigation system installed	10,000	
	Final sampling	3,500	
	Low biomass disposal cost	10,000	

Examples	Tasks	Unit Cost ($)	Average Cost ($/CY)
C	Three crops	90,000	127.40
	Liner system (ex situ)	59,000	
	Irrigation system installed	10,000	
	Water management	10,000	
	Initial and final sampling	6,500	
	Report preparation	10,000	
	High biomass disposal cost	20,000	

Summary of Observations and Lessons Learned

Both phytoextraction demonstrations met their lead reduction objectives. The Magic Marker SITE demonstration showed a 17% reduction in the soil lead concentration from baseline to final, meeting the objective of 15%. At Fort Dix, the final average concentration of lead in the soil was 290 mg/kg, lower than the 400 mg/kg New Jersey residential standard. Although these objectives were met, there was a discrepancy between the observed soil reductions and the quantity of lead extracted into the harvestable plant biomass.

For the Magic Marker SITE demonstration, a lead accounting analysis was performed to assess the amount of lead extracted into the aboveground biomass and to compare this value to the soil reduction results. The analysis assumed that: (1) 190 yd^2 of soil was treated; (2) 50% of the soil is less than 2mm (data from particle size distribution study); (3) average soil moisture is 15% (from study results); (4) all lead was extracted from the top six inches of soil; and (5) 31.67 yd^3 of soil was treated with an assumed density of 1,180 kg/yd^3, resulting in a total weight of 37,371 kg treated. The analysis showed that in order to get a 17% reduction in the treatment plot at a starting concentration of 1,800 ppm (results from study), approximately 4,700 grams of lead would need to be removed from the treatment plot. Based on the plant uptake data, approximately 51 grams of lead were removed. If 51 grams of lead were removed from the treatment plot, this would result in a 0.18% reduction at a baseline concentration of 1,800 ppm, and result in an overall 3 ppm reduction in soil concentration. Although the concentration of lead in the aboveground plant tissue met project objectives, the overall crop productivity (biomass) was very low. Therefore, the total mass of lead extracted (biomass x concentration) was low. Possible explanations for the discrepancy include: (1) chelating agents that were applied to the soil mobilized and transported the lead out of the system, (2) high spatial and temporal variability in crop productivity, resulting in a poor estimate of crop productivity, or (3) laboratory bias associated with preparing and analyzing soil samples between long periods of time.

At the Fort Dix site, the phytoextraction process was applied on a lined and bermed site with a water recycling system to re-apply excess precipitation and irrigation water. The excess water was stored in tanks, measured, and analyzed for lead at the conclusion of the study, allowing for an assessment of the quantity of lead leached from the soil. The average lead concentration from the 105,000 gallons stored in the five tanks was 160 mg/L, which equates to a total of approximately 66.7 kg of lead removed from the entire 1,606 m^3 volume of soil within the demonstration cell. With a total soil mass of approximately 2,250,000 kg (assuming a bulk density of 1.47 g/cm^3), the amount of lead in the remaining drainage water corresponded to a maximum 30 mg/kg decrease in the overall soil lead concentration. Although determining the biomass of each of these crops was outside the project scope of work, an upper limit on the biomass was calculated. The total demonstration biomass was estimated to have been 9 tons or less. Based on the concentration of lead in the biomass, the amount of biomass generated, and the soil volume treated, up to 20 mg/kg of the lead from the soil was identified in the biomass. Therefore, of the 226 mg/kg soil reduction measured, 20 mg/kg can be attributed to harvestable plant uptake and 30 mg/kg was leached from the soil. Therefore, more lead was removed through leaching processes than by plant uptake. In addition, the majority of lead cannot be accounted for in either the plant biomass or the recycled water.

Lessons learned from these studies include:

1. Greater care should be taken regarding the types of chelating agents applied to the soil and the timing of application. Both studies exhibited unusually high rainfall during the growing seasons. Since climatological conditions are hard to predict, the exact timing of amendment applications may be difficult. If the chelating agents are applied prior to a severe precipitation event, then there is a risk of mobilizing the contaminants out of the soil before they can interact with the root system. The use of time-released chelating agents may minimize leaching. In addition, on-site automated sensors and dosing equipment may be employed to release chemical additives during optimal site conditions.

2. Many contaminated sites may exhibit poor soil conditions that may not be conducive to maximizing crop productivity and biomass. The soil conditions at both the Magic Marker site and Fort Dix were not conducive to supporting a high biomass. The Magic Marker site exhibited a high gravel content, which proved difficult for establishing a high crop density. Portions of the site exhibited little or no plant growth. The Fort Dix soil was previously treated by soil-washing which removed many of the soil constituents that are required for vigorous plant growth. Future applications should consider maximizing the soil characteristics for plant growth by adding soil amendments. However, care should be taken in avoiding the overuse of amendments since a greater volume of soil will be generated for disposal if the phytoextraction process proves ineffective.

3. In terms of evaluating phytoextraction progress, greater emphasis could be placed on plant uptake/biomass as a measure of performance. To accomplish this, two pieces of information are required; metal concentration in harvestable plant parts, and biomass of harvestable plant parts. Due to potentially high spatial and temporal variability in crop productivity, it is important to retrieve a statistically significant sampling of the plants for both metal concentration and biomass determinations. Other measures of plant productivity, such as remote sensing, may be helpful.

4. If soil reductions are required as a measure of performance, special methods may be necessary to eliminate or minimize operator or laboratory variability during preparation activities. Specifically, subjective actions, such as crushing and sieving, should be quantified, and if applicable, automated to assure consistent operation. Surrogate materials could be added to the soil to measure recovery and provide acceptance limits for the process.

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