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October 26, 2004

Engineering Field Activity Northeast
Naval Facilities Engineering Command
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Lester, PA 19113-2090

Attention: Ms. Michele DiGeambeardino

Dear Ms. DiGeambeardino:

Contract No. N62472-00-D-1300/D.O. 008
Bioslurper Optimization Study Report for Site 16F,
Naval Weapons Station Earle, Colts Neck, New Jersey

Attached is the *Final Bioslurper Optimization Study Report for Site 16F*. This version includes changes based on the comments received by Mr. Brian Hammond. In addition, the report has been updated to incorporate data included in the *Bioslurper Status Report for December 2003 through February 2004 Naval Weapons Station – Earle, Colts Neck, New Jersey* prepared by Tetra Tech FW, April 2004.

We appreciate the opportunity to participate in this optimization study and make these recommendations. Please call Mark Nielsen at (215) 579-2330 or Steve Rosansky at (614) 424-7289 should you have any questions.

Sincerely,

Stephen H. Rosansky, P.E.
Senior Environmental Engineer
Environmental Restoration Department

for MN

Mark Nielson, P.E.
Program Manager
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cc: John Mayhew (EFANE)
Debra Felton (EFANE)
Lawrence S. Burg (NWS Earle)

EXECUTIVE SUMMARY

Objectives

The objectives of this project are to assess the existing remedial actions at Site 16F, and provide recommendations to the Navy that help the systems achieve remedial action objectives (RA Objectives) and ultimate site closure while optimizing life-cycle costs. This report follows the seven-step optimization guidance presented in NAVFAC Guidance for Optimizing Remedial Action Operation Special Report SR-2101-ENV (Radian, 2001):

Step 1: Review and Evaluate Remedial Action Objectives
Step 2: Evaluate Remediation Effectiveness
Step 3: Evaluate Cost Efficiency
Step 4: Identify Remediation Alternatives
Step 5: Develop and Prioritize Optimization Strategy
Step 6: Prepare Optimization Report
Step 7: Implement Optimization Strategy.

Where appropriate, specific recommendations are included based on the results of the document review and observations made during the site visit. These recommendations are intended to provide the first step in the optimization process, and are not necessarily all encompassing. The optimization process should be refined as operational data become available.

Site Investigation and Remediation Activities

Site 16F is located in the north-central portion of NWS Earle, northeast of the intersection of Coral and Saipan roads, in an area currently used for industrial purposes. The site is about 8 acres in size, and several areas contain fuel-related contaminants, including a light, nonaqueous-phase liquid (LNAPL) plume southeast of Building C-16, an LNAPL plume northwest of Building C-50, and a former gas station near Building C-17.

A pilot-scale vacuum-enhanced free product recovery (bioslurper) pilot test was performed in 1996 to determine if the LNAPL could be recovered. High concentrations of iron in the shallow groundwater interfered with the operation of the system, but system modifications were made to overcome this problem.

A full-scale bioslurper system was designed and installed to treat the LNAPL contamination. Installation was completed in January 1998. The system includes two self-contained units, each housed in its own cargo container for protection from the elements. Nine extraction wells were installed for the full-scale bioslurper system to be used with two existing wells. Approximately 4,000 gallons of LNAPL were recovered from February 1998 through April 2001. Five additional wells were installed April 2001 to better delineate the LNAPL plume and increase hydrocarbon recovery. Approximately 700 gallons of additional LNAPL was recovered between April 1999 and May 2003.

Remediation System Performance

Battelle reviewed available site-specific documents and visited the site on November 21, 2003 to observe and discuss remedial operations being conducted at Site 16F. Key issues addressed include:

Remedial Action Objectives – The RA Objectives are summarized as: recover free product until it is removed or no longer practicable to continue recovery, and demonstrate the efficacy of natural attenuation at the site. The New Jersey Department of Environmental Protection (NJDEP) requires the removal of free product at contaminated sites, regardless of any site-specific risks caused by the free product. Based on regulation NJAC 7:26E-6, free product recovery can be terminated when free product is no longer present or when free product removal is no longer practicable. The NJDEP has approved natural attenuation as the long-term remedial action for dissolved benzene in the groundwater, and also has granted a Classification Exception Area (CEA) for the site. The objective of the groundwater monitoring program is to "assess and document migration, degradation, and attenuation of target constituents at the site."

LNAPL Recovery – The rate of recovery of LNAPL has decreased significantly since the beginning of operation. In fact, neither bioslurper unit has recovered significant amounts of LNAPL during the last four months of operation for which data were available (February through May 2003). The rate of recovery during these four months decreased by more than 98% from the average recovery rate achieved during the first six months of operation.

LNAPL Remaining – LNAPL thickness in site wells is gradually decreasing; however, in general there is considerable variability in the measurements from month to month. One trend that can easily be observed is that the thickness of LNAPL in the wells increases as the water table decreases.

Well Spacing – Based on the locations of the bioslurper extraction wells, several portions of the LNAPL plume are not within the bioslurper radius of influence of 40 feet that was determined during the pilot test performed in 1996. Also, of particular importance is the portion of the plume that is thought to be located beneath the former C-16 building. Wells were not previously installed in this area because of costly logistical issues associated with installing them in an operational facility. However, the building was removed in early 2002, and additional wells could easily be installed at this time.

Cost Efficiency – The monthly operations, monitoring and maintenance (OM&M) cost for the bioslurper system was estimated to be about $14,800. The primary contributor to the monthly cost is labor, which represents approximately 57% of the monthly costs. The second largest cost factor is the air and vapor analyses, which are an average of $2,600 or 18% of the average monthly costs. The cost per pound of TPH recovered per quarter was calculated to range from a low of $47/lb to a high of about $140/lb. The primary factor that appears to influence this cost is the mass of LNAPL recovered. The price per pound of hydrocarbons recovered drops significantly during times in which a greater mass of hydrocarbons was recovered.

Recommendations

Bioslurper data from Site 16F indicated a need for several operational and system modifications to improve performance. Also, at some point in the future, it will be necessary to collect data that indicate if LNAPL has been recovered to the maximum extent practicable, or whether an alternate approach will be needed as site conditions change and remediation nears completion. In order to collect these data, the following optimization recommendations were developed for Site 16F:

1. Install at least two additional wells and collect soil borings in the area where the southeast portion of Building C-16 formerly was located. All of the site-specific documentation reviewed indicates that hydrocarbon contamination (and likely LNAPL) is present in this area; however, this area was never investigated due to the complications associated with installing wells inside or underneath Building C-16.

2. Install at least three additional wells within the boundaries of the known LNAPL plume to improve the rate of LNAPL recovery while operating the bioslurper system. If the number of wells located within the LNAPL plume is increased, thereby decreasing the distance between the wells, it may be possible to sustain higher recovery rates for a longer period and achieve site cleanup faster, which would result in lower overall costs.

3. Continue LNAPL recovery with the bioslurper system extracting from wells that contain LNAPL.

4. Focus on operating the system when the water table is naturally depressed. Data indicate that the recovery of hydrocarbons will be greater while operating costs will remain the same (or less if a lower groundwater flowrate is realized).

5. Operate the system for a longer period of time each month (especially at times when the groundwater table is depressed). Based on cost data provided for the period January 2002 through January 2004, the water and vapor treatment costs made up a small percentage of the overall monthly project costs (on average about 15% total). Costs that should be relatively insensitive to operating time, such as water and vapor analyses and other direct costs (ODCs), make up an average of 24% of the average monthly costs. Therefore, if the system is operated for a longer period each month, provided that product recovery can be maintained, overall project costs will be minimized.

6. Place the drop tube at the oil/water interface. This may improve LNAPL recovery to some extent without increasing the groundwater extraction rate. A test also may be performed to determine if lowering the drop tube several feet beneath the oil/water interface can increase LNAPL recovery. The associated increase in water recovery also must be carefully monitored. A cost-benefit analysis may be performed to determine if there is substantial benefit to operating the system in this fashion.

7. Reevaluate aqueous and vapor treatment. The costs associated with treating these streams have reportedly been a major portion of the OM&M costs. Hydrocarbon concentrations typically decrease significantly during operation of the bioslurper system. After the new extraction wells have been installed and extracted for a period, hydrocarbon concentrations in both the aqueous and vapor phases should decrease. Regulatory and treatment requirements should be reassessed to determine if treatment of these streams remains necessary based on new site and operating conditions. At many sites, it can be demonstrated that treatment of the water and vapor streams can be reduced or eliminated without adversely impacting the environment.

1.0 BACKGROUND

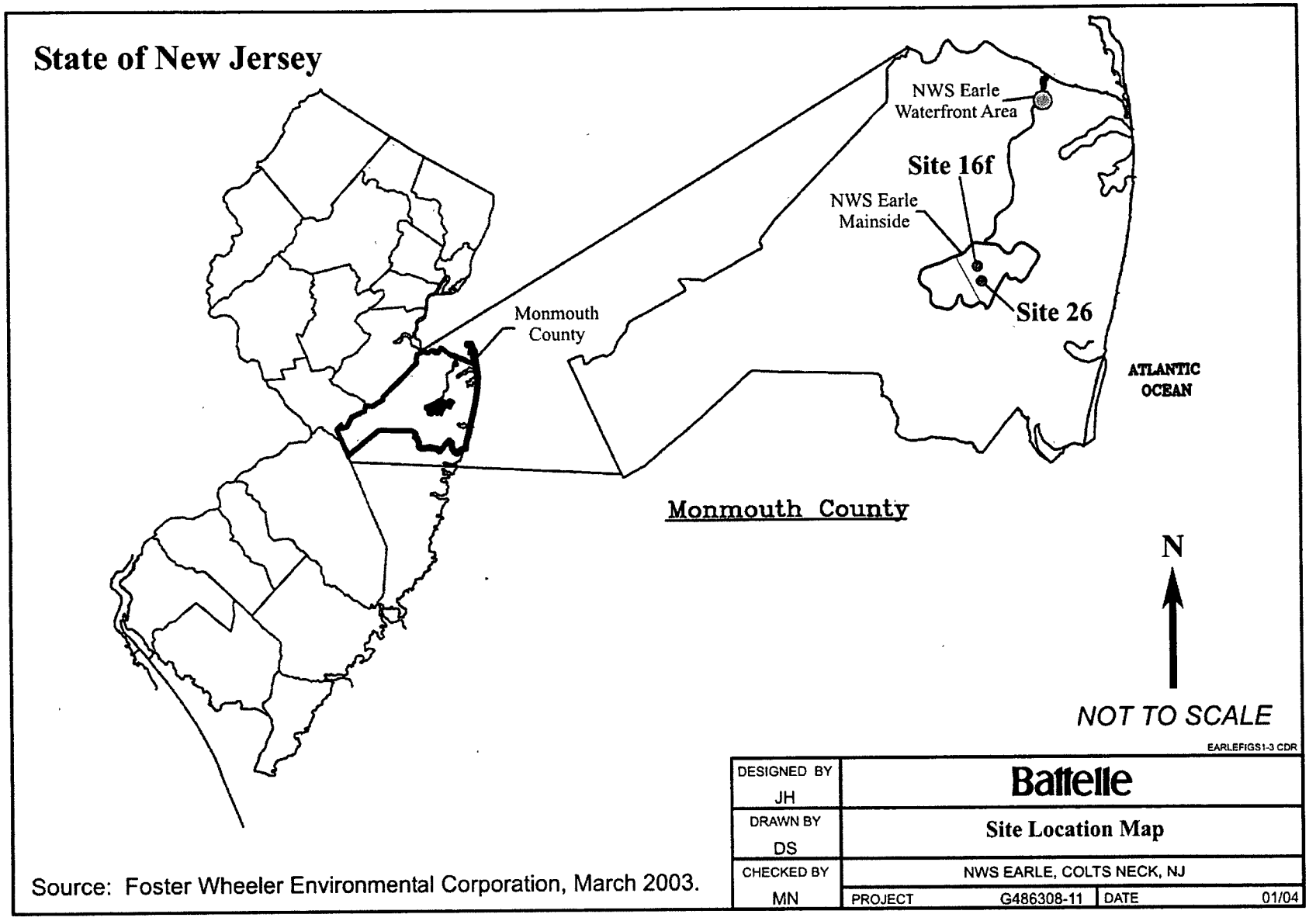
Site 16F is located in the north-central portion of Naval Weapons Station (NWS) Earle (Figure 1), and consists of two areas that contain light, nonaqueous-phase liquid (LNAPL) contamination and fuel-related constituents: a larger LNAPL plume southeast of Building C-16, and a second smaller plume northwest of Building C-50 (Figure 2). The larger LNAPL plume is suspected to have been caused by a leaking underground diesel fuel transfer line, which fed from an underground storage tank (UST) at the northwest corner of Building C-18 to a fuel dispenser located between the railroad tracks north of Building C-50. The leak was detected in 1977 and the use of the transfer line was discontinued (FWEC, 1997).

A pilot-scale vacuum-enhanced free product recovery (bioslurper) pilot test was performed in 1996 to determine whether the LNAPL could be recovered. High concentrations of iron in the shallow groundwater interfered with the operation of the system, but system modifications were made to overcome this problem.

Installation of a full-scale bioslurper system was completed in January 1998. The system includes two self-contained units, each housed in its own cargo container for protection from the elements. Each unit consists of liquid extraction, process, and treatment equipment. Each extraction system is connected to a series of wells by a manifold system. A vapor treatment system was installed with Unit #1. Vapor from Unit #2 is discharged directly to the atmosphere. Aqueous effluent from each unit is treated and discharged to the Base sanitary sewer system. Both systems include safety controls and alarms to reduce the risk of accidental discharge of contaminants to the environment.

Nine extraction wells were installed for the full-scale bioslurper system to be used with two existing wells. Two of the new wells, 16-MW20 and 16-MW21, were installed 60 feet apart in the plume north of Building C-50. The remaining wells were installed in the contaminated area adjacent to Building C-16, and were spaced 35 to 40 feet apart.

Approximately 4,000 gallons of LNAPL were recovered from February 1998 through April 2001. An independent evaluation was performed to assess the feasibility and effectiveness of removing additional hydrocarbons (Battelle, 2000). Five additional wells (16-MW24, 16-MW25, 16-MW26, 16-MW27, and 16-MW28) were installed April 2001 to better delineate the LNAPL plume and increase hydrocarbon recovery. Approximately 700 gallons of additional LNAPL were recovered between April 1999 and May 2003.



Source: Foster Wheeler Environmental Corporation, March 2003.

Figure 1. Site Location Map

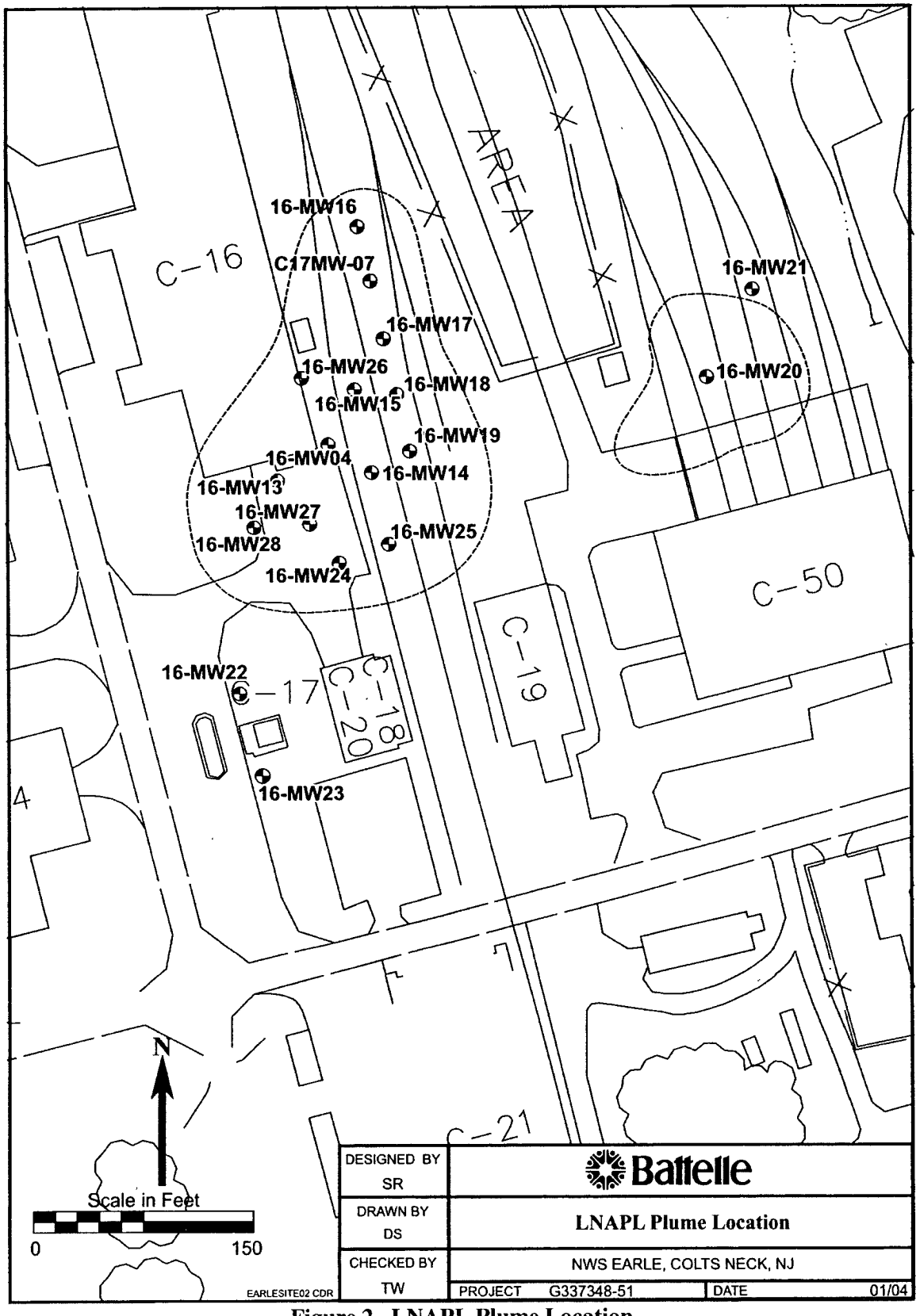


Figure 2. LNAPL Plume Location

2.0 SITE CONCEPTUAL MODEL

2.1 Setting

Site 16F is located in the north-central portion of NWS Earle, northeast of the intersection of Coral and Saipan roads, in an area currently used for industrial purposes. The site is about 8 acres in size. The larger of the two areas of contamination is located adjacent to former Building C-16 (removed late 2001 early 2002), a shop building with power tools and a vehicle high bay. The smaller area of contamination is located to the north of Building C-50, which is used for railroad car maintenance. The area also contains multiple rail lines running north from Building C-50 and north and south to the east of former Building C-16. The majority of the area is paved, with the exception of the soil where Building C-16 formerly was located.

2.2 Geology and Hydrogeology

According to regional maps, surface sediments at Site 16F consist of the Vincentown Formation and upper colluvium. The Vincentown Formation is described as a gray and green fine- to coarse-grained glauconitic sand with silt, and the upper colluvium consists of a shallow massive sand and silty sand (FWEC, 1999). Boring logs and Site Characterization and Analysis Penetrometer System (SCAPS) data indicate that the soil underlying Site 16F consists of fine- to medium-grained sand and silty sand. Relief at the site is minimal, with the drainage channels between the railroad tracks being the most significant local differences in surface elevation.

Groundwater at the site occurs in the shallow unconfined aquifer consisting of the upper colluvium and the Vincentown Formation. Monitoring of the wells at Site 16F indicates that the groundwater occurs 6 to 10 feet below ground surface (bgs). Water table elevations vary seasonally within this range. Slug testing performed during the Remedial Investigation (RI) indicates that the hydraulic conductivity at the site is approximately 1 foot/day, which is approximately ⅓ of the average value for the upper colluvium and Vincentown Formation (Brown and Root Environmental, 1996). Water table elevations measured during the RI and during the operation of the bioslurper system indicate a northerly groundwater flow direction, with some localized flow to the west/northwest near Building C-16 (FWEC, 1999).

2.3 Contamination Description

Site 16F consists of several areas that contain fuel-related contaminants. These areas include an LNAPL plume southeast of Building C-16, an LNAPL plume northwest of Building C-50, and a former gas station near Building C-17 (FWEC, 1997).

Elevated total petroleum hydrocarbon (TPH) concentrations were detected in soil borings advanced as part of a site investigation performed in 1992. Additional sampling was performed during an RI conducted in 1995 (Brown and Root Environmental, 1996). This investigation demonstrated that groundwater at Site 16F had been impacted by the hydrocarbon contamination in the subsurface. Monitoring wells installed during the RI contained up to 2 feet of LNAPL (FWEC, 1997). The LNAPL and contaminated soil act as sources of hydrocarbon contamination to the groundwater.

SCAPS investigations using laser-induced fluorescence (LIF) to detect the presence of polycyclic aromatic hydrocarbons (PAHs) in the subsurface were conducted by the Navy in 1995 and covered the areas between Buildings C-17 and C-18 and north of Building C-50. A mercury vapor lamp investigation was conducted in 1996 (FWEC, 1997) to further delineate the extent of the soil contamination (Figure 2).

The dissolved contaminant plume is being monitored simultaneously with the LNAPL removal effort. Concentrations of dissolved hydrocarbons (benzene, toluene, ethylbenzene, xylenes [BTEX], and naphthalene) are being monitored in eight wells at Site 16F. Dissolved hydrocarbons have been observed in several of the monitoring wells.

2.4 Exposure Pathways

Based on the Focused Investigation and Remedial Action Work Plan for B.C-17/20/16/50 (Brown and Root Environmental, 1997), it is understood that there is no current or reasonably likely future use of groundwater and that there is little ecological habitat associated with Site 16F. The primary migration pathway for contamination detected at Site 16F is via shallow, northerly groundwater flow. The area immediately downgradient of the source area is characterized by similar industrial-type structures and open ground covered only by railroad lines.

A second exposure pathway is through the development of the land under which Building C-16 was constructed. A portion of the soil beneath the former building likely is contaminated with petroleum constituents. However, at this time, there is no planned future use of this land.

3.0 SITE VISIT

A site visit was performed on November 21, 2003, by Mr. Stephen Rosansky of Battelle and Mr. Mark Nielsen of ENVIRON Corporation (now with Battelle). Mr. Rosansky and Mr. Nielsen were accompanied by Ms. Michele DiGeambeardino and Mr. John Mayhew of EFANE, and Mr. Larry Burg of NWS Earle. The visit was made to observe and discuss remedial operations being conducted at Site 16F. Prior to the site visit, Battelle had received and reviewed certain site-specific documentation received from EFANE, including operation and maintenance (O&M) data from bioslurper system startup (February 1998) through May 2003.

Several items were observed and discussed during the site visit. These included:

- The bioslurper systems were not operational during the site visit. Mr. Mayhew indicated that it is normal for the bioslurper systems only to be operational for a short time each month in order to allow LNAPL to migrate into the extraction wells during extended shutdown periods.
- Five additional wells were installed in April 2001 to better delineate and remediate the LNAPL plume located in the vicinity of former Building C-16.
- Building C-16 was removed some time during late 2001 or early 2002.
- Few significant changes have been made to the bioslurper systems during the last few years of operation.

4.0 OPTIMIZATION STRATEGY

The remainder of this report uses steps from the seven-step optimization approach to organize recommendations for optimizing the remedial activities at Site 16F. Where appropriate, specific recommendations are included based on the results of the document review and observations made during the site visit.

4.1 Review and Evaluate Remedial Action Objectives

The New Jersey Department of Environmental Protection (NJDEP) requires the removal of free product at contaminated sites, regardless of any site-specific risks caused by the free product. Based on regulation NJAC 7:26E-6, free product recovery can be terminated when free product is no longer present or when free product removal is no longer practicable. Natural attenuation for free-phase product or residual product remaining in the soil is not permitted. Decisions regarding the practicability of a remedial decision are made by the NJDEP on a case-by-case basis.

According to a 1999 Groundwater Monitoring Report (Tetra Tech NUS, 1999), the NJDEP has approved natural attenuation as the long-term remedial action for dissolved benzene in the groundwater, and also has granted a Classification Exception Area (CEA) for the site. The objective of the groundwater monitoring program is to "assess and document migration, degradation, and attenuation of target constituents at the site." The program includes short-term monitoring and provisions for long-term monitoring if NJDEP Groundwater Quality Standards (GQSs) are exceeded during the short-term monitoring.

The RA Objectives are summarized as: recover free product until it is removed or no longer practicable to continue recovery, and demonstrate the efficacy of natural attenuation at the site. It will be critical to collect enough data to demonstrate to the NJDEP that the LNAPL has been recovered to "the maximum extent practicable." This may involve implementing an alternative (less costly) technology in order to remove the small amount of LNAPL remaining if it is determined that the bioslurper system is no longer cost-effective, or is the most technically practicable solution based on changed site conditions.

4.2 Evaluate Remedial Action Effectiveness

The effectiveness of the bioslurper systems must be evaluated continuously to determine if vacuum-enhanced free product recovery remains the most effective treatment option. In accordance with post-construction submittal requirements, FWEC submits quarterly status reports, which summarize system operation activities, system performance monitoring results and groundwater sampling results. As part of this task, Battelle reviewed the following status reports provided by EFANE:

- *Bioslurper Status Report for April 2001 through February 2002* (FWEC, 2002a)
- *Bioslurper Status Report for March 2002 through May 2002* (FWEC, 2002b)
- *Bioslurper Status Report for June 2002 through August 2002* (FWEC, 2002c)
- *Bioslurper Status Report for September 2002 through November 2002* (FWEC, 2003a)
- *Bioslurper Status Report for December 2002 through February 2003* (FWEC, 2003b)
- *Bioslurper Status Report for March 2003 through May 2003* (FWEC, 2003c).
- *Bioslurper Status Report for December 2003 through February 2004* (FWEC, 2004).

Hydrocarbon Recovery – According to the status reports, the rate of recovery of LNAPL has decreased significantly since the beginning of operation. In fact, neither unit has recovered significant amounts of LNAPL during 2003 and the first two months of 2004 (for which data were available). Figure 3 shows the cumulative recovery for each of the units. Little LNAPL was recovered by Unit 1 in 2003 and even less has been recovered by Unit 2.

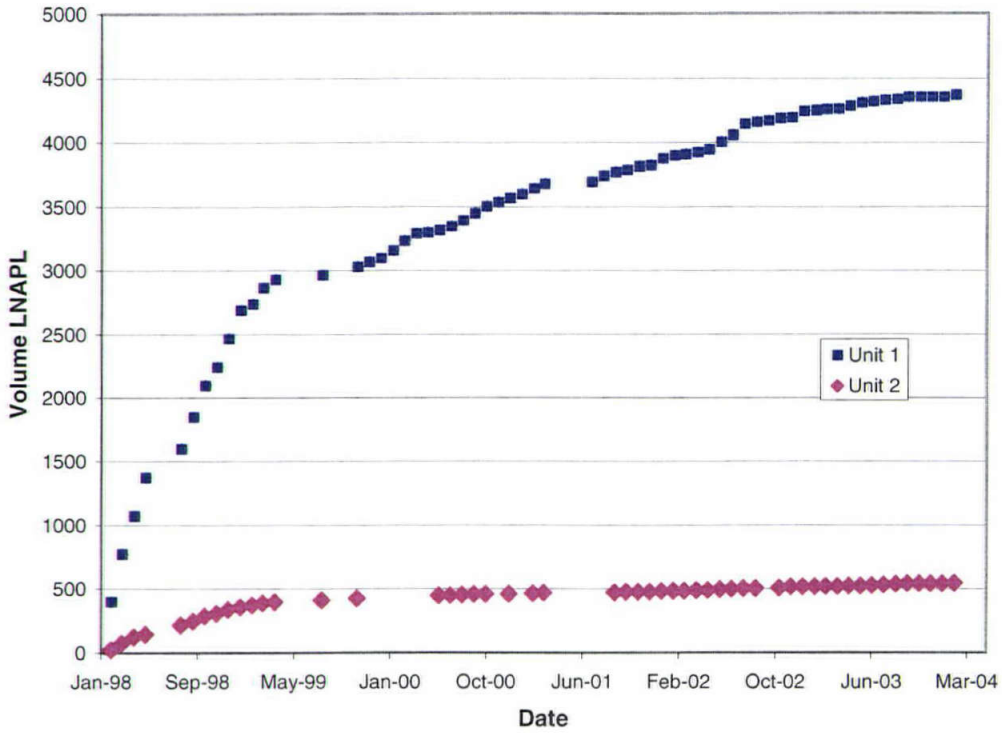


Figure 3. Cumulative LNAPL Recovery

Figure 4 illustrates the decrease in the monthly recovery rate since bioslurper operation began in 1998. The LNAPL recovery data presented in the bioslurper status reports were used to calculate an average daily recovery rate for a six-month period. The total volume recovered in a six-month period was divided by the hours of operation within that period. The rate of recovery during the last year of operation for which data was available (February 2003 through February 2004) has decreased by more than 98% and 90% for Units 1 and 2, respectively, compared to the average recovery rate achieved during the first six months of operation for each of these units.

The hydrocarbon recovery rate for Unit 1 was plotted against the operational time (Figure 5) to determine if a relationship exists between these variables. The first year of operational data was not included in this analysis because recovery rates are much greater at the beginning of operation and are not representative of current site conditions. As can be seen from these data, as the operating time increases, the rate of recovery decreases. Therefore, the operating strategy of operating the system for a short period of time each month to maximize LNAPL recovery while minimizing water recovered (as well as treatment costs) appears to be valid. However, it should be noted that if the well-field design was modified by adding more wells with a closer spacing, the rate of LNAPL recovery could be maximized for a longer period reducing the overall time and cost required to remediate the site.

Hydrocarbons removed in the vapor and aqueous streams and through in situ biodegradation also should be considered part of the optimization analysis for the purpose of demonstrating that recovery has been performed to the maximum extent practicable. Removal of hydrocarbons in the vapor and aqueous phases and through biodegradation also is important when performing a cost-benefit analysis of the bio-slurper technology against alternative technologies such as passive skimming or bailing.

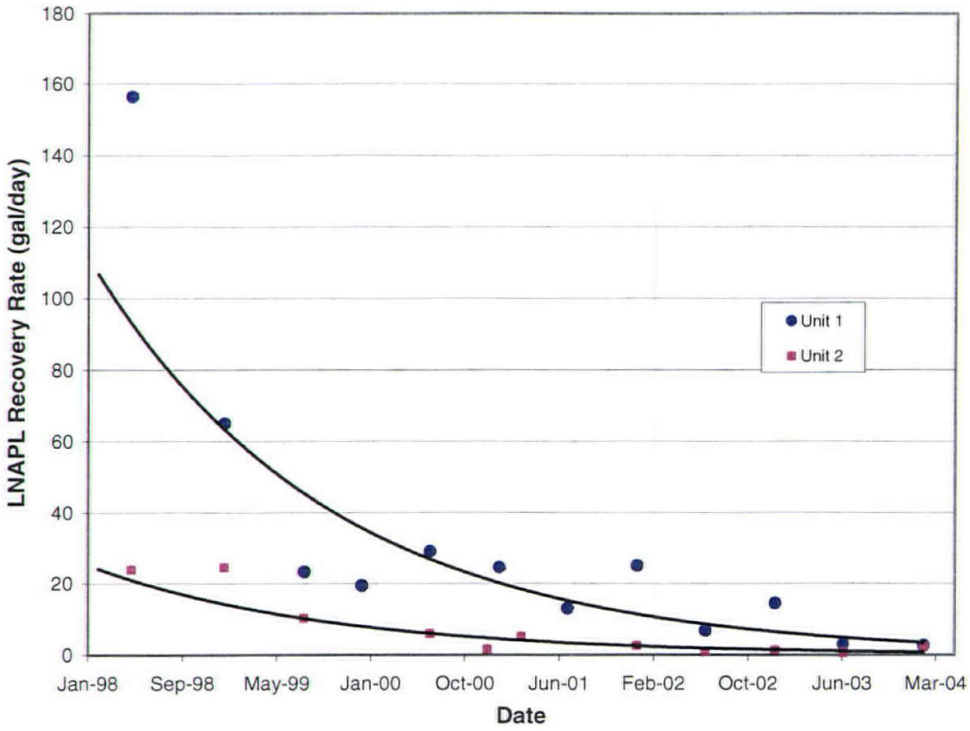


Figure 4. LNAPL Recovery Rates

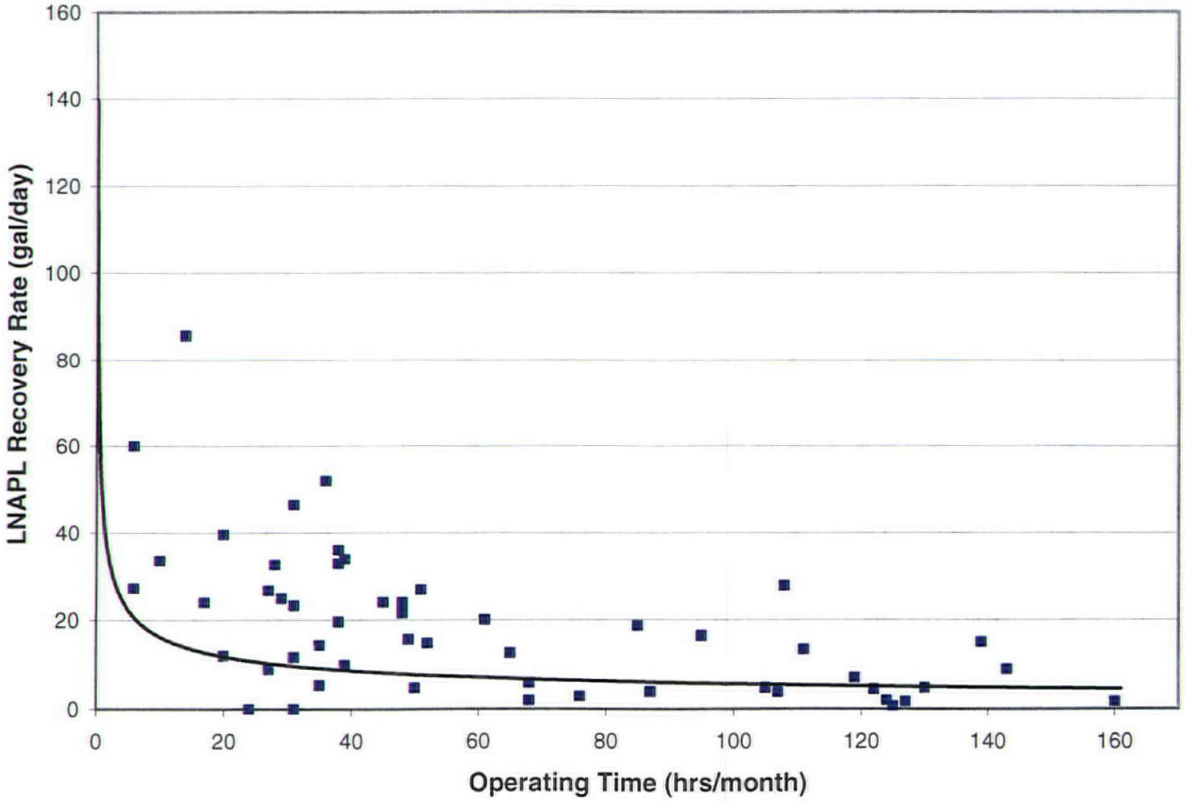


Figure 5. Relationship Between Operating Time and LNAPL Recovery

Biodegradation data were not available at the time this report was prepared. Respiration tests are not being performed to determine the mass of hydrocarbons that are being degraded in situ through the action of aeration and stimulation of naturally occurring microorganisms. However, the fuel is weathered and consists of fairly long-chained hydrocarbons, so it is likely that the biodegradation rate is fairly low. Therefore, the mass of hydrocarbons removed through biodegradation at this site may be minimal.

The mass of hydrocarbons removed in the aqueous stream is presented in Figure 6. This graph was constructed using the monthly recovery data presented in the quarterly status reports. A specific gravity of 0.85 for the LNAPL was used to convert the mass values presented in the status reports to gallons. FWEC routinely monitors the volume of water treated and the flowrate of vapor that is discharged from the system. Aqueous and vapor samples are collected on a monthly basis and analyzed for TPH. The results are used to calculate an estimated mass of hydrocarbons in each of these streams.

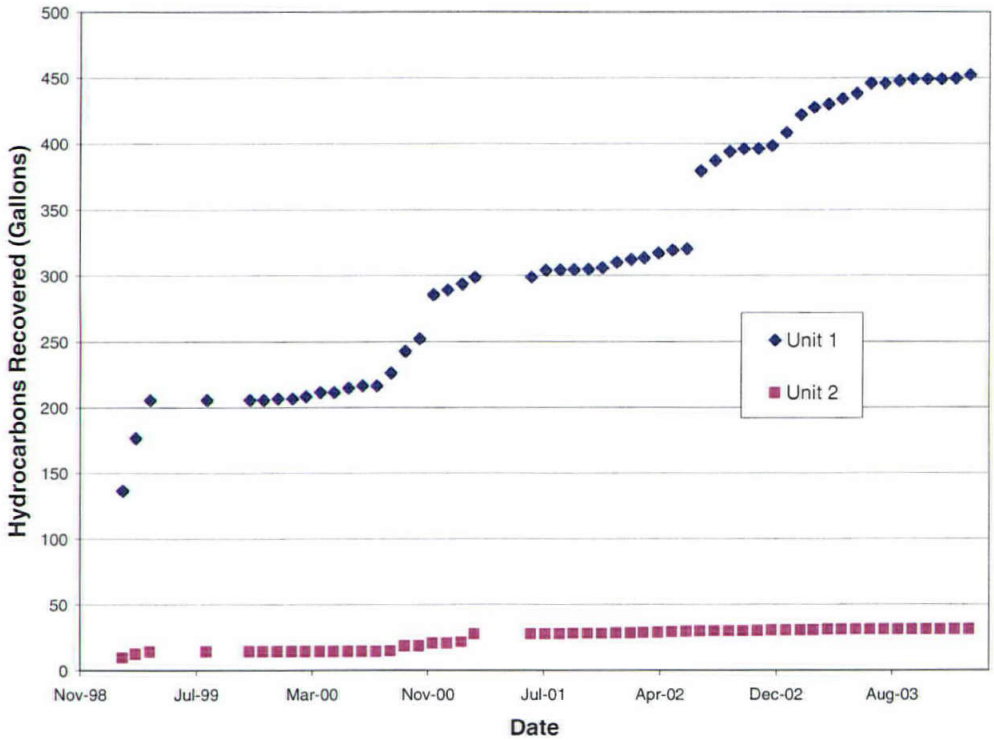


Figure 6. Cumulative Volume of Hydrocarbons Removed in Aqueous Stream

The volume of hydrocarbons recovered from the aqueous stream in Unit 1 is about 10 times greater than the volume recovered by Unit 2. These results are consistent with the LNAPL recovery data that is presented in Figure 3. Also, the volume of hydrocarbons recovered in the aqueous phase by both systems is about 10% of the volume that is recovered as LNAPL.

The hydrocarbon recovery rate of Unit 1 increased significantly between March and August of 2002. This corresponds to a time when the water table was very low. At many sites, it is observed that LNAPL trapped beneath the water table is released as the water table elevation decreases, at which point the LNAPL can more easily flow into the well under the influence of the vacuum induced by the bioslurper system.

The mass of hydrocarbons removed in the vapor phase by each unit from September 2001 through May 2003 and December 2003 through February 2004 is plotted in Figure 7. The mass of hydrocarbons removed in the vapor phase has been relatively low. This is typically observed at sites that are contaminated with relatively heavy (i.e., diesel, JP-5, heating oil, etc.) fuels. Virtually no hydrocarbon removal was achieved in the vapor phase during the last three months of operation (December 2003 through February 2004) for which data was available.

Assuming a specific gravity of 0.85 and converting the mass to an equivalent volume, an equivalent of 123 and 23 gallons of hydrocarbons were removed by Unit 1 and Unit 2, respectively, during this period. Loadings were much greater between May and July 2002. The groundwater table was depressed during this time; therefore, the bioslurping system was able to strip hydrocarbons from the previously saturated soils. Also, system operating time was greater, allowing more time for mass to be removed.

Product Remaining – In addition to tracking the mass of hydrocarbons removed from the subsurface, it is extremely important to track the quantity of contamination remaining. FWEC includes a plot of the depth to LNAPL and the depth to the water table for each well in each quarterly status report. The difference between these two lines is the LNAPL thickness in the well. Based on the plots contained in the status reports reviewed by Battelle, it is apparent that the LNAPL thickness remaining in the wells is highly variable from month to month. However, one trend that can easily be observed is that the thickness of LNAPL in the wells increases as the water table decreases.

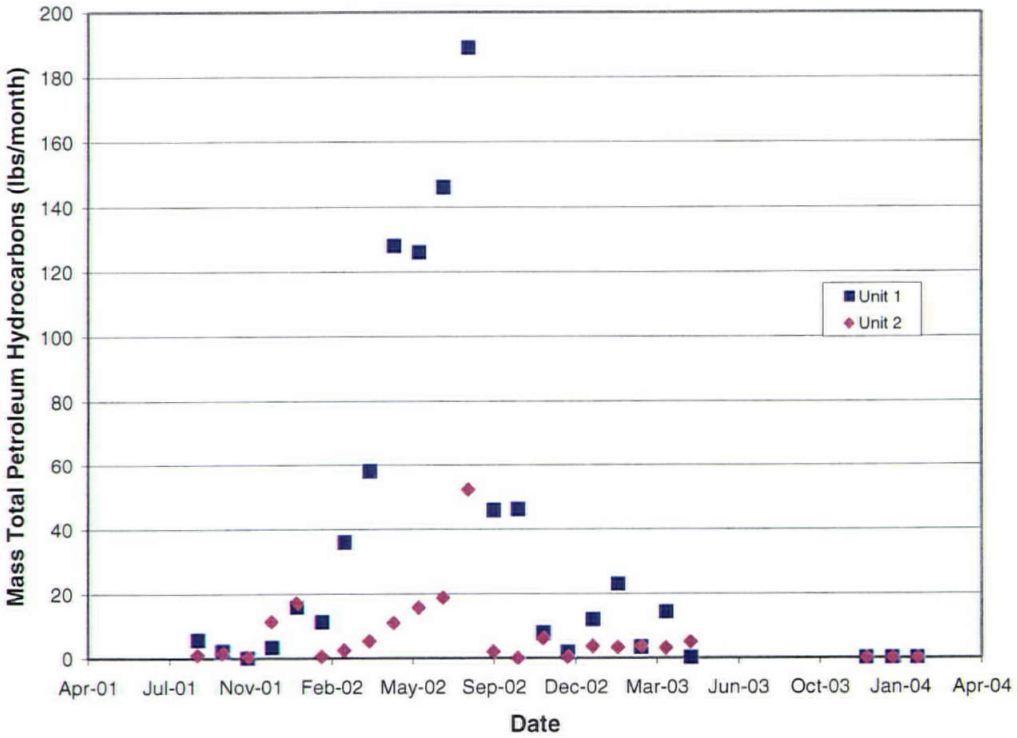


Figure 7. Hydrocarbon Loading in Vapor Phase

FWEC also prepares product thickness isopleths for each month of operation. A review of the isopleths indicates that the LNAPL thickness is gradually decreasing; however, there is considerable variability in the measurements from month to month. This may be a result of fluctuating groundwater table elevation.

This type of variation also is observed at sites where the LNAPL thickness is measured at varying intervals after shutting off the bioslurper system. If measurements are not collected uniformly, varying amounts of rebound from month to month will influence the thickness of LNAPL in the wells.

Well Spacing – The pilot test performed by FWEC in 1996 determined that a pressure radius of influence of up to 40 feet could be achieved (FWEC, 1997). Based on the locations of the wells as shown in Figure 2, several portions of the LNAPL plume are not within the radius of influence of the existing extraction wells. Of particular importance is the portion of the plume that is thought to be located beneath the former C-16 building. Wells were not previously installed in this area because of costly logistical issues associated with installing them in an operational facility; however, the building was removed in early 2002. Additional wells could easily be installed at this time.

It is important to note that the radius of influence determined in 1996 is the pressure radius of influence. The pressure radius of influence is a measurement of the distance from the extraction well at which a flow of vapor can be induced. Although the pressure radius is important because it is directly related to stripping and biodegradation processes, it cannot be used as an accurate indicator of the distance from a well at which LNAPL will be induced to flow into the well. Multiphase modeling, which is beyond the current scope of this project, is one means to estimate the radius of influence for the flow of LNAPL.

As discussed above, a greater LNAPL recovery rate is achieved when the bioslurper systems are only operated for a short period each month. This phenomenon occurs because an extended period of shutdown allows time for rebound to occur in the well and soil surrounding the well. Therefore, the rate of LNAPL recovery is boosted upon turning on the system. However, a vacuum-enhanced recovery system should not rely on the passive recovery of LNAPL into the wells, but rather should induce a gradient to induce the flow of LNAPL toward and into the wells. If wells are spaced properly and if the entire plume is within the radius of influence of the extraction wells, then product outside of the radius of influence of one extraction well is within the radius of influence of another, and free product recovery will be more optimal. When the bioslurper is shut down, only product that is trapped within the water table will eventually migrate into the wells, and it will take a long time for this product to migrate back into the extraction wells.

System Operating Time – Minor O&M problems such as occasional freezing of pipe, scale in the heat exchanger, or fault of a controller resulting in a minor spill have occurred during the last several years of operation. However, these O&M issues have been overcome in a relatively short time and operation resumed. Of primary concern is the lack of operating time due to intentional shutdowns. The bioslurper systems are only operated for a short duration each month in order to reduce operating costs because treating the extracted groundwater is cost-prohibitive (Battelle, 2000) and the average rate of LNAPL recovery decreases during extended periods of operation.

Drop Tube Placement – The quarterly status reports indicate that the drop tubes inside the extraction wells have been placed at the top of the LNAPL layer. Typically, bioslurper drop tubes are placed at the LNAPL/water interface in the well. Experience at other sites indicates that placing the drop tube opening above the interface can cause mounding of the groundwater table. The locally mounded water table saturates the pores with water, which then can obstruct the flow of LNAPL into the well by lowering the relative permeability of the formation to LNAPL. The effect of this situation is reduced LNAPL extraction rates. A discussion of relative permeability can be found in Domenico and Schwartz (1990).

There also may be some benefit to placing the drop tubes at some depth beneath the water table in an effort to dewater the area and improve LNAPL recovery. Based on the results reviewed in the quarterly status reports, recovery of hydrocarbons is improved at times of low water table. However, the disadvan-

tage of this approach is that the rate of water extraction will increase, resulting in increased treatment costs.

4.3 Evaluate Cost Efficiency

As part of this task, Battelle reviewed O&M costs for the bioslurper system (Tetra Tech FW, 2004). The information provided included the following monthly cost elements for the period of January 2002 to January 2004 (a copy of this cost summary is provided in Attachment A):

- Direct costs (combined costs between Site 16F and Site 26)
  - Labor
  - Equipment
  - ODCs (e.g., temporary utilities, office supplies, phones, etc.)
  - Materials (e.g., PPE, filters, sampling supplies, etc.).

- Subcontract costs
  - Quarterly groundwater analysis
  - Monthly air analysis
  - Vapor-phase carbon supply/disposal.

Over the period of operation for which cost information was provided, the monthly O&M cost for the Site 16 bioslurper system is approximately $15,000, assuming that the direct costs are split evenly between the Site 16F and Site 26 operations. The primary contributor to the monthly cost is labor, which represents approximately 57% of the monthly costs. The second largest cost factor is the air and vapor analyses, which are an average of $2,600 or about 17% of the average monthly costs. Based on the information available to Battelle, it is understood that this analytical cost is fixed with respect to the amount of time the systems are operational each month. The costs for granular activated carbon (GAC) to treat the vapor stream and for GAC/hydrophobic clay to treat the aqueous stream vary with the amount of time the systems are operational; these costs average $1,000 (6.7%) and $1,400 (9.1%), respectively, of the operating cost.

Cost and hydrocarbon mass extraction data were both available for the period of January 2002 through January 2004. The quarterly mass extraction rate and operation costs are presented on Figure 8. The mass of hydrocarbons recovered was calculated by adding the mass in the three separate streams – LNAPL, aqueous, and vapor. Only two months of operation and costs were used to calculate the last data point shown in Figure 8, so both cost and recovery are lower for this period. From this figure it can be observed that operating costs typically range between $40,000 and $60,000 for a three-month period and hydrocarbon recovery tends to fluctuate between a few hundred and 1,500 lb in the same period.

The resulting cost per pound of TPH recovered per quarter was calculated to range from a low of $47/lb to a high of about $140/lb between January 2002 and September 2003. The primary factor that appears to influence this cost is the mass of LNAPL recovered. The price per pound of hydrocarbons recovered drops significantly during times in which a greater mass of hydrocarbons was recovered. The cost per pound of TPH recovered was plotted against system operating time (Figure 9). It was not possible to distinguish individual costs associated with the O&M of Units 1 and 2, so the operating times of both Units 1 and 2 also were summed. Figure 9 appears to indicate that the longer the systems are operated in a quarter, the lower the cost per gallon of TPH recovered. However, more data should be collected to confirm this trend.

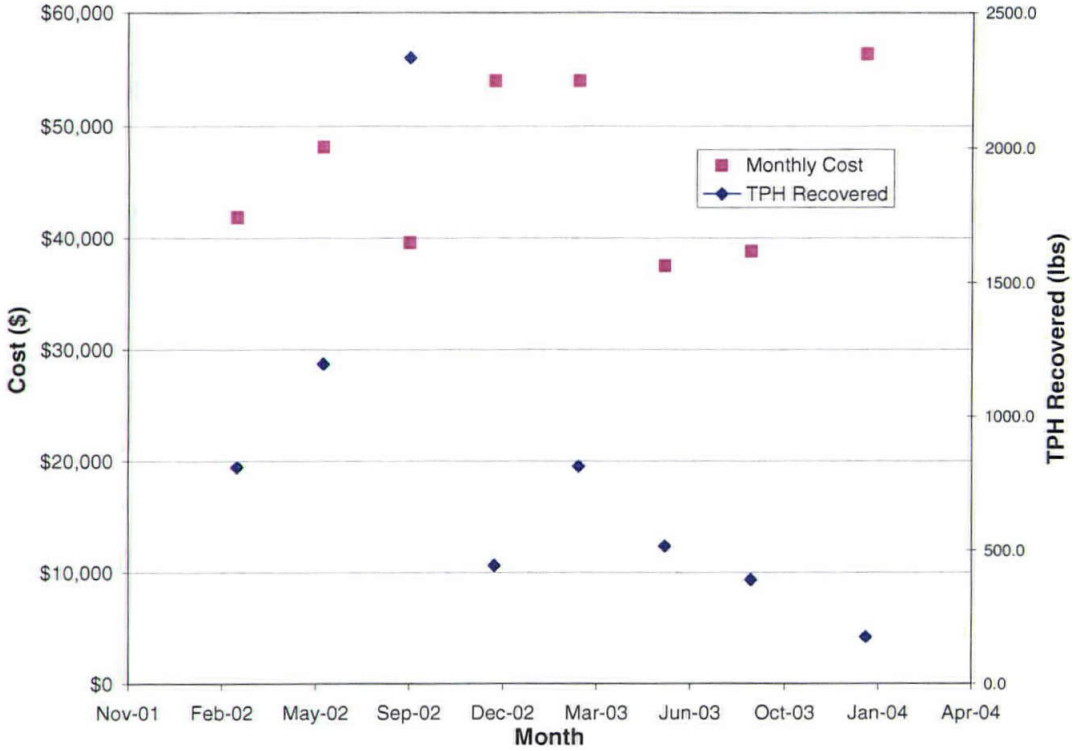


Figure 8. Approximate Quarterly Costs and Mass Recovery Rates

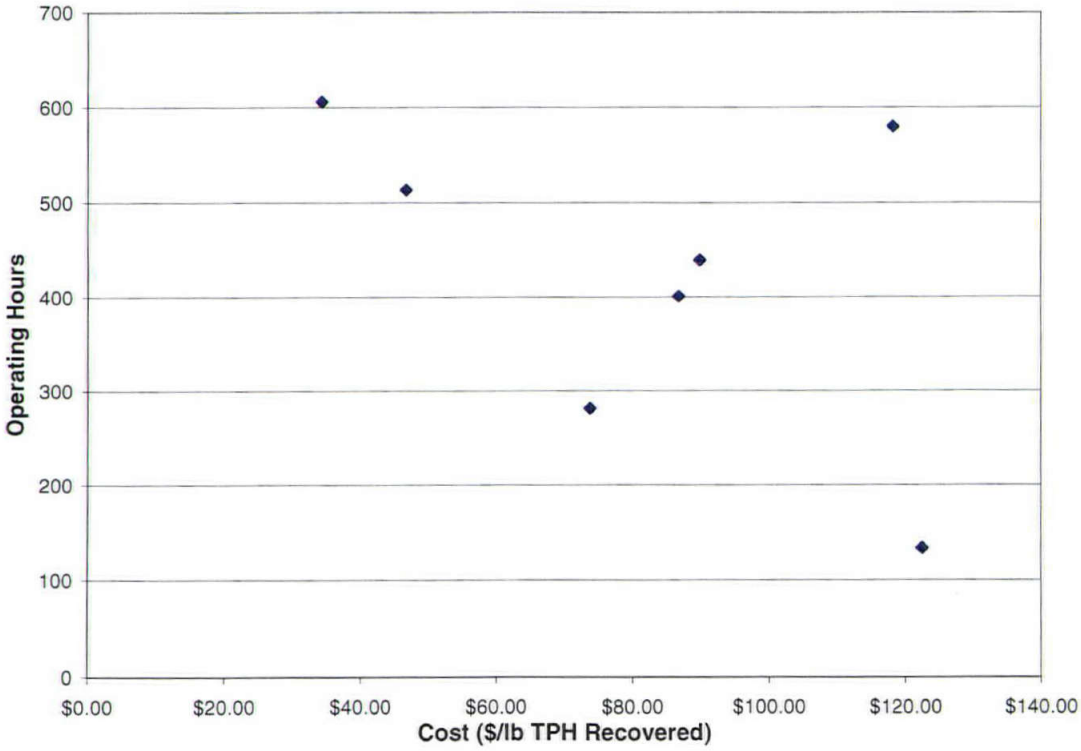


Figure 9. Comparison of Recovery Costs and Operating Hours

5.0 CONCLUSIONS AND RECOMMENDATIONS

Bioslurping is the best available technology for removal of LNAPL from the subsurface. However, the technology has its limitations. These include:

- Relatively high water and vapor treatment costs
- Channeling may occur in the subsurface
- As with all pump-and-treat technologies, it is not possible to remove all of the LNAPL in the subsurface, so a residual layer may periodically be observed in the extraction wells.

At some point it will no longer be cost-effective or practical to continue treatment with this technology, so alternative technologies should be considered. Therefore, the rate of hydrocarbon recovery and the decrease of LNAPL remaining in the wells must be closely evaluated as these above-mentioned recommendations are implemented. Also, a cost and technical analysis based on new data must be performed. If it is determined that the recovery of hydrocarbons is not significantly greater than what might be expected using a technology such as passive skimming (or bailing) and if it appears that the cost per recovered gallon of LNAPL is prohibitive, an argument can be made to modify the recovery approach based on technical impracticability of bioslurping at this time. Bioslurping is most effective at the beginning of the recovery phase; it can (and usually does) become cost-prohibitive later in the remediation phase after the majority of the hydrocarbon contamination has been extracted, degraded, or stripped from the subsurface. At this time, if a small volume of LNAPL remains in the well, a more passive approach such as skimming, absorbent socks, or bailing should be implemented.

An optimization strategy should be developed based on applicable remediation alternatives and cost-benefit analysis. At Site 16F, prior to discontinuing free product recovery, it must be demonstrated that LNAPL has been recovered to the maximum extent practicable. It is unclear at this time if LNAPL has been recovered to the maximum extent practicable (probably not) or that an alternative remediation technology would be more cost-effective or technically appropriate.

The following optimization strategy is recommended for Site 16F:

1. Install at least two additional wells in the area where the southeast portion of Building C-16 formerly was located (Figure 10). All of the site-specific documentation reviewed indicates that hydrocarbon contamination (and likely LNAPL) is present in this area; however, this area was never investigated due to the complications associated with installing wells inside or underneath Building C-16. Soil borings should be collected during the installation of these wells and carefully examined to detect the presence of hydrocarbon contamination and LNAPL.

2. Install at least three additional wells within the boundaries of the known LNAPL plume (Figure 10) to improve the rate of LNAPL recovery while operating the bioslurper system. If the number of wells located within the LNAPL plume is increased, thereby decreasing the distance between the wells, it may be possible to sustain higher recovery rates for a longer period and achieve site cleanup faster, which would resulting in lower overall costs.

3. Continue LNAPL recovery with the bioslurper system. Based on the analysis of the data reviewed by Battelle, it appears that hydrocarbon recovery (as LNAPL, in the vapor phase, and in the aqueous phase) is greater when the water table is low.

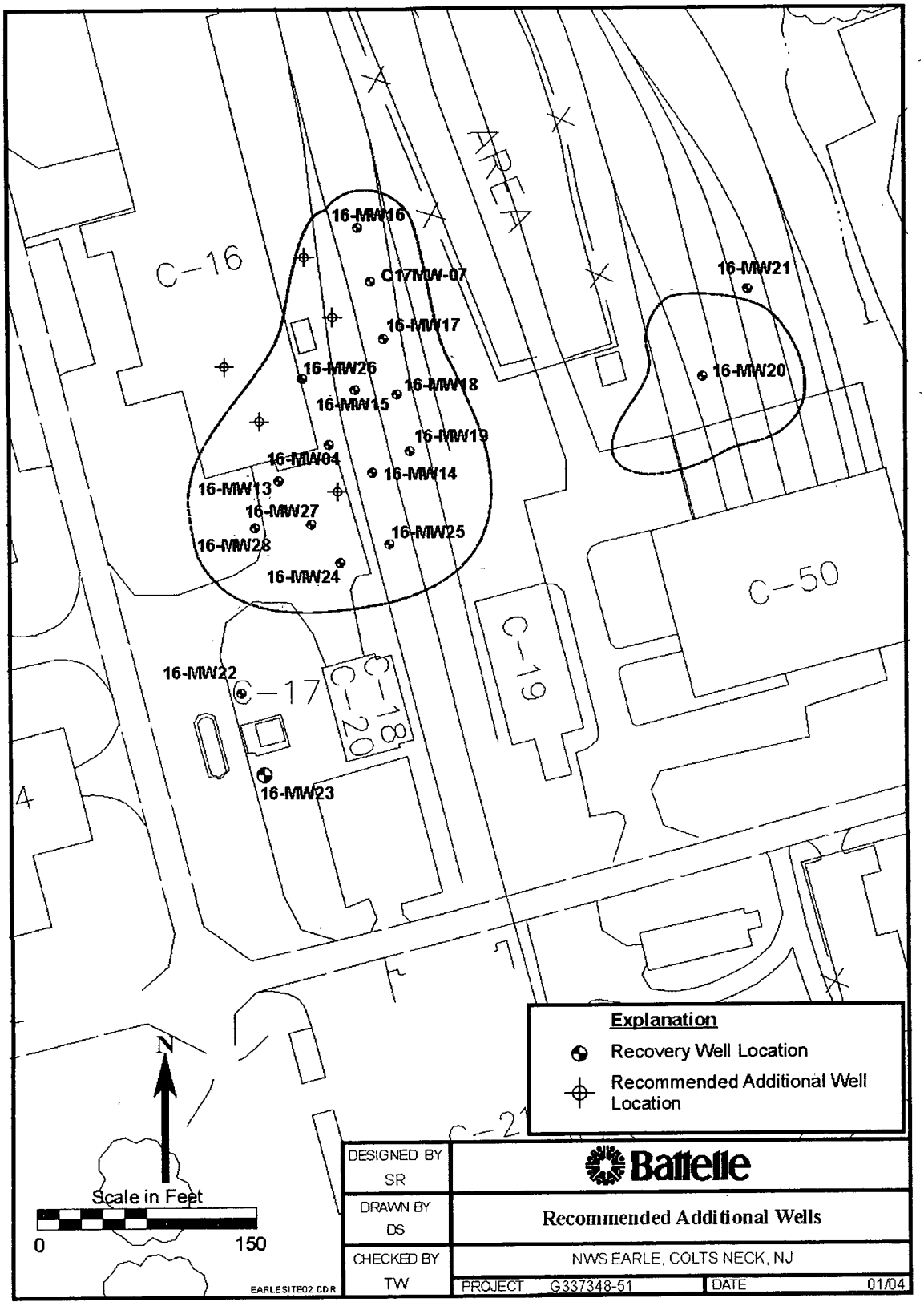


Figure 10. Locations of Additional Extraction Wells

Typically, at bioslurper sites, the water recovery (as well as associated water treatment costs) also is at times when the groundwater table is depressed; however, this relationship could not be confirmed from the operational data reviewed by Battelle.

4. Focus on operating the system when the water table is naturally depressed. Data indicate that the recovery of hydrocarbons will be greater while operating costs will remain the same (or less if a lower groundwater flowrate is realized).

5. Operate the system for a longer period of time each month (especially at times when the groundwater table is depressed). Based on cost data provided for the period January 2002 through January 2004, the water and vapor treatment costs made up a small percentage of the overall monthly project costs (on average, about 16% total). Costs that should be relatively insensitive to operating time, such as water and vapor analyses and other direct costs (ODCs), make up an average of 30% of the average monthly costs. Therefore, if the system is operated for a longer period each month, provided that product recovery can be maintained, overall project costs will be minimized.

6. Place the drop tube at the oil/water interface. This may improve LNAPL recovery to some extent without increasing the groundwater extraction rate. A test also may be performed to determine if lowering the drop tube several feet beneath the oil/water interface can increase LNAPL recovery. The associated increase in water recovery also must be carefully monitored. A cost-benefit analysis may be performed to determine if there is substantial benefit to operating the system in this fashion.

7. Reevaluate aqueous and vapor treatment. The costs associated with treating these streams have reportedly been a major portion of the O&M costs. Hydrocarbon concentrations typically decrease significantly during operation of the bioslurper system. After the new extraction wells have been installed and extracted for a period, hydrocarbon concentrations in both the aqueous and vapor phases should decrease. Regulatory and treatment requirements should be reassessed to determine if treatment of these streams remains necessary based on new site and operating conditions. At many sites, it can be demonstrated that treatment of the water and vapor streams can be reduced or eliminated without adversely impacting the environment.

6.0 REFERENCES

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ATTACHMENT A

Site 16F and Site 26 O&M Costs
January 2002 through January 2004

CTO 49 Spreadsheet for Bioslurper & AS/SVE Monthly Operating Costs

	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02
Labor	$14,135.43	$12,246.66	$21,403.11	$10,939.21	$18,133.61	$16,007.24	$7,419.74	$11,464.94	$23,163.48
Equip. Includes air monitors, misc tools, Geoguard eqip , etc	$0.00	$2,620.86	$373.65	$1,013.43	$384 25	$373.65	$0.00	$0.00	$185.50
ODCs Includes temporary utilities, office supplies, postage, reproduction, phones, etc.	$1,574 22	$937.60	$3,204 34	$1,326.53	$1,269.31	$1,149.97	$937.97	$908.23	$1,271.56
Material Includes PPE, filters, sampling supplies, etc.	$0.00	$989.80	$0.00	$0 00	$396.45	$80 06	$5.15	$50.05	$590.36
Subcontracts									
Environmental Chemical Corp. Site 16F - Monthly water analysis	$0.00	$4,050.00	$1,405.00	$0.00	$0.00	$0.00	$0.00	$580.00	$0.00
Chem-Trade Site 16F - Vapor-phase carbon supply/disposal	$1,775 00	$1,345.00	$0.00	$1,345 00	$1,345.00	$1,345 00	$1,345.00	$1,345.00	$2,690.00
*** Apollo Analytical**									
Site 16F - monthly air analysis	$955.30	$722.00	$640.00	$0 00	$0.00	$3,060.00	$0.00	$0.00	$0.00
Site 26 - monthly air analysis	$955 30	$722.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Lorco Petroleum Site 16F - Oil & oily water recycle/disposal	$0 00	$0.00	$0 00	$0.00	$0.00	$0.00	$0.00	$0 00	$276.25
ChemTech Site 26 - Quarterly groundwater analysis	$0.00	$0.00	$0.00	$0.00	$1,800 00	$2,067.50	$0.00	$0.00	$1,710.00
Barnebey Sutcliff									
Site 16F - Carbon & clay supply/disposal	$0.00	$0.00	$0.00	$4,684 00	$0.00	$0.00	$3,406.00	$0.00	$0.00
Site 26 - Vapor-phase carbon supply/disposal	$0.00	$0.00	$0 00	$0 00	$0 00	$0.00	$2,754.00	$0 00	$0.00
*** Air Toxics**									
Site 16F - Monthly air analysis	$0.00	$0.00	$2,265.00	$2,265 00	$2,261 25	$2,261.25	$1,665.00	$1,665.00	$1,665.00
Site 26 - Monthly air analysis	$0.00	$0.00	$720.00	$720.00	$720 00	$720.00	$720.00	$720.00	$720.00
Simalabs Site 16F - Monthly water analysis	$0 00	$0.00	$0 00	$0.00	$2,810.00	$1,240.00	$0 00	$0.00	$1,985.00
Danka Office Imaging Site 16F - Copier rental	$0 00	$0.00	$0.00	$340.10	$0.00	$0.00	$0.00	$0.00	$0 00
Analytical Labs Site 16F - Monthly water analysis	$0 00	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0 00
Subcontract Total	$3,685 60	$6,839 00	$5,030.00	$9,354.10	$8,936.25	$10,693.75	$9,890.00	$4,310.00	$9,046.25
Totals	$19,395.25	$23,633.92	$30,011 10	$22,633.27	$29,119 87	$28,304.67	$18,252.86	$16,733.22	$34,257.15

* Costs per month are approximate for Site 16F and Site 26. Costs were actually invoiced on a quarterly basis

CTO 49 Spreadsheet for Bioslurper & AS/SVE Monthly Operating Costs

	Oct-02	Nov-02	Dec-02	Jan-03	Feb-03	Mar-03	Apr-03	May-03	Jun-03	Jul-03
Labor	$19,482.26	$16,685.57	$22,033.80	$23,876.77	$15,525.55	$26,025.77	$14,640 97	$11,650.09	$18,481.48	$13,127.27
Equip.	$0 00	$1,408.25	$2,570.98	$848.00	$0 00	$0 00	$1,196 25	$777.08	$0 00	$1,152 75
Includes air monitors, misc tools, Geoguard eqip , etc.										
ODCs	$725.68	$1,127.85	$1,666.50	$2,771.92	$2,315 83	$3,522.90	$1,944 82	$1,677.92	$1,526.25	$1,664 74
Includes temporary utilities, office supplies, postage, reproduction, phones, etc										
Material	$1,240.72	$786.23	$6,786.02	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00	$0 00
Includes PPE, filters, sampling supplies, etc										
Subcontracts										
Environmental Chemical Corp.										
Site 16F - Monthly water analysis	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Chem-Trade										
Site 16F - Vapor-phase carbon supply/disposal	$0 00	$1,345 00	$0.00	$0 00	$1,447 24	$0.00	$1,447.24	$0.00	$0.00	$2,894.48
*** Apollo Analytical**										
Site 16F - monthly air analysis	$0.00	$0.00	$0.00	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Site 26 - monthly air analysis	$0 00	$0.00	$0.00	$0.00	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00
Lorco Petroleum										
Site 16F - Oil & oily water recycle/disposal	$0.00	$0.00	$0.00	$0 00	$0.00	$1,089.65	$0.00	$0.00	$0.00	$0.00
ChemTech										
Site 26 - Quarterly groundwater analysis	$0 00	$0 00	$1,800.00	$0.00	$0.00	$1,710.00	$0.00	$1,710.00	$0.00	$0.00
Barnebey Sutcliff										
Site 16F - Carbon & clay supply/disposal	$4,394.00	$3,833.00	$0.00	$4,109 00	$0.00	$2,343.00	$3,822 00	$0.00	$0.00	$3,406.00
Site 26 - Vapor-phase carbon supply/disposal	$0.00	$0 00	$0.00	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
*** Air Toxics**										
Site 16F - Monthly air analysis	$1,665.00	$2,025.00	$2,025.00	$2,025.00	$2,535.00	$2,535.00	$2,025.00	$2,025 00	$1,560.00	$645 00
Site 26 - Monthly air analysis	$720.00	$720.00	$720.00	$720.00	$720.00	$720.00	$720.00	$720.00	$720.00	$0.00
Simalabs										
Site 16F - Monthly water analysis	$0.00	$580.00	$0 00	$0 00	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00
Danka Office Imaging										
Site 16F - Copier rental	$0.00	$0.00	$0.00	$0 00	$0.00	$0.00	$0.00	$0 00	$0.00	$0.00
Analytical Labs										
Site 16F - Monthly water analysis	$0.00	$680 00	$260.00	$260.00	$260.00	$0.00	$260.00	$470.00	$0.00	$260.00
Subcontract Total	$6,779 00	$9,183.00	$4,805.00	$7,114.00	$4,962.24	$8,397.65	$8,274.24	$4,925.00	$2,280.00	$7,205.48
Totals	$28,227.66	$29,190 90	$37,862.30	$34,610 69	$22,803 62	$37,946.32	$26,056.28	$19,030.09	$22,287.73	$23,150 24

* Costs per month are approximate for Site 16F and Site 26. Costs were actually invoiced on a quarterly basis

CTO 49 Spreadsheet for Bioslurper & AS/SVE Monthly Operating Costs

	Aug-03	Sep-03	Oct-03	Nov-03	Dec-03	Jan-04	
Labor	$15,965.17	$12,858.28	$20,184.62	$15,820.46	$16,117.67	$21,808.55	
Equip. Includes air monitors, misc tools, Geoguard eqip., etc	$0 00	$0 00	$0.00	$0.00	$1,537 00	$0.00	
ODCs Includes temporary utilities, office supplies, postage, reproduction, phones, etc.	$1,896.01	$1,967.95	$1,773.74	$1,937.50	$1,879 42	$2,251.66	
Material Includes PPE, filters, sampling supplies, etc.	$0.00	$0.00	$0.00	$0 00	$532.50	$0.00	
Subcontracts							
Environmental Chemical Corp.							
Site 16F - Monthly water analysis	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00	
Chem-Trade							
Site 16F - Vapor-phase carbon supply/disposal	$1,447.24	$1,447 24	$1,447.24	$1,447 24	$0 00	$0.00	
*** Apollo Analytical**							
Site 16F - monthly air analysis	$0.00	$0.00	$0.00	$0.00	$0 00	$0.00	
Site 26 - monthly air analysis	$0 00	$0.00	$0.00	$0.00	$0.00	$0.00	
Lorco Petroleum							
Site 16F - Oil & oily water recycle/disposal	$0.00	$0 00	$0 00	$0 00	$0 00	$0.00	
ChemTech							
Site 26 - Quarterly groundwater analysis	$0.00	$720.00	$0 00	$0.00	$1,710.00	$0.00	
Barnebey Sutcliff							
Site 16F - Carbon & clay supply/disposal	$0.00	$0.00	$0.00	$0.00	$0.00	$3,385.00	
Site 26 - Vapor-phase carbon supply/disposal	$0.00	$0 00	$0.00	$0.00	$0.00	$5,539.56	Inv. Received but not paid yet
*** Air Toxics**							
Site 16F - Monthly air analysis	$1,665 00	$1,665.00	$1,665.00	$2,025 00	$1,800.00	$0.00	
Site 26 - Monthly air analysis	$720.00	$720.00	$720.00	$720.00	$0 00	$0.00	
Simalabs							
Site 16F - Monthly water analysis	$0.00	$0.00	$0.00	$0.00	$0.00	$0 00	
Danka Office Imaging							
Site 16F - Copier rental	$0 00	$0.00	$0.00	$0 00	$0.00	$0.00	
Analytical Labs							
Site 16F - Monthly water analysis	$260.00	$835.00	$470.00	$0.00	$130.00	$0.00	
Subcontract Total	$4,092 24	$5,387.24	$4,302.24	$4,192.24	$3,640.00	$8,924.56	
Totals	$21,953 42	$20,213.47	$26,260.60	$21,950 20	$23,706.59	$32,984.77	

* Costs per month are approximate for Site 16F and Site 26 Costs were actually invoiced on a quarterly basis