COST AND PERFORMANCE REPORT

Bioaugmentation (Accelerated Anaerobic Bioremediation)
at Area 6 of the Dover Air Force Base
Dover, Delaware

March 2000

EPA
U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Technology Innovation Office

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at Area 6 of the Dover Air Force Base, Dover, Delaware

Summary Information [1]

Site Name, Location	Dover Air Force Base, Area 6, Dover, Delaware
EPA ID Number	DE8570024010
Mechanism(s)	Anaerobic Reductive Dechlorination (Cometabolic and Direct)
Technology	Bioaugmentation Nutrient Addition Electron Donor Addition (Lactate)
Configuration	Groundwater Recirculation
Technology Scale	Field demonstration (pilot proof of technology test)
Media/Matrix Treated	Groundwater
Contaminants Targeted	TCE, PCE
Period of Operation	Proof of Technology Test: September 1996 to March 1998 (subject of this case study report) Testing for Technology Scale-up: April 1998 to June 1999 (planned) Full-scale System: Summer 1999 (planned)

Site History/Source of Contamination [1,2, 5]

Dover Air Force Base (AFB), located in Dover, Delaware, is a 4,000 acre military installation that began operating in 1941. An estimated 23,000 cubic feet of waste, including solvents, waste fuels and oils, and a variety of other wastes, were disposed at the site from 1951 to 1970. Soil and groundwater at the base were found to be contaminated with volatile organic compounds (VOCs), including TCE and PCE, and with heavy metals, including arsenic and cadmium. In March 1989, the site was listed on the National Priorities List. During a remedial investigation, “Area 6" was one of the areas at the base that was determined to have been contaminated with chlorinated solvents; a plume of VOCs was identified in groundwater in this area. Based on the results of that investigation as well as additional sampling, the area was selected for pilot testing of a bioaugmentation process. Concentrations of PCE, TCE, cis-DCE, and vinyl chloride in the pilot area before the test were 46 ug/L, 7,500 ug/L, 2,000 ug/L, and 34 ug/L, respectively.

The remediation of Dover AFB is managed by EPA Region 3 and the Delaware Department of Natural Resources and Environmental Control (DNREC). Records of Decision (RODs) have been signed for nine of the 12 operable units at the site, including operable units within Area 6. Interim RODs were signed in September 1995 that identify the following technologies for remediation at Dover: anaerobic reductive dehalogenation, cometabolic bioventing, and monitored natural attenuation. The pilot test was

performed as part of the Bioremediation Consortium of the Remediation Technology Development Forum.

Geology/Hydrogeology [1, 2, 5]

Dover AFB is underlain by glacial-fluvial deposits of sand, silt, and clay of the Columbia Formation. Within the Area 6 pilot test area, the saturated portion of the formation consists of fine, medium, and coarse sands and is about 38 feet thick. The aquifer acts as one unconfined unit that includes three zones (approximately equal thickness) - an upper zone of fine sand (0 to 12 ft below ground surface or bgs), an intermediate zone of medium sand (12 to 25 ft bgs), and a deep zone also of medium sand (25 to 48 ft bgs). Groundwater is found in the intermediate and deep zones, starting at 10 to 12 ft bgs.

Matrix Characteristics for Area 6 of the Dover AFB Site [1, 5]

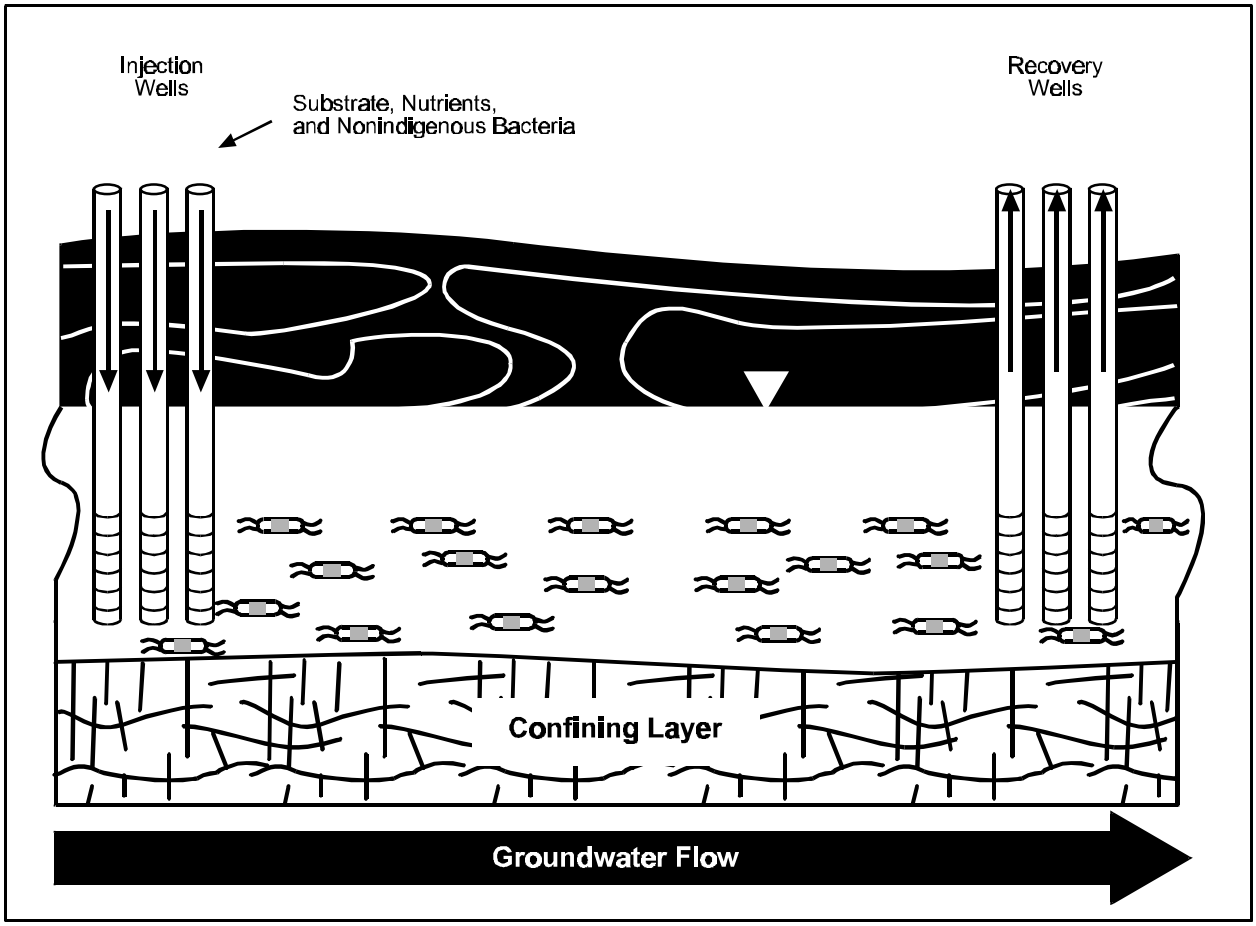
Matrix Characteristic	Value
Soil Type	Sand with varying amounts of clay, silt and gravel. Fine-grained clay and silt to a depth of 5 ft bgs; underlain by more permeable layer of silt and sand.
Soil Permeability	Not provided
Depth to Groundwater	10 to 12 ft bgs
Fraction of Organic Carbon	0.2
Thickness of Aquifer	38 ft (saturated portion)
DNAPL Presence	None identified
Hydraulic Conductivity	60 ft/day
pH	5.6 (average)
Porosity	30%
Hydraulic Gradient	0.001 ft/ft
Groundwater Velocity	140 ft/year (0.38 ft/day)

Technology Description [1, 2, 5]

Groundwater flow and three-dimensional transport models (MODFLOW and MT3D) were used in designing the pilot system. The models were used to simulate groundwater flow under different test scenarios and to simulate the three-dimensional transport of substrates.

The pilot system, shown in Figure 1, included three extraction or pumping wells and three injection wells, each screened to a depth of 38 to 48 ft bgs. The pilot system was designed to operate as an isolated or “closed-loop” recirculation cell and the wells formed a rectangular, hydraulically-controlled cell that was 40 ft wide and 60 ft long.

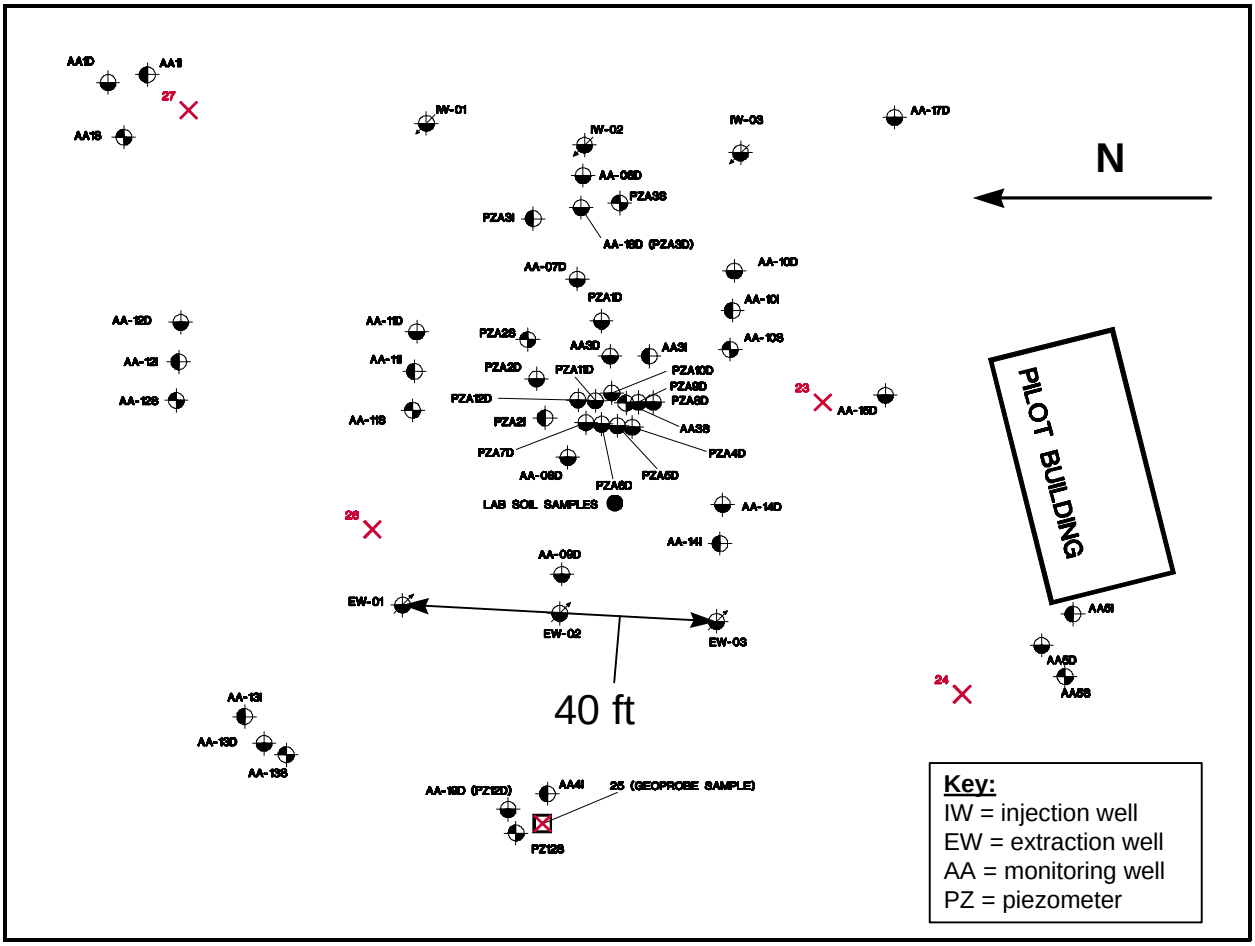
Figure 1: Process Diagram of Accelerated Anaerobic Biodegradation at Dover AFB [3, 5]



The pumping wells were operated at a combined rate of 3.75 gpm (1.25 gpm each), providing a residence time of about 60 days for groundwater from the deep zone of the aquifer.

Monitoring wells, shown in Figure 2, were located within the cell (wells 3D, 6D, 7D, 8D, 9D, and 18D) and outside of the cell. Groundwater samples were collected from the monitoring wells and analyzed for field parameters such as dissolved oxygen and temperature, water chemistry such as total organic carbon and ammonia, injected amendments, and VOCs and degradation products (PCE, TCE, DCE, vinyl chloride, ethene, ethane, and methane). The interior wells were sampled weekly; the exterior wells were sampled monthly. Sampling frequency was determined based on the results of the groundwater modeling. In addition, flow rate, total flow, and pressure were monitored. Prior to the start of the pilot system in September of 1996, a tracer test was conducted to verify groundwater flow patterns, collect data to calibrate and verify modeling results, and to verify system operation.

Figure 2: Well Locations [5]



The system was designed to allow operation with any combination of extraction pumps. The extracted groundwater was combined into a single stream and passed through a filter to remove suspended solids that could cause fouling problems in the injection wells. Using high precision, low volume metering pumps, substrate and nutrients were injected into the combined groundwater stream downstream of the filter. The substrate used in the pilot test was sodium lactate, and for most of the pilot test was delivered as 200 mg/L as carbon to all of the injection wells. The nutrients added to the system were ammonia and phosphate.

Terra Systems, Inc., of Wilmington, Delaware, operated the pilot system at Dover. For the pilot test, a method of cycling substrate and nutrient injection was used to minimize biogrowth in the system tanks and at the well screens. The substrate was fed into the system for 3.75 days, followed by 8 hours of circulation with groundwater (unamended). The nutrient was then injected into the system for 2.25 days, followed by 8 hours of circulation with unamended groundwater. This cycle was used throughout the pilot test.

Technology Performance [1, 2, 5]

The goals of the pilot test, as specified in the design report, were to 1) demonstrate that TCE and PCE degradation can be stimulated in the deep portion of an aquifer; 2) confirm that degradation will proceed to nontoxic end products; 3) develop operation and cost data for a full-scale system; and 4) document the methodology used in the pilot system.

The proof of technology portion of the pilot system was operated 18 months, from September 1996 to March 1998. During the first five months of operation, the concentration of TCE in the groundwater gradually decreased, while concentrations of cis-DCE increased slightly. There was no change in the concentrations of vinyl chloride or ethene, indicating that limited dechlorination was occurring.

In January 1997, the substrate feed concentration was increased from 100 to 200 mg/L as carbon in an attempt to stimulate dechlorination. In the monitoring well nearest the injection wells (well 6D), an increase in DCE concentrations was observed almost immediately, along with a decrease in TCE concentrations. Total organic carbon and lactate concentrations also reportedly increased in monitoring wells near and downgradient of the injection wells. However, there was no evidence that dechlorination beyond DCE to vinyl chloride or ethene was occurring. Analyses of the geochemistry of the aquifer before and after test cell operation showed that the indigenous bacteria consumed the lactate; the test cell area showed reductions in nitrate and sulfate concentrations to nondetectable levels and the generation of methane.

In February 1997, a decision was made by the RTDF to evaluate the potential for bioaugmentation for this pilot system. The bioaugmentation plan was approved by EPA Region 3 and DNREC. A number of microcosm tests and column studies were performed with known dechlorinating strains from other sites to evaluate candidate cultures. Based on the screening tests, a culture from the Department of Energy's Pinellas site in Largo, Florida was selected for use at Dover. The culture was grown in liquid media to allow aqueous addition for the pilot test.

Between February and May 1997, TCE continued to degrade to DCE, but the DCE was not further degraded to vinyl chloride. Consequently, the RTDF decided to implement bioaugmentation, in an attempt to further degrade the DCE to vinyl chloride. On June 5, 1997, 180 liters of the aqueous culture (augmenting solution) was injected into the cell through injection well no. 2. On June 20, 1997, another 171 liters of augmenting solution were injected through the same well. Substrate feed concentrations were maintained at 200 mg/L as carbon after bioaugmentation.

For the first 90-days following bioaugmentation, TCE concentrations continued to decrease and DCE concentrations continued to increase; however, there was no evidence of vinyl chloride or ethene in the groundwater. At the beginning of September 1997, vinyl chloride and ethene began appearing in wells closest to the injection wells (well 6D, 18D, and 7D), indicating that DCE degradation was occurring. Vinyl chloride and ethene continued to be detected in downgradient wells within the recirculation cell (wells 3D, 8D, and 9D), and by December 1997, these constituents had been detected in wells inside the recirculation cell but outside the bioaugmented area of the recirculation cell (well 14D and 11D).

Between December 1997 and February 1998, the concentrations of ethene increased, while TCE and DCE concentrations continued to decrease. By March 1998, all TCE and DCE in the groundwater were converted to ethene and between 75 and 80% of the TCE and DCE had been recovered as ethene, indicating that the bioaugmentation was successful in destroying TCE by reductive dechlorination.

Reasons for incomplete recovery included biodegradation of ethene or a decline in overall plume contaminant concentrations during the pilot test. Data from a background well upgradient from the pilot test showed an overall decline in VOC concentrations; however, there was no significant change in the ratio of TCE to DCE in this location.

The proof of technology portion of the pilot test was completed in March 1998. From April 1998 through June 1999, the test is focusing on testing of parameters involved with technology scale up.

Well Plugging During Pilot Test [1]

During the operation of the pilot test, plugging of the injection wells was a problem. As early as 50 days from the start of the system (mid-October 1996), the injection wells became plugged. Biogrowth in the injection wells and on the well screens was the primary cause of the plugging problem. The injection wells were redeveloped and operations resumed. In March 1997, the injection wells again became clogged and another well redevelopment was performed. However, the redevelopment was not as successful as the one performed in October. In an attempt to alleviate the plugging, the substrate was changed to lactic acid in April 1997. However, no appreciable increase in the efficiency of the injection wells was noted and the substrate feed was changed back to sodium lactate on June 8, 1997. Routine brushing of screens and hydrogen peroxide treatments were implemented to keep the wells open.

Future Plans [4, 5]

Funding has been approved for a full-scale application of the technology at an area upgradient of the pilot test. Treatment is scheduled to begin in the summer of 1999. The full-scale system is planned to be a one pass flow through system, with wells used to control the flow of groundwater, directing it through one to two “gates”.

The U.S. Army Corps of Engineers (USACE) and Dames and Moore will design the full-scale system.

Technology Cost [2]

Costs for in situ enhanced anaerobic biodegradation are presented in Table 1. The total capital costs were $285,563. The total operating costs were $164,962 for the first three months of operation (through November 30, 1996) and $522,620 for the first fifteen months of operation (through November 30, 1997).

According to the RTDF contact, a typical full-scale bioaugmentation system would cost substantially less than the system used in the pilot test at Dover. The pilot system included oversized stainless steel wells, wire-wrapped screens, duplicate control equipment, a monitoring well network that allowed for three-dimensional modeling, a frequent sampling and analysis program, one full-time equivalent operator, and a control building that was designed to be reused to store gymnasium equipment after the project was completed.

Table 1. Costs for In Situ Enhanced Anaerobic Biodegradation at Dover AFB [2]

Element	Cost ($)	
Capital		
Site preparation	5,742	
Structures	39,818	
Process equipment and appurtenances	24,067	
Utility infrastructure hookups (electricity, gas, sewer)	50,716	
Installation labor	8,600	
Monitoring wells	78,306	
Dedicated pumps	18,224	
Other equipment	5,690	
Injection wells	30,400	
Extraction wells	24,000	
Total Capital Costs	**285,563**	
Operating Costs		
Period	**Startup through 11/30/96**	**Startup through 11/30/97**
Direct Labor	74,096	168,850
Materials:		
Substrate	771	6,700
Nutrients	230	580
Supplies	2,272	10,140
Laboratory analysis	75,196	286,000
Sampling	2,018	11,000
Shipping	5,061	22,900
Overhead	975	7,000
Injection well maintenance	4,343	9,450
Total Operating Costs	**164,962**	**522,620**

Summary Observations and Lessons Learned [1]

The Dover AFB pilot project was the first successful bioaugmentation project using live bacteria from another site to destroy TCE using reductive dechlorination.

Data from the pilot test indicated that an extended period of time was required for the bacteria to exhibit functional dechlorination. At the start of bioaugmentation, lag periods of about 180 days between bioaugmentation and complete reduction of TCE and DCE to ethene were observed, including a 90-day lag period before vinyl chloride was first observed. The factors that likely contributed to the lag times included slow growth under the conditions at Dover AFB and time required for acclimatization. In addition, the initial mass of bacteria injected during the augmentation (about 35 grams) was relatively small, and may have increased the time required to grow a bacteria population at Dover that was sufficient to dechlorinate the target contaminants.

Laboratory studies are recommended to ensure that the bacterial culture selected will be effective given the site conditions and contaminants. For the Dover pilot test, a number of laboratory studies were performed using soil and groundwater from the Dover site to evaluate candidate cultures. Screening parameters included growth in liquid culture, growth on lactate, and dechlorination to ethene.

Injection well plugging was a problem during the pilot test. Several methods were used to keep the wells unplugged including cleaning the well screens with wire brushes and pumping out residue from the screened interval, using hydrogen peroxide to clean the wells, and changing substrates from sodium lactate to lactic acid. Hydrogen peroxide proved the most effective technique for keeping the wells from clogging.

Contact Information [2,3]

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2. Cost and Performance Reporting for In Situ Bioremediation Technologies. Prepared by the Interstate Technology and Regulatory Cooperation Work Group. December 1997.

3. RTDF Update. May 1998.

4. Telephone Conversation. Richard Weisman, Tetra Tech EM Inc. and Mick Mikula, Dover AFB. December 1, 1998.

5. Telephone Conversation. Richard Weisman, Tetra Tech EM Inc. and Dr. David Ellis, DuPont. January 29 and February 24, 1999.