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BEST PRACTICES MANUAL FOR BIOSLURPING

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BEST PRACTICES MANUAL

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Section 1.0: INTRODUCTION

Petroleum hydrocarbons, when released to the ground, may exist in the subsurface environment in the following forms: as vapors in pore spaces, as liquids adsorbed to solids, as liquids in pore spaces (also known as light, nonaqueous-phase liquids [LNAPLs]), and in the dissolved phase. The extent of partitioning and distribution of petroleum products in different phases is governed primarily by the physical properties of the constituents of the petroleum hydrocarbon (e.g., vapor pressure, solubility in water, adsorptivity to solids) and soil characteristics (e.g., organic carbon and/or clay content, porosity). The fate and transport of petroleum hydrocarbons, including the potential for microbial degradation and chemical transformation, also depend on the above properties.

Petroleum hydrocarbons released to the environment can result in soil and groundwater contamination at levels exceeding the applicable cleanup criteria or regulatory standards for those media. After the extent of contamination that exceeds the cleanup objectives has been determined, implementation of remedial action involves source removal followed by remediation of contaminated media. This includes primarily the removal of free product or LNAPLs and remediation of hydrocarbon residual contaminants in soil and groundwater. Bioslurping is a cost-effective in situ remedial technology that simultaneously accomplishes LNAPL removal and remediation of soil in the vadose (unsaturated) zone. Battelle has developed and advanced a field demonstration program on the bioslurping technology for the Air Force Center for Environmental Excellence (AFCEE) and the Naval Facilities Engineering Service Center (NFESC). The purpose of this report is to present the general approach for field implementation of the bioslurping technology. The following subsections present the technology description, scope of the report, and report organization.

1.1 Bioslurping.

Bioslurping is the adaptation and application of vacuum-enhanced dewatering technology to remediate hydrocarbon-contaminated sites. Bioslurping combines the two remedial approaches of bioventing and vacuum-enhanced free-product recovery. The role of bioventing is to stimulate the aerobic bioremediation of hydrocarbon-contaminated soils in situ. Most of the aliphatic and aromatic constituents of petroleum hydrocarbons are degradable under aerobic conditions. Vacuum-enhanced free-product recovery extracts LNAPLs from the capillary fringe and the water table. An understanding of both technologies is necessary to understand the bioslurping technology.

1.1.1 Bioventing Component of Bioslurping.

Bioventing is the process of aerating subsurface soils, which stimulates soil-indigenous microorganisms to aerobically metabolize fuel hydrocarbons in unsaturated soils. Application of bioventing has been tested extensively by Battelle at a number of sites contaminated with fuel hydrocarbons. Bioslurping is similar in design to soil venting (a.k.a. soil vacuum extraction, soil gas extraction, or in situ soil stripping). The significant difference is that soil venting is designed and operated to maximize volatilization of low-molecular-weight compounds. Some biodegradation occurs in most soil venting remediation. In contrast, bioslurping uses bioventing to maximize biodegradation of aerobically biodegradable compounds, regardless of molecular weight. The significant difference is that the objective of soil venting is to volatilize compounds, and the main objective of bioslurping is to enhance biodegradation via bioventing. Although these technologies involve venting of air through the vadose zone, the differences in objectives result in significantly different designs and operations of the remedial systems.

Petroleum distillate fuel hydrocarbons such as JP-5 and JP-8 jet fuel are generally biodegradable if naturally occurring microorganisms are provided an adequate supply of oxygen and basic nutrients (Atlas, 1981). Natural biodegradation does occur at many sites and eventually may mineralize most fuel contamination. However, the process is dependent on the natural oxygen diffusion rate at the site (Ostendorf and Kampbell, 1989), which frequently is too slow to promote effective biodegradation. At such sites, acceleration of the oxygen transport process via (bio)venting may prove to be the most effective way to enhance bioremediation.

The significant features of bioventing technology include the following:

- Optimizing air flow to minimize volatilization while maintaining aerobic conditions for biodegradation

- Monitoring local soil gas conditions to ensure that aerobic conditions exist (not just monitoring vent gas composition)

- Conducting in situ respiration tests that provide for the effective measurement of continued contaminant biodegradation

- Manipulating the water table as required for air/contaminant contact.

1.1.2 LNAPL Recovery by Vacuum-Enhanced Pumping. Vacuum-enhanced recovery is a common groundwater pumping technique used in construction dewatering projects (Powers, 1981). Vacuum-enhanced pumping involves the application of a negative pressure to a well point system to increase the rate of flow of groundwater and soil gas into the wells. In recent years vacuum-enhanced pumping has been applied to groundwater remediation pump-and-treat systems, and to LNAPL recovery systems. Blake and Gates (1986) reported increased groundwater extraction rates and increased residual LNAPL recovery through the use of vacuum-enhanced pumping. Blake et al. (1990) reported applying vacuum-enhanced pumping techniques to hydrocarbon-contaminated sites to facilitate:

- Increased liquid recovery and gradient control
- Vapor and residual hydrocarbon recovery
- Combined vapor recovery and gradient control.

Reisinger et al. (1993) reported enhancing groundwater extraction by a factor of 47% as a result of vacuum extraction.

Two important factors that influence the movement of fluids into a recovery well are the hydraulic gradient, or hydraulic head difference between the well and the surrounding strata, and aquifer transmissivity, i.e., the rate at which groundwater moves through a unit thickness of the aquifer. Vacuum-enhanced recovery improves recovery rates by increasing the hydraulic gradient and increasing the aquifer transmissivity. Conventional dual-pump free-product recovery (FPR) systems increase the hydraulic gradient into a well by setting a pump below the water table to establish a cone of depression in the water table around the well. Free product then flows down the gradient diagonally into the well to be recovered by a second LNAPL extraction pump. Vacuum-enhanced pumping systems use the same concept, except that the cone of depression actually is a cone of reduced pressure around the well. Fluids then flow horizontally across the pressure-induced gradient, from higher pressure outside the well to lower pressure inside the well. The transmissivity of the saturated zone is an intrinsic characteristic of an aquifer and is a function of the hydraulic conductivity and the saturated thickness of the aquifer. Vacuum-enhanced pumping increases transmissivity by promoting flow along more-permeable horizontal flow lines and by decreasing the local pressure above the aquifer to, in effect, increase the saturated thickness of the aquifer. In addition, vacuum-enhanced pumping promotes continuity in the LNAPL phase (i.e., lower capillary pressure and fewer air pockets in the capillary fringe). The cumulative effect of the increase in hydraulic gradient and aquifer transmissivity results in an enhanced liquid recovery rate.

Suction lift might appear to be a limitation to the application of vacuum-enhanced dewatering. In theory, the maximum suction lift attainable with an extremely efficient vacuum pump is approximately 25 ft, depending on elevation (Powers, 1981). In practice, however, greater suction lifts are attainable. Lifts greater than the theoretical maximum can be attained when the extracted fluid is not only water, but a mixture of soil gas and groundwater (Powers, 1981). A mixture of soil gas and water has a specific gravity less than 1.0 and, therefore, can be lifted higher than a standard water column. When LNAPL (specific gravity <1.0) is extracted with the soil gas and groundwater there is a greater increase in suction lift. Another phenomenon that can help in achieving greater than the theoretical suction lift is liquid entrainment or entrapment. Liquid entrainment occurs when the primary extraction fluid is soil gas, rather than a liquid. At high velocities, extracted soil gas can entrain water droplets and carry them to the surface via slug flow at high liquid extraction rates.

1.1.3 Bioslurper Technology Description. Bioslurping combines vacuum-assisted free-product recovery with bioventing to simultaneously recover free product and bioremediate the vadose zone. Bioslurping pumps are designed to extract free-phase fuel from the water table and to aerate vadose zone soils through soil gas/vapor extraction by entraining LNAPL and water droplets in the soil gas extracted by the vacuum. The systems are designed to achieve hydraulic control as is done with conventional pump-and-treat technologies. The bioslurper system withdraws LNAPL, relatively small amounts of groundwater, and soil gas in the same process stream using the air lift created by a single pump. Groundwater is then separated from the free product and is treated (when required) and discharged. Free product is recovered and can be recycled. Soil gas vapor is treated (when required) and discharged.

Bioslurping can improve free-product recovery efficiency without extracting large quantities of groundwater when compared to other LNAPL recovery technologies. The bioslurper system may pull a vacuum of up to 25 ft of water on the recovery well to create the pressure gradient needed to force movement of fuel into the well. The system is operated to minimize drawdown in the water table, thus, reducing the problem of free-product entrapment in soil.

Bioventing of the vadose zone soils is achieved by withdrawing soil gas via the recovery well. The slurping action of the bioslurper system cycles between recovering liquid (free product and/or groundwater) and soil gas. The rate of soil gas extraction is dependent on the recovery rate of liquid into the well. When free-product removal activities are complete, the bioslurper system is easily converted to a conventional bioventing system to complete remediation of the vadose zone soils.

Bioslurper systems are designed to minimize environmental discharges of groundwater and soil gas. As done in bioventing, bioslurper systems extract soil gas at a low rate to reduce volatilization of contaminants. In some instances volatile discharges can be kept below treatment action levels. The slurping action of a bioslurping system greatly reduces the volume of groundwater that must be extracted compared to conventional LNAPL recovery systems, thus greatly reducing groundwater treatment costs. Figure 1 illustrates the differences between conventional dual-pump LNAPL recovery and bioslurping.

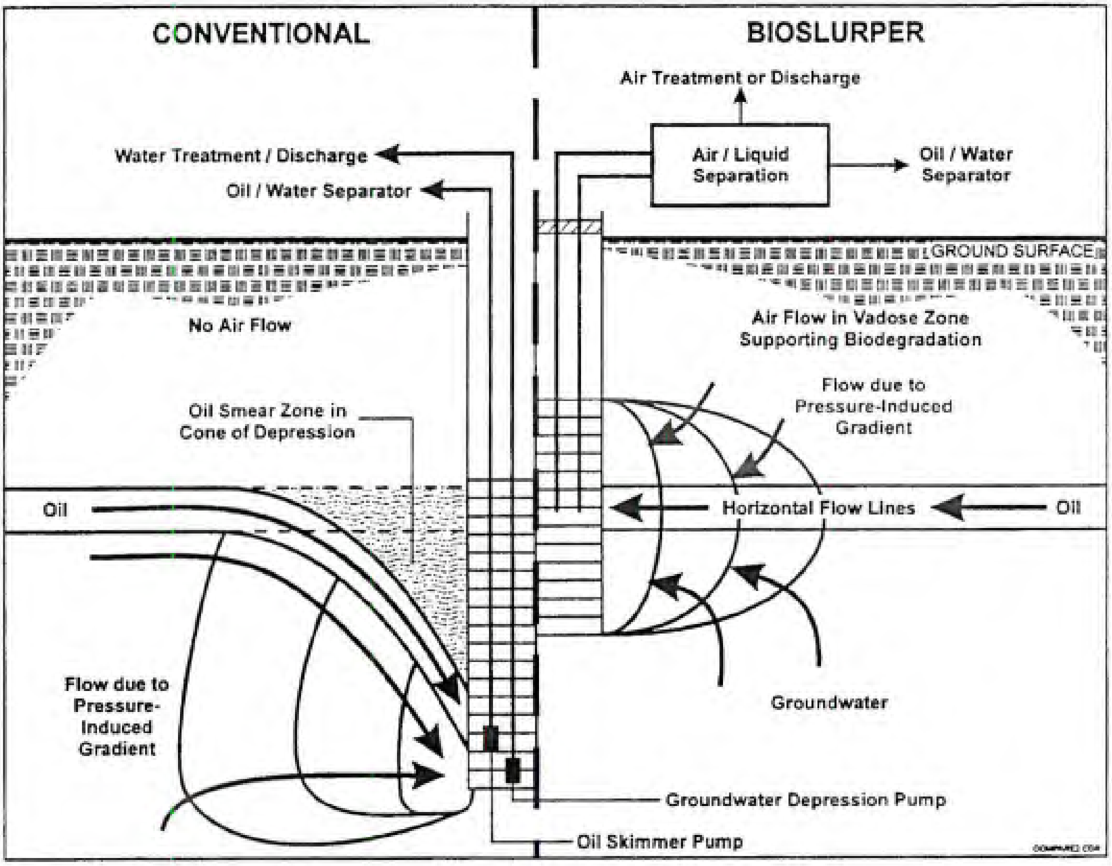

Figure 1. Comparison of the Dual-Pump and Bioslurping Methods for LNAPL Recovery

Nonaqueous-phase liquids that are less dense than water move downward through the vadose zone and accumulate at and above the zone of saturation. Near the top of the LNAPL zone, most of the pore space is occupied by air. The LNAPL concentration usually is greatest toward the center of the LNAPL zone and declines towards the bottom where the pore space is fully occupied by water.

A significant feature of the bioslurping process is the induced air flow created by the vacuum, which also causes LNAPL to flow toward the well. The pressure gradient created in the air phase results in a driving force on the LNAPL that is significantly greater than that which can be induced by pumping the LNAPL with no air flow. Also of importance is the fact that the air flow created by the vacuum actually increases the LNAPL content around the well. That is, the LNAPL tends to accumulate around the well, so that it is easily extracted.

Other technologies commonly used in LNAPL recovery include skimming and drawdown pumping. Preliminary data from short-term bioslurper tests conducted by Battelle for the AFCEE and the NFESC indicate that the LNAPL recovery rate by bioslurping is up to six times the rate of skimming and as much as two times the rate of drawdown pumping. Mathematical modeling programs comparing conventional pumping technology to bioslurping (Parker, 1995) have predicted that free product mass removal from the affected soils will be twice as fast when bioslurping technology is used. Furthermore, the total volume of groundwater pumped, and hence the water treatment costs, may be substantially less with bioslurping systems than with conventional serial technology applications (Barnes and McWhorter, 1995). Because the performance and process efficiency of these technologies depend heavily on the site characteristics, it is difficult to compare the costs for these technologies. Typically, bioslurper operations at full-scale sites reduce system operations and maintenance costs. A Bioslurping Implementation Cost-Estimating Guide is included as Appendix A. Reasonable cost estimates of bioslurper installation, operations, and maintenance can be made by using this guide. Because the bioslurper system does appear to remove free product more rapidly than conventional serial pumping technologies, it is also reasonable to assume that operations and maintenance (O&M) costs will be lower than the O&M costs of the conventional technologies.

In summary, the preliminary analysis of the available field data indicates that bioslurping is a cost-competitive technology for LNAPL recovery with the added advantage of simultaneous vadose zone remediation. Like skimming and drawdown pumping, bioslurping would be less effective in tight (low-permeability) soils. Bioslurping is applicable at sites with a deep groundwater table (>30 ft), although adjustments to the system components, such as pump and pipe resizing, are required to increase the air lift needed to entrain LNAPL and water droplets. Prior to technology selection, the feasibility of bioslurping, or any LNAPL removal/vadose zone remediation technology must be evaluated based on the site characterizations. If the evaluation indicates that bioslurping is practical, then the data required for the system design should be generated as discussed in Section 2.0 of this manual.

1.2 Scope and Organization of the Report. The purpose of this Best Practices Manual for Bioslurping is to present the procedures to construct and operate a bioslurping unit at a remediation site. Battelle has conducted limited pilot-scale and full-scale tests, and, as such, this report includes only a general approach for implementing bioslurping at an LNAPL-contaminated site.

This report consists of six sections including the Introduction (Section 1.0). Section 2.0 presents how the feasibility of bioslurping should be investigated by evaluation of site characterization data and additional pilot-scale field tests. The equipment and instruments required to conduct this pilot testing are given in Section 3.0; the procedures to implement the tests are given in Section 4.0. Analysis of the data generated during the pilot-test will be used to establish the feasibility of full-scale bioslurping and to generate preliminary design data. Section 5 presents the general approach for development and construction of a full-scale bioslurper remediation system. This section includes different system components that should be considered during the full-scale design and installation. Section 6.0 of the manual describes the procedures for system operation, including issues of concern based on previous experience, and performance monitoring methods. Bibliographic data for references cited in this document are given in Section 7.0. Appendix A is the Bioslurping Implementation Cost-Estimating Guide. Appendix B presents the acronyms and abbreviations used in text.

Section 2.0: BIOSLURPER FEASIBILITY TESTING

Field tests are required to evaluate the feasibility of bioslurping a site and generating the data required to design and install a full-scale bioslurping remediation system. The first step of bioslurper feasibility evaluation involves reviewing the site characterization data. Based on the site characterization data, a pilot test should be performed at a location representative of the site characteristics and contamination. If the geologic and physical characteristics of the subsurface soils and aquifer vary significantly at the site, pilot tests at more than one location may be required.

2.1 Site Characterization Data Review. The site characterization data review should include a review of information sources describing when the release of LNAPLs occurred, the quantity and type of the LNAPL release, measured LNAPL thickness (free product) in monitoring wells located in the area, petroleum hydrocarbon levels in soils, areas/extent of contamination, and the site geology and hydrogeology. Most of this information is expected to be in the Initial Assessment and Confirmation Studies, site characterization reports, and remedial investigation/feasibility studies. If the available information is limited, a site characterization program will have to be implemented to obtain the above data.

2.2 Scope of the Feasibility Tests. Site characterization tests and pilot-scale testing are needed to establish the feasibility of bioslurping for source removal/remediation of a site contaminated with fuel. The site characterization and pilot-scale testing should include any additional soil characterization that is necessary, a soil gas survey, in situ aeration/respiration testing, and soil gas permeability testing to determine radius of influence, followed by a pilot-scale bioslurper pumping test. Sections 2.2.1 through 2.2.5 briefly describe the significance of these analyses/tests in the development and construction of full-scale bioslurper wells.

2.2.1 Soil Characterization. It is expected that soil characterization data are available for sites designated for remediation. However, additional soil characterization may be performed to determine the concentration and distribution of organic contaminants such as total petroleum hydrocarbons (TPH) and benzene, toluene, ethylbenzene, and xylenes (BTEX) in soil. Furthermore, physical parameters such as moisture content and particle size should be collected as part of the site characterization. Particle size analysis enables the lateral variability of soil type to be defined. Significant lateral variability in soil type may require more than one bioslurper well for pilot testing.

2.2.2 Soil Gas Survey. A soil gas survey is required to identify optimum locations for installation of the bioslurper well and soil gas monitoring points. Three soil gas components of interest are oxygen, carbon dioxide, and hydrocarbon vapors. Concentrations of these indicators in soil gas in relation to atmospheric air and uncontaminated background soils can provide valuable information on the ongoing natural biodegradation of hydrocarbons and the potential for enhanced biodegradation resulting from bioslurper-mediated aeration.

The best locations for the bioslurper well and soil gas monitoring points are soils containing measurable hydrocarbon contamination where the oxygen is depleted and the carbon dioxide levels are elevated. Typical ranges are 0 to 2% oxygen, 5 to 20% carbon dioxide, and TPH levels exceeding 10,000 ppmv.

2.2.3 In Situ Aeration/Respiration Testing. The in situ aeration/respiration tests were developed by Battelle (see Hinchee et al., 1992) to provide rapid field measurement of in situ biodegradation rates. These tests are important in determining how bioslurping would remediate the fuel hydrocarbon-contaminated soils in the vadose zone. The testing involves aerating the subsurface to increase the oxygen levels in soil gas, followed by measurement of reduction of oxygen and the increase in carbon dioxide levels. Based on the rates of oxygen utilization, the rate of petroleum hydrocarbon degradation can be estimated. In addition, if high oxygen utilization rates (e.g., >1.0%/day) are observed, it is likely that bioslurping will result in significant degradation of fuel hydrocarbons.

2.2.4 Bioslurper Radius of Influence. The bioslurper radius of influence is the maximum distance from the air extraction well (i.e., the bioslurper well) at which a vacuum is exerted. As discussed in Section 1.0, the vacuum gradient created in the subsurface environment facilitates the movement of free product toward the bioslurper well. Thus, the calculation of the radius of influence is an important element in determining full-scale bioslurper well spacing. Proper well spacing is required to ensure that optimum free-product recovery is achieved while ensuring that the entire site receives a supply of oxygen-rich air adequate to sustain in situ biodegradation. The radius of influence is also the most critical factor involved in scale-up costs. The number of wells installed at a full-scale bioslurper site is determined by the radius of influence a particular well exerts on the affected area. By accurately calculating the radius of influence during pilot-scale testing, the full-scale costs can be minimized by spacing the bioslurper wells so that the radii of influence for the wells are overlapping to cover the entire site. Because scale-up costs are based on the number of wells installed, this calculation is extremely important in keeping full-scale capital costs at competitive levels.

For practical purposes, the radius of influence usually is considered to be the maximum extent to which pressure changes can be measured. The radius of influence is a function of soil properties, but also is dependent on the configuration of the bioslurper well, and is altered by soil stratification.

2.2.5 Bioslurper Pilot Testing. Following site characterization and soil gas survey, a bioslurper system (one or more wells) should be installed to conduct the pilot tests. Pilot-scale bioslurper testing can usually be performed using existing monitoring wells that have a known LNAPL thickness to reduce cost. The bioslurper pilot tests should be operated for at least 5 days, or as long as 4 weeks. This time frame will enable the operators to gather the data required to accurately evaluate the bioslurper system. The extracted soil gas composition, free-product thickness, and groundwater levels should be measured during these tests, and the pressure distribution in the subsurface must be measured to establish the radius of influence exerted by the pump on the test well. The amount of extracted free product, groundwater, and soil gas should be quantified over the time of the tests. At the conclusion of the study, the respiration test can be performed. All these measurements will be used to design the full-scale system and to evaluate the potential long-term effectiveness of bioslurping.

2.3 Construction and Discharge Permits. If an existing monitoring well cannot be used, construction permits may be required to construct the bioslurper well. Regulatory approval and/or permits may be required for venting off-gas and discharging aqueous wastestreams. In general, the permitting requirements and/or regulatory approvals are not applicable for short-term pilot tests that generate relatively low environmental releases. When bioslurping is planned at full-scale sites for long periods of time, prior approvals from regulatory agencies as well as construction permits may be required. Types of permits or regulatory approvals that are likely to be required include:

- Drilling and/or well installation permits for the bioslurper well and/or monitoring points

- An air emissions permit for the bioslurper well vapor discharge

- Regulatory approval for discharge of water from the bioslurper system

- A site investigation permit or approval.

The permit requirements should be investigated with the appropriate local, state, and federal (e.g., regional U.S. Environmental Protection Agency) offices. Air and water discharges measured during the pilot test can be used to estimate the potential discharges during the full-scale remedial action. Depending on the available discharge options, the off-gas stream and wastewater generated during the remedial action may have to be treated to reduce the contaminant levels to acceptable discharge limits. Off-gas treatment methods include vadose zone reinjection, activated carbon treatment, and catalytic combustion. On-site wastewater treatment, if required, includes clay-based or hydrophilic fiber filters to remove oil/grease and air stripping or activated carbon to reduce dissolved contaminant levels.

Section 3.0: PILOT TESTS — SELECTION AND INSTALLATION

This section describes the test wells and equipment that are required to conduct the field treatability tests. It must be recognized that site-specific flexibility will be required and, thus, details will vary. To the extent possible, the following sections identify equipment or system components that may be used under different site conditions. Some information presented in this section was obtained from the Test Plan and Technical Protocol for Bioslurping (prepared by Battelle for the U.S. Air Force, January 1995).

3.1 **Bioslurper Extraction Wells.** A bioslurper well should allow for (1) extraction of groundwater, free product, and soil gas from the subsurface; (2) the creation of a pressure/vacuum gradient for enhanced fluid recovery; (3) air permeability/radius of influence testing; and (4) increasing the subsurface oxygen levels as measured by in situ aeration/respiration testing. In some cases, existing monitoring wells with a history of free-product contamination could be used as the bioslurper pilot test well. A well that has a history of sustained free-product recovery using a conventional recovery technique (e.g., skimming or baildown) is recommended for bioslurper pilot testing. When no suitable monitoring well is present, a bioslurper well should be installed. Installed bioslurper wells must be placed with the screened section in both the contaminated vadose zone soil and groundwater. Following are several specifications for siting and construction of the bioslurper well:

1. The bioslurper system should be installed in the well with the thickest free product measured. The largest thickness measurements generally are found in the center of the contamination plume. In addition, these wells will ensure that the data gathered from the test are representative of the contaminated soil and groundwater conditions found in the area.

2. The recommended diameter of the bioslurper well is either 2 or 4 in. and depends on the ease of drilling and the horizontal and vertical extent of the contamination. Generally, a 2-inch-diameter bioslurper well would provide adequate airflow for air permeability/radius of influence testing.

3. The bioslurper well casing should be constructed of schedule 40 polyvinyl chloride (PVC), and screened with a slot size that easily allows soil gas to flow into the well while minimizing transport of fine soils into the well. The slot sizes generally range from 0.006 to 0.010 in (#6 to #10 slots). The screened interval will start above the water table in contaminated soil and may extend up to 10 ft into the water table, depending on the thickness of the saturated zone and the seasonal fluctuations of depth to groundwater.

4. Hollow-stem auguring is the recommended drilling method. Whenever possible, the diameter of the annular space should be at least two times greater than the vent well outside diameter. The annular space corresponding to the screened interval should be filled with silica sand or equivalent. The annular space above the screened interval should be sealed with wet bentonite and grout to prevent short-

circuiting of air to or from the surface. Figure 2 shows a typical bioslurper well.

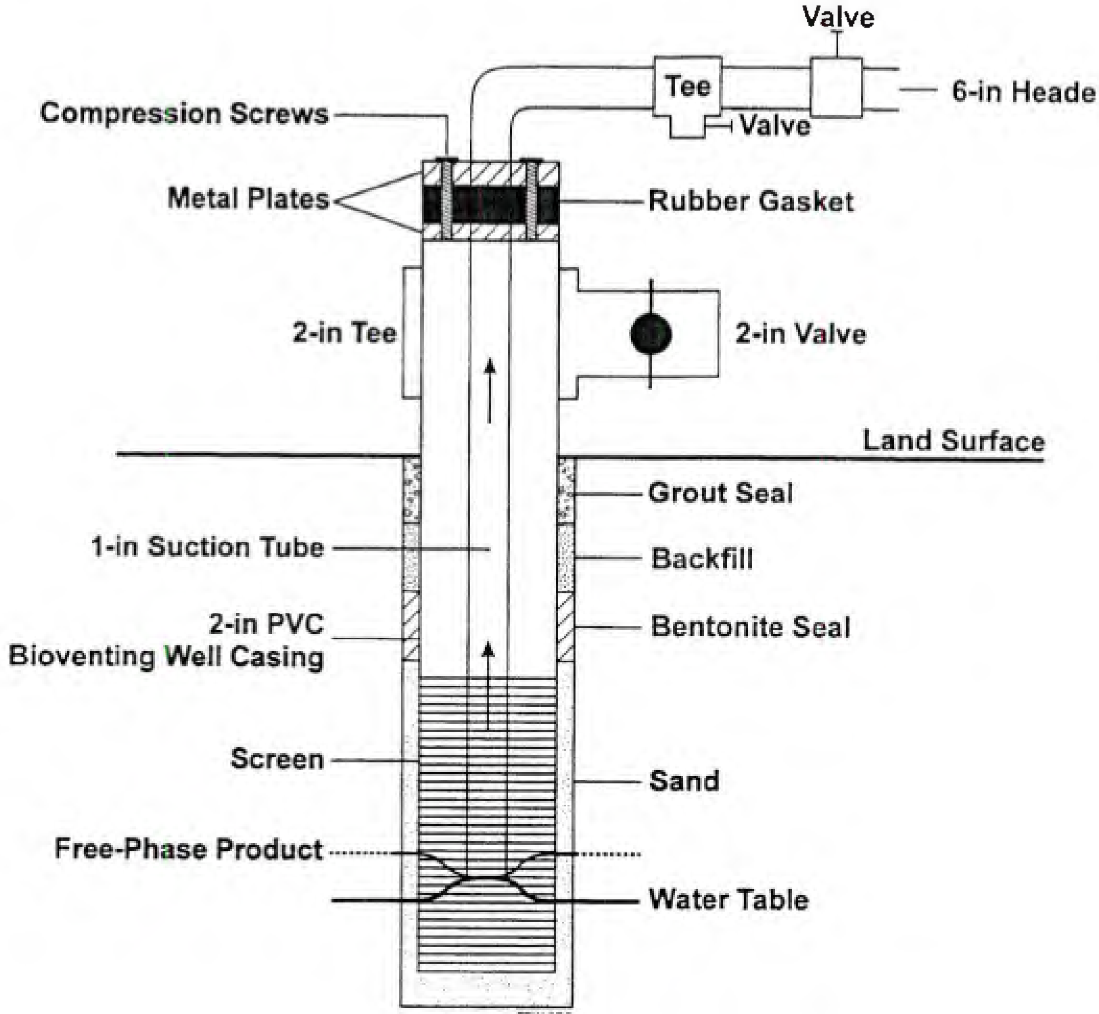

Figure 2. Diagram of a Typical Bioslurper Well

5. The suction tube is generally constructed of 1-inch sch. 40 PVC pipe. A rubber gasket with metal plates (Figure 2) is used to keep the suction tube in place and airtight. A gas sampling/pressure monitoring point may be installed on the pipe outside the well. A valve should also be installed to control the air/liquid flow in the suction tube.

3.2 **Soil Gas Monitoring.** Soil gas monitoring points (Figure 3) are used for pressure measurements and soil gas sampling. They generally are installed at three or more depths and a minimum of three locations. To the extent possible, the monitoring points should be located in contaminated soils with >1,000 mg/kg of total petroleum hydrocarbons. It may not be possible to locate all the monitoring points in contaminated soil, especially the points furthest from the bioslurper well. In this case, it is important to ensure that the point closest to the vent well is located in contaminated soil, and if possible, that the intermediate point also is placed in contaminated soil. It is important to note that, if no monitoring points are located in contaminated soil, no meaningful in situ respiration test results can be derived. Based on Battelle's experience, for successful in situ respiration testing, the monitoring points should be selected to have significant soil gas hydrocarbon concentrations (ideally >10,000 ppmv) and low oxygen concentrations (ideally 5% O_2 or less). A background soil gas monitoring point may also be established to sample background soil gas concentrations. This monitoring point may be an existing monitoring point or monitoring well in an uncontaminated location.

3.2.1 **Locations of Monitoring Points.** Monitoring points should be located in a generally straight line radially out from the bioslurping well at the intervals recommended in Table 1. Typically three monitoring points constructed at these depths and distances will be appropriate. Additional monitoring point locations may be necessary for a variety of site-specific reasons including, but not limited to, spatial heterogeneity, obstructions (buildings, underground tanks, etc.), or if it is desirable to monitor a specific location.

Table 1. Recommended Spacing for Monitoring Points

Soil Type	Depth to Top of Bioslurping Well Screen[(a)] (ft)	Lateral Spacing from Bioslurping Well[(a)] (ft)
Coarse Sand	5	5-10-20
	10	10-20-40
	>15	20-30-60
Medium Sand	5	10-20-30
	10	15-25-40
	>15	20-40-60
Fine Sand	5	10-20-40
	10	15-30-60
	>15	20-40-80
Silts	5	10-20-40
	10	15-30-60
	>15	20-40-80
Clays	5	10-20-30
	10	10-20-40
	>15	15-30-60

(a) Assuming 10 ft of well screen. If more screen is used, the >15-ft spacing will be used.

In general, each monitoring point should be screened to at least three depths (Figure 3). The deepest screen should be placed approximately 1 ft above the water table or liquid interface. Consideration should be given to potential seasonal water table fluctuations and soil type in determining the depth. In more-permeable soils, the monitoring point can be screened closer to the water table. In less-permeable soils, it should be screened further above the water table. The shallowest screen traditionally is placed 3 to 5 ft below land surface. The intermediate screen is positioned at a depth which is ideally equidistant from the deepest and the shallowest depths. However, it is generally a good practice to place the intermediate monitoring point depth within the upper screened section of the bioslurper well to maximize its pressure-monitoring capabilities.

For example, in a sandy soil with a groundwater depth of 15 ft and a bioslurper well screened from 10 to 20 ft below land surface, acceptable depths for the soil gas monitoring points to be installed would be 14 ft, 10 ft, and 3 ft. It may be necessary in some cases to add additional screened depths to ensure a contaminated soil is encountered, to monitor differing stratigraphic intervals, or to adequately monitor deeper sites with broadly screened bioslurper wells. Consideration should be given to placing monitoring points in distinct lithologic units.

3.2.2 Monitoring Point Construction. Monitoring point construction varies depending on the depth of drilling and the drilling technique. The monitoring points generally consist of a small-diameter nylon (¼-in.) tube to the specified depth connected to a gravel-filled screen of ½ to 1 in. in diameter and approximately 6 inches long. In shallow hand-augured installations, rigid tubing (i.e., schedule 80 3-in. PVC) terminating in the center of a sand pack may be adequate. The sand pack normally extends for an interval of 1 to 2 ft from the center of the screened tube. In low-permeability soils, a longer sand pack may be desirable. In wet soils, a longer sand pack with the screen near the top may also be desirable. A bentonite seal at least 2 ft thick is required above and below the sand pack to ensure that pressure and soil gas samples taken are discrete to that depth. Figure 3 shows a typical installation.

Tubes may be used to collect soil gas for carbon dioxide and oxygen analysis in the 0 to 25% range, and for fuel hydrocarbons in the 100-ppmv range or higher. The tubing material must have sufficient strength and be nonreactive. Sorption and gas interaction with the tubing materials have not been significant problems for this application. All tubing from each monitoring point may be finished with quick-connect couplings. The monitoring points should be finished by placement in a watertight cast aluminum well box.

3.3 Bioslurper Extraction and Treatment System. The system components/equipment associated with the extraction system generally include a liquid pump, pressure/vacuum gauges, valves, and pipes. Components of the treatment system include primarily an oil/water separator (OWS), holding tanks for free product and water, a sump pump, and totalizers (Figure 4). Depending on the characteristics of the fuel/water emulsion, a groundwater pretreatment system using holding tanks or bag filters may be installed to improve the performance of the OWS.

The bioslurper system generates a point source vapor emission and an aqueous discharge. Distribution of hydrocarbon constituents (e.g., BTEX) in each discharge depends on the fuel type and the extraction rate. In general, during the pilot tests, the discharge rate (lb/day) of low-volatility fuels in the vapor stream is expected to be below local regulatory treatment levels, and the vapors may be discharged directly to the atmosphere with regulatory approval. The mass of dissolved hydrocarbons that are released with the aqueous discharge is expected to be much lower than the mass released with

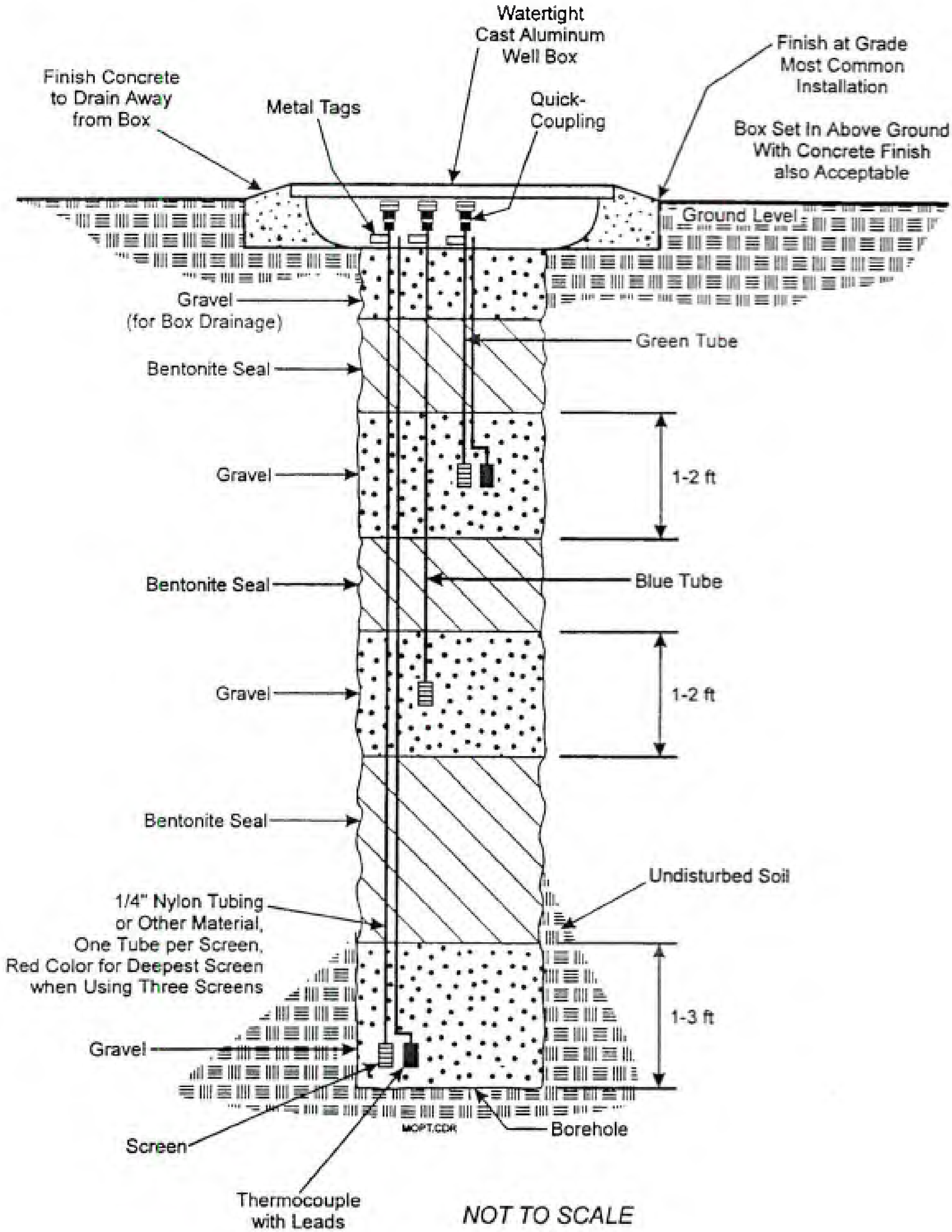

Figure 3. Diagram of a Typical Soil Gas Monitoring Point

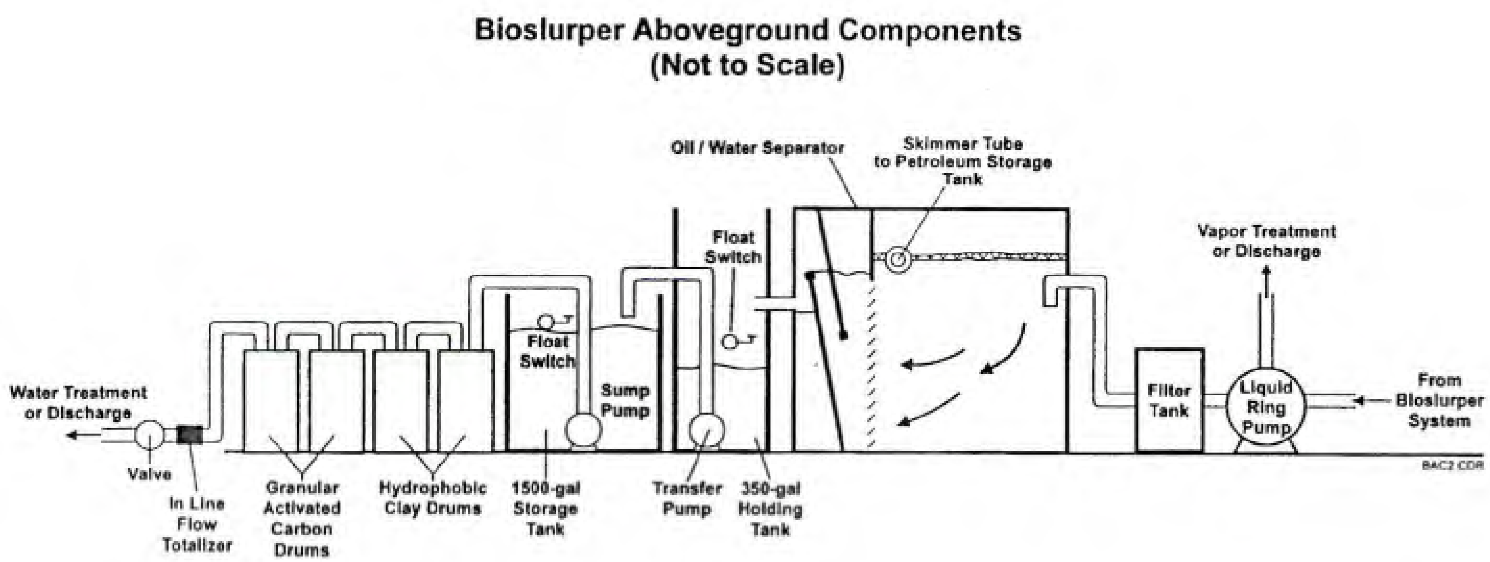

Figure 4. Diagram of the Bioslurper Pilot Test System

the off-gas as vapors. In most cases, bioslurper aqueous effluent from pilot tests can be discharged to the sanitary sewer.

In some instances, the vapor and/or the aqueous effluent require treatment before discharge. Generally, the contaminant of concern will be benzene, which is present in relatively high concentrations in AVGAS and gasoline. Local regulatory requirements vary and, therefore, it will be necessary for the Navy to determine effluent treatment requirements prior to mobilization to the field site. Groundwater and vapor treatment options that may be employed during pilot testing and/or full-scale remediation are given in Sections 3.3.3 and 3.3.4, respectively.

3.3.1 Pumps. Pumps are required to extract the fuel from the wells. In addition, effluent transfer pumps may be required to facilitate discharge of water separated from fuels.

3.3.1.1 Liquid Ring Pump. Liquid ring pumps are generally used to extract liquids and soil gas. Advantages of using liquid ring pumps are that they have efficient pump curves (i.e., pump performance remains relatively uniform even at vacuums as high as 29 in. Hg), and they are intrinsically safe total fluid pumps. Varying conditions will require the use of different pump sizes. Liquid ring pumps used during bioslurper testing are 3 horsepower (hp), 5 hp, 7.5 hp, and 10 hp (Atlantic Fluidics Models A20, A75, A100, and A130, respectively). Because only one well is expected to be used for the majority of the pilot testing, the 3-hp pumps probably will be sufficient for most test sites. However, the larger pumps are more applicable for use at sites with deeper groundwater (greater than 25 ft) and for pilot tests where two or three wells will be utilized.

3.3.1.2 Effluent Transfer Pump. The aqueous effluent from the OWS generally gravity-drains into an effluent transfer tank. A float-switch-activated transfer pump can be used to discharge the effluent from the liquid holding tank to the appropriate receiving points. At some sites groundwater may have to be pumped through a water treatment system (e.g., activated carbon canisters) prior to discharge.

3.3.2 **Oil/Water Separator (OWS).** The bioslurper system generates a liquid stream consisting of a mixture of LNAPL and groundwater. In most cases the LNAPL can be effectively separated from the aqueous phase by passing the liquid discharge stream through a gravity oil/water separator (OWS). Battelle uses Megator Corp. Model #S-1-A-1.5 for its pilot tests. Recovered LNAPL gravity-drains into a small holding tank. Extracted groundwater gravity-drains into an effluent transfer tank.

3.3.3 Groundwater Effluent Treatment. The preferred disposal option for the bioslurper system aqueous discharge is a tie-in to the sanitary sewer. The groundwater extraction rate is expected to be low at most sites (less than 5 gallons per minute [gpm]), and the concentration in the aqueous phase leaving the OWS generally will be less than 100 ppm TPH. These two factors will result in low mass loading rates to the sanitary sewers, most of which typically have throughputs in the millions of gallons per day (mgd). In instances where discharge to the sanitary sewer is not feasible, or is not allowed, and treatment is required by local regulations, granular activated carbon (GAC) filtration treatment systems may be used. In such cases, the discharge line from the effluent transfer pump should be plumbed to two canisters of GAC (Carbtrol Corp. Model L-1, or equivalent) connected in series. If an oil/grease emulsion is present, a clay-based filter (Filter-sorb™ of Carbtrol Corp.) may be used prior to the GAC treatment. The treated groundwater generally can be discharged to either a storm or sanitary sewer, or directly to the ground surface.

3.3.4 Vapor Treatment. The cost-effectiveness of bioslurper technology is greatly increased if treatment is necessary for the system vapor discharge. The requirements for treatment depend on local regulations, the composition and concentration of hydrocarbons in the extracted vapor, and the system vapor extraction rate. The vapor extraction rate is dependent on site soil gas permeability and bioslurper pump size. The composition and concentration of fuel hydrocarbons in the vapor discharge is dependent on the fuel type present at the site and the age of the release (degree of weathering). As with the groundwater discharge, treatment requirements generally will be driven by the mass of benzene released in the vapor discharge. For example, at sites contaminated with JP-5 or diesel fuel, benzene concentrations will be very low and off-gas may not require any treatment. However, at sites contaminated with JP-4 or gasoline, the concentration of benzene in the bioslurper vapor discharge may be higher than regulatory limits allow; thus, vapor treatment would be required.

In general, local or state regulatory agencies can waive permitting and vapor treatment requirements for short-term pilot tests. When waivers cannot be obtained, there are several vapor treatment options. The following sections describe vapor treatment options used with the bioslurper system.

3.3.4.1 Reinjection/In Situ Biodegradation of Vapor Emissions. In situ bioremediation of the bioslurper vapor emissions may be the most cost-effective and environmentally sound treatment option. This treatment technology consists of the reinjection of hydrocarbon vapors into the subsurface where they are remediated in situ via aerobic biodegradation (biofiltration). If vapor treatment is required, reinjection of vapors should be considered as one of the primary treatment options. Regulatory approval may be required for vapor reinjection.

Vapor reinjection can be accomplished as follows. Results of the soil gas survey must indicate that the contaminated soil at the site is oxygen-limited to ensure that the site is biologically active. An existing vent well or monitoring well could be identified for use as the vapor injection well. If no existing well is available, a vent well should be installed using hand-auguring. The vapor discharge stack needs to be plumbed to the injection well. A pressure gauge, a pitot tube flow indicator, and a vapor sampling port should be installed in line between the vapor stack and the injection well. After the connections to the injection well have been made, a short-term air injection test should be conducted to ensure that the proper flow rate can be maintained.

At sites with low-permeability soils, vapor reinjection may require the use of additional reinjection wells and/or a secondary blower to boost injection pressure. In this case, vapor reinjection of the vapor discharge may be impossible.

3.3.4.2 Carbon Treatment. Activated carbon vapor treatment is a proven technology for removing petroleum hydrocarbon constituents from a vapor stream. At sites where it is determined that reinjection of vapors is not feasible or permitted, activated carbon generally is used as the vapor treatment technique for short-term pilot testing.

Typically when activated carbon is used for vapor treatment, two 200-lb carbon canisters (Carbtrol Model G-1, or equivalent) are plumbed in series to the bioslurper vapor discharge stack (Figure 5). A pressure gauge is placed on the vapor discharge stack, and vapor sampling ports are placed before, between, and after the two carbon canisters. The discharge line from the second canister is fitted with a pitot tube flow indicator.

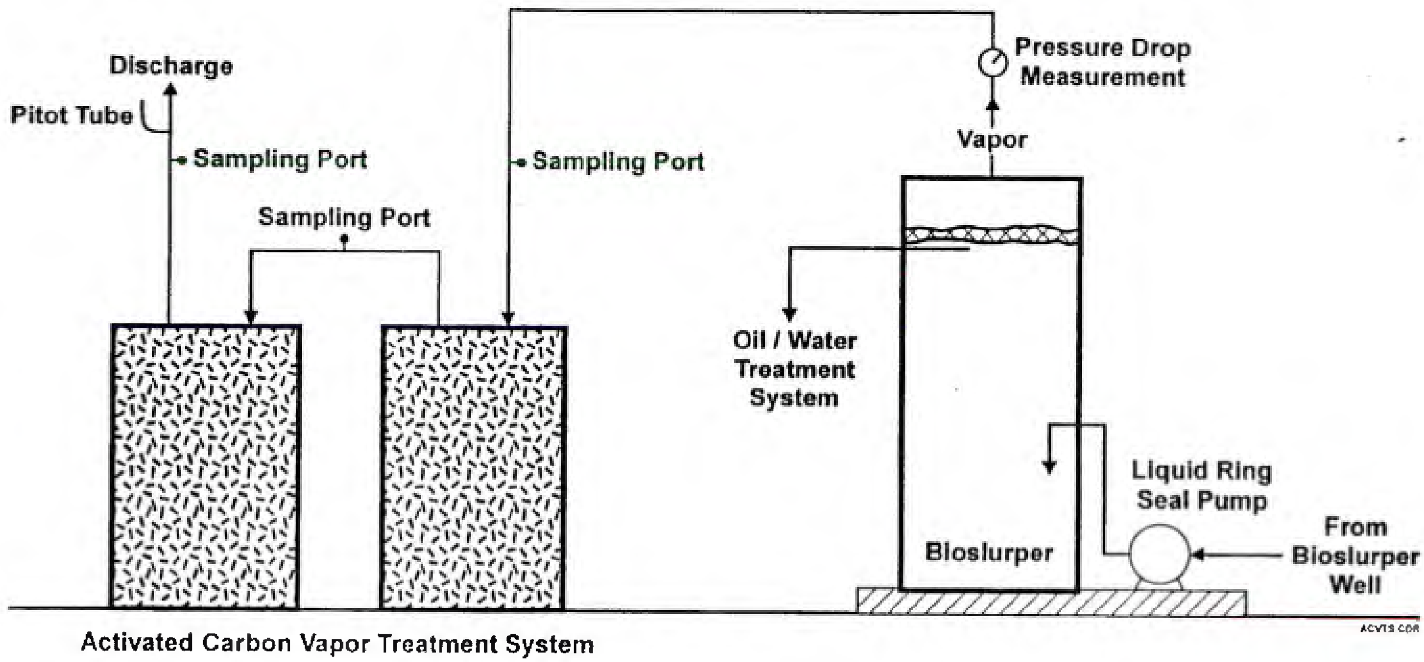

Figure 5. Setup of the Activated Carbon Vapor Treatment System

After the bioslurper system has been started, vapor concentrations should be monitored in the discharge piping ahead of the carbon canisters, between the carbon canisters, and at the discharge from the second carbon canister. Monitoring may be conducted using a field hydrocarbon detector (GasTech Model TraceTector™, or equivalent) calibrated versus a 50-ppm hexane standard. If hydrocarbons are detected in line between the two canisters, a third canister should be added to ensure that no breakthrough occurs.

3.3.4.3 Destruction in an Internal Combustion Engine. The third vapor treatment alternative is an internal combustion engine (ICE). The ICE is a modified automobile engine with a special carburetor that allows it to operate using the petroleum hydrocarbons in the extracted soil gas as the fuel source. ICE technology has been permitted for hydrocarbon vapor treatment in several states, including California. ICE systems are capable of running solely on hydrocarbon vapors if the volatile organic carbon (VOC) concentrations are high enough. If vapor concentrations are not sufficient to fuel the ICE, then a makeup fuel, such as natural gas or propane, will be required to ensure complete combustion of the contaminants. Because of the cost of using makeup fuels, use of the ICE unit may be cost-effective only at sites with gasoline or AVGAS contamination (i.e., high-volatility fuels). When the ICE unit is selected for use in vapor treatment at a site, the air intake of the trailer-mounted ICE unit (RSI, Inc. Model S.A.V.E., or equivalent) is plumbed directly to the bioslurper system vapor discharge stack. The ICE system should be operated according to the manufacturer's specifications. ICE vapor discharge concentrations may be monitored using a Horiba engine analyzer, Model MEXA-53AGE, or equivalent.

Section 4.0: PILOT TEST IMPLEMENTATION

Initiation of the bioslurper field pilot test can begin after completion of the site characterization and system installation phases. This section describes the pilot test implementation and data evaluation procedures. If no existing wells can be used for bioslurper pilot tests, baseline measurements, including soil characterization and a soil gas survey as described below, should be performed to determine the optimum location for the bioslurper test well.

4.1 Mobilization and Baseline Measurements. Bioslurper systems are constructed for quick and easy transport. The system components are generally mounted on a mobile flatbed trailer. Prior to initiating the free-product recovery tests, baseline field data must be gathered and recorded. Parameters that are collected include soil gas concentrations, initial soil gas pressures, depth-to-groundwater, and LNAPL thickness measurements. Furthermore, ambient soil, atmospheric temperatures, and other weather conditions (i.e., rain, snow, etc.), should be noted.

4.1.1 Soil Sampling and Analysis. Soil samples should be collected across the capillary fringe and analyzed for physical characteristics and the presence of organics. The soil organic analyses will indicate the contaminant constituents (BTEX and TPH) present in the subsurface. Physical properties of the soil will assist in formulating the design of the demonstration system by identifying how well air would be expected to move through the soil profile. In addition, groundwater and soil gas may be screened for BTEX and TPH. These concentrations can be tracked especially during large-scale remediation, to show the extent of remediation.

Soil samples may be collected with a 2-in.-inside-diameter (ID) ´ 6-in.-long split-spoon sampler containing brass sampling sleeves. All attempts should be made to collect two soil samples from a single borehole across the capillary fringe to evaluate the chemical/physical properties at the test site. Following collection of the soil samples, the sleeves should be sealed with inert caps, labeled, sealed in plastic bags, and placed in insulated boxes or coolers. The coolers will also contain dry ice or precooled Blue Ice™ to maintain a low enough temperature for sample preservation. Recommended analyses for the samples include particle size distribution, bulk density, porosity, moisture content, BTEX, and TPH. The analytical methods and relevant sampling information are summarized in Table 2.

4.1.2 Soil Gas Survey. When sites are lacking a suitable existing well, a soil gas survey should be conducted to find an optimum location for installation of the bioslurper well and the soil gas monitoring points. Ideally, the bioslurper well and soil gas monitoring points will be located in soils containing measurable hydrocarbon contamination where the oxygen is depleted and the carbon dioxide levels are elevated. If at least three monitoring point screens are not located in the most contaminated soils, the in situ aeration/respiration test may not provide adequate information on oxygen utilization rates resulting from biodegradation. Refer to Section 3.2.2 for installation procedures of soil gas monitoring points.

Soil gas sampling can be conducted using small-diameter (3-in.-OD) stainless steel probes (KVA Associates or equivalent) with a slotted well point assembly. A soil gas survey can be conducted using hand-driven gas probes primarily at sites with relatively shallow groundwater where soils are penetrable to a depth of within 5 ft of the water table. The maximum depth for hand-driven probes typically is 10 to 15 ft, depending on the soil texture. In some dense silts or clays, penetration of the soil gas probe is less, whereas in some unconsolidated sands, deeper penetration may be possible. At a given location, the probe should be driven (manually or with a power hammer) to a

Table 2. Sampling and Analytical Methods

Analysis	Method	MDL[a]	Container	Sample Size	Preservation	Holding Time
Soil Samples						
Particle Size Distribution[b]	ASTM D422	NA	Brass sleeve, polyethylene or glass container	200 g	Cool, @ 4EC	180 days
Bulk Density[b]	ASTM D4531	NA	Brass sleeve, polyethylene or glass container	200 g	Cool, @ 4EC	28 days
Porosity[b]	ASTM D2434	NA	Brass sleeve, polyethylene or glass container	200 g	Cool, @ 4EC	28 days
Moisture Content[b]	ASTM D2216	NA	Brass sleeve, polyethylene or glass container	50-300 g	Cool, @ 4EC	28 days
BTEX	EPA 8020/624/8240	10 µg/kg	Brass sleeve	100 g	Cool, @ 4EC	14 days
TPH (as JP-4)	EPA Mod. 8015/5030	10 mg/kg	Brass sleeve	100 g	Cool, @ 4EC	14 days
Soil Gas						
BTEX	EPA TO-14 (Modified)	0.1 ppmv	Summa Canister	1-L canister	NA	30 days
TPH	EPA TO-14 (Modified)	0.1 ppmv	Summa Canister	1-L canister	NA	30 days
Groundwater Samples						
BTEX	EPA 602	1 µg/L	Borosilicate glass, VOA vials	3 H 40-mL vials	HCl to pH <2, @ 4EC	14 days
TPH	EPA Mod. 8015/5030	0.5 mg/L	Borosilicate glass, VOA vials	3 H 40-mL vials	HCl to pH <2, @ 4EC	14 days
Light, Nonaqueous-Phase Liquid (optional)						
BTEX	EPA Mod. 8020	100 mg/L	Glass vial with Teflon™ septum or lined cap	5-10 mL	Cool, @ 4EC	14 days

(a) MDL = method detection limit.
(b) Particle size distribution, bulk density, porosity, and moisture content can be derived from the same oven-dried soil sample.
NA = not applicable.
ppmv = parts per million by volume.
VOA = volatile organic analysis.

depth determined by preliminary review of the site characterization/contamination documents. Soil gas at this depth should be analyzed for oxygen, carbon dioxide, and total hydrocarbons. The probe then may be driven deeper, for additional soil gas measurements. For a typical site with a depth to groundwater of 9 ft, soil gas will be measured at depths of 2.5 ft, 5 ft, and 7.5 ft.

The main criterion for selecting a suitable bioslurper pilot test location is the existence of oxygen-limited microbial activity. Under such conditions, the oxygen level is generally low (usually 0 to 2%), carbon dioxide is high (typically 5 to 20%, depending on soil type), and the hydrocarbon vapor content in the soil gas will be high (> 10,000 ppmv). An uncontaminated location may also be located to be used as an experimental control to monitor background respiration of natural organic matter and inorganic sources of carbon dioxide. Typical oxygen and carbon dioxide levels at an uncontaminated site are 15 to 20% and 1 to 5%, respectively. The hydrocarbon vapor content in the soil gas of an uncontaminated site generally is below 100 ppmv.

Prior to sampling, soil gas probes should be purged with a sample pump. To determine adequate purging time, soil gas concentrations should be monitored until the concentrations stabilize. This may not always be possible, particularly when shallow soil gas samples are being collected, as atmospheric air may be drawn into the probe and produce false readings. When shallow soil gas samples are collected, air withdrawal will be kept to a minimum. Figure 6 shows a typical setup for monitoring soil gas.

4.1.3 LNAPL Thickness and Groundwater Level Measurements. The depth to groundwater and apparent thickness of LNAPL in site wells can be measured with an oil/water interface probe (ORS Model #1068013 or equivalent). The interface probe distinguishes between polar and nonpolar fluids in the well. The probe gives a solid tone when it encounters a nonpolar liquid (LNAPL) and a constant beep when it encounters a polar liquid (water). The probe lead is a 50- to 200-ft measuring tape marked at 0.01-ft increments.

In addition to the baseline measurements, the depth to groundwater and product thickness may be monitored in wells adjacent to the bioslurper well during the bioslurper testing. If there are no existing wells, one or more wells may be constructed, as necessary. Figure 7 depicts the system that has been used by Battelle to install an oil/water interface probe in a site monitoring well with a vacuum-tight well seal. Product thickness and depth to groundwater at subsurface soil pressures in situ should be monitored during the pilot test. In order to measure the product thickness and water levels in situ the oil/water interface probe is threaded through a section of clear 1-in. PVC, which is fitted to a specialized well seal. The probe is placed in the well at the top of the liquid layer (LNAPL or groundwater) and sealed tightly at the wellhead. The sanitary well seal has a Teflon™ gasket that seals the PVC to the well seal. Teflon™ is self-lubricating, so the PVC tubing can be moved up and down in the well without short-circuiting to the atmosphere.

4.1.4 Baildown Tests. After the depth to groundwater and the initial LNAPL thickness have been determined, the rate of LNAPL recovery may be determined via baildown testing. Simple baildown tests can be conducted on all site wells that have LNAPL present at the time of pilot test initiation. In these tests, a clean Teflon™ bailer (bottom filling) is lowered into each well to collect any floating LNAPL. The LNAPL is removed from the well and poured into a graduated cylinder to determine its volume. Efforts should be made to minimize the volume of water removed from the well, and bailing should cease when the measurable thickness of LNAPL in the well cannot be further significantly reduced (confirmed with the oil/water interface probe).

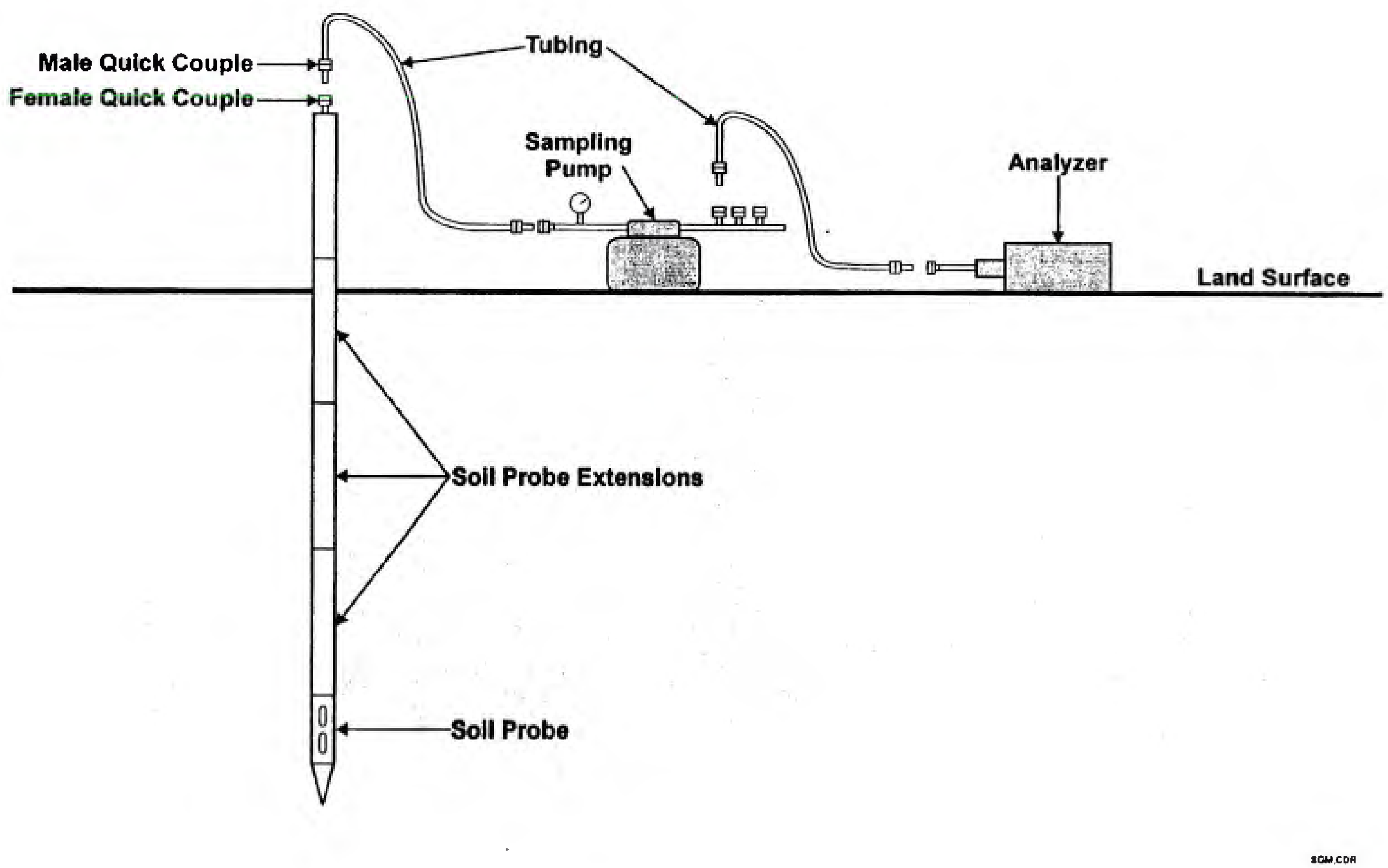

Figure 6. Typical Setup for a Soil Gas Monitoring Point

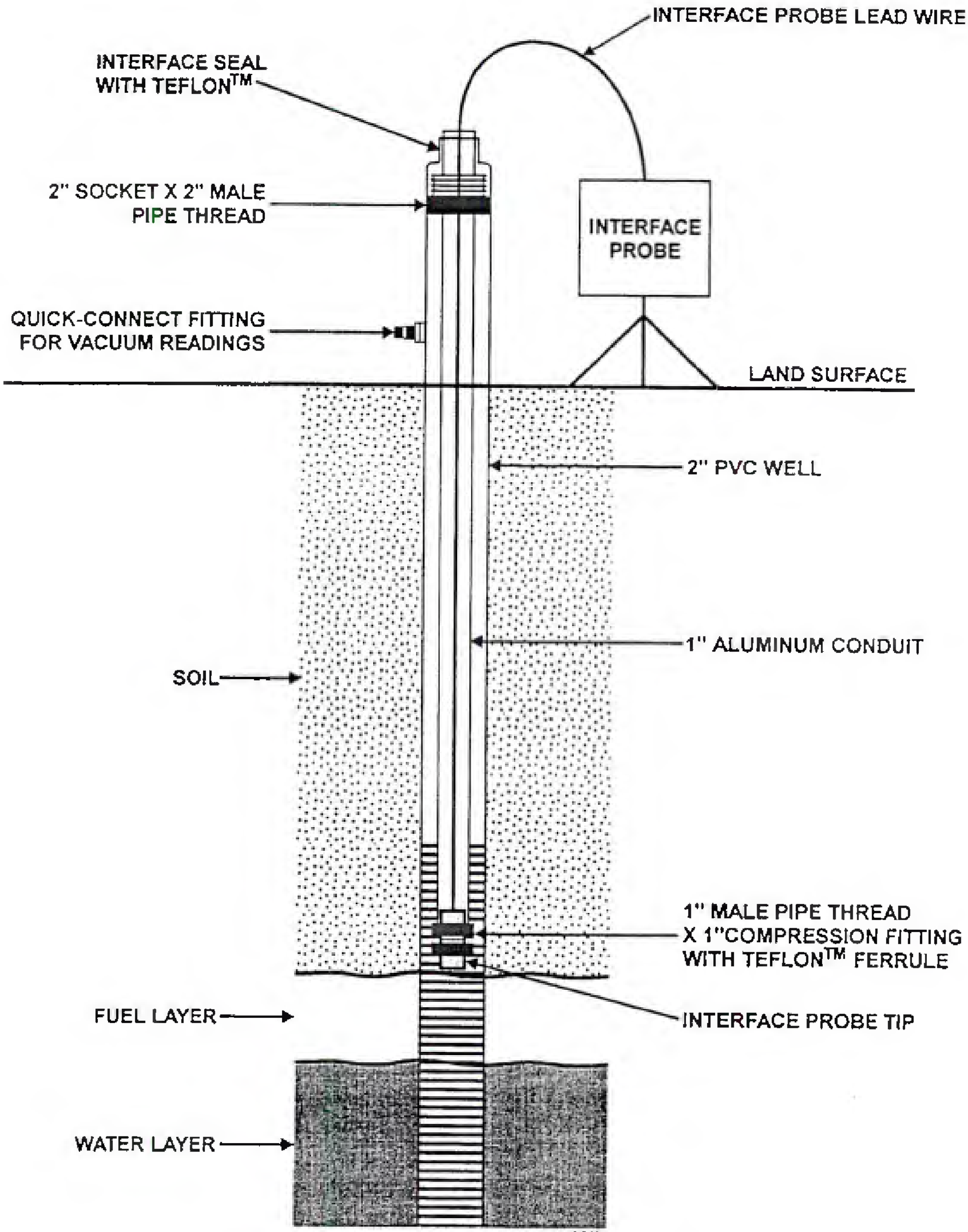

Figure 7. Diagram of the In Situ Interface Probe Setup

Baildown test wells are monitored periodically using the oil/water interface probe to determine the rate of LNAPL recovery. Measurements may be taken every hour for 2 hours, then every 2 to 4 hours for a maximum of 24 hours. Measurements can be made more frequently if LNAPL recovery is rapid or less frequently if recovery is very slow. Data should be recorded on a baildown test record sheet (Figure 8).

4.2 System Shakedown. A brief startup test should be conducted to ensure that all system components are operating properly. Components to be checked include the liquid ring pump; aqueous effluent transfer pump; vapor, fuel, and water flowmeter; oil/water interface probes; soil gas analysis instrumentation; emergency shutoff float switches in the OWS and the effluent transfer tank; and any vapor/effluent treatment system components. A checklist is provided in Figure 9 to document the system shakedown.

4.3 Bioslurper System Startup

4.3.1 Bioslurper Extraction Test. When the baildown test is complete, initial soil gas pressures will be taken at all soil gas monitoring points and from any site monitoring wells fitted with the vacuum-tight oil/water interface probe. The ball valve at the extraction wellhead should be closed to begin bioslurping (Figure 10).

4.3.2 Bioslurper Radius of Influence. The bioslurper radius of influence is estimated by measuring the pressure change versus distance from the vent well and plotting the log of the pressure versus the distance from the vent well. The radius of influence is defined as the distance at which the curve intersects a pressure of 0.1 in. of water. Determining the radius of influence in this manner is quick and can be accomplished in the field.

4.3.3 In Situ Aeration/Respiration Testing. After the bioslurper test has been completed, the soil gas will be measured for oxygen, carbon dioxide, and total hydrocarbon. Soil gas may be extracted from the contaminated area with a soil gas sampling pump system similar to that shown in Figure 6 or using the soil gas monitoring system discussed previously. Typically, the soil gas is measured at 2, 4, 6, and 8 hours and then every 4 to 12 hours, depending on the rate at which the oxygen is utilized. If oxygen uptake is rapid, more frequent monitoring will be required. If it is slower, less frequent readings will be acceptable. Soil gas sampling for in situ respiration testing generally lasts for 2 days. The temperature of the soil before air injection and after the in situ respiration test should be recorded.

At shallow monitoring points, there is a risk of pulling in atmospheric air during purging and sampling. Also, excessive purging and sampling may result in erroneous readings. There is no benefit in oversampling, and when sampling shallow points, care should be taken to minimize the volume of air extracted. In these cases, a low-flow extraction pump operating at 2 to 4 ft^3 per hour may be used. Field judgment is required at each site in determining the sampling frequency. Table 3 provides a summary of the various parameters that will be measured. The in situ respiration test can be terminated when the oxygen level is about 5%, or after 2 days of sampling.

4.4 Process and Site Monitoring. The objective of process and site monitoring is primarily to estimate the mass of hydrocarbons removed in the free phase (LNAPL), aqueous phase (dissolved in groundwater), and vapor phase (gaseous), and to determine enhanced microbial activity in terms of oxygen utilization. A typical format for data collection during the pilot tests is given in Figure 11. (Note: This figure does not include the format for soil gas data recording.)

Baildown Test Record Sheet

Site: ____________________

Well Identification: ________________

Well Diameter (OD/ID): ____________________

Date at Start of Test: __________ Sampler's Initials: ____

Time at Start of Test: __________

Initial Readings

Depth to Groundwater (ft)	Depth to LNAPL (ft)	LNAPL Thickness (ft)	Total Volume Bailed (L)

Test Data

Sample Collection Time	Depth to Groundwater (ft)	Depth to LNAPL (ft)	LNAPL Thickness (ft)

Figure 8. Typical Baildown Test Record Sheet

Checklist for System Shakedown

Site: ______________

Date: ______________ Operator's Initials: ________

Equipment	Check if Okay	Comments
Liquid Ring Pump		
Aqueous Effluent Transfer Pump		
Oil/Water Separator		
Vapor Flowmeter		
Fuel Flowmeter		
Water Flowmeter		
Emergency Shut off Float Switch Effluent Transfer Tank		
Analytical Field Instrumentation GasTector™ O_2/CO_2 Analyzer TraceTector™ Hydrocarbon Analyzer Oil/Water Interface Probe Magnehelic Boards Thermocouple Thermometer		

Figure 9. Bioslurper Pilot Test Shakedown Checklist

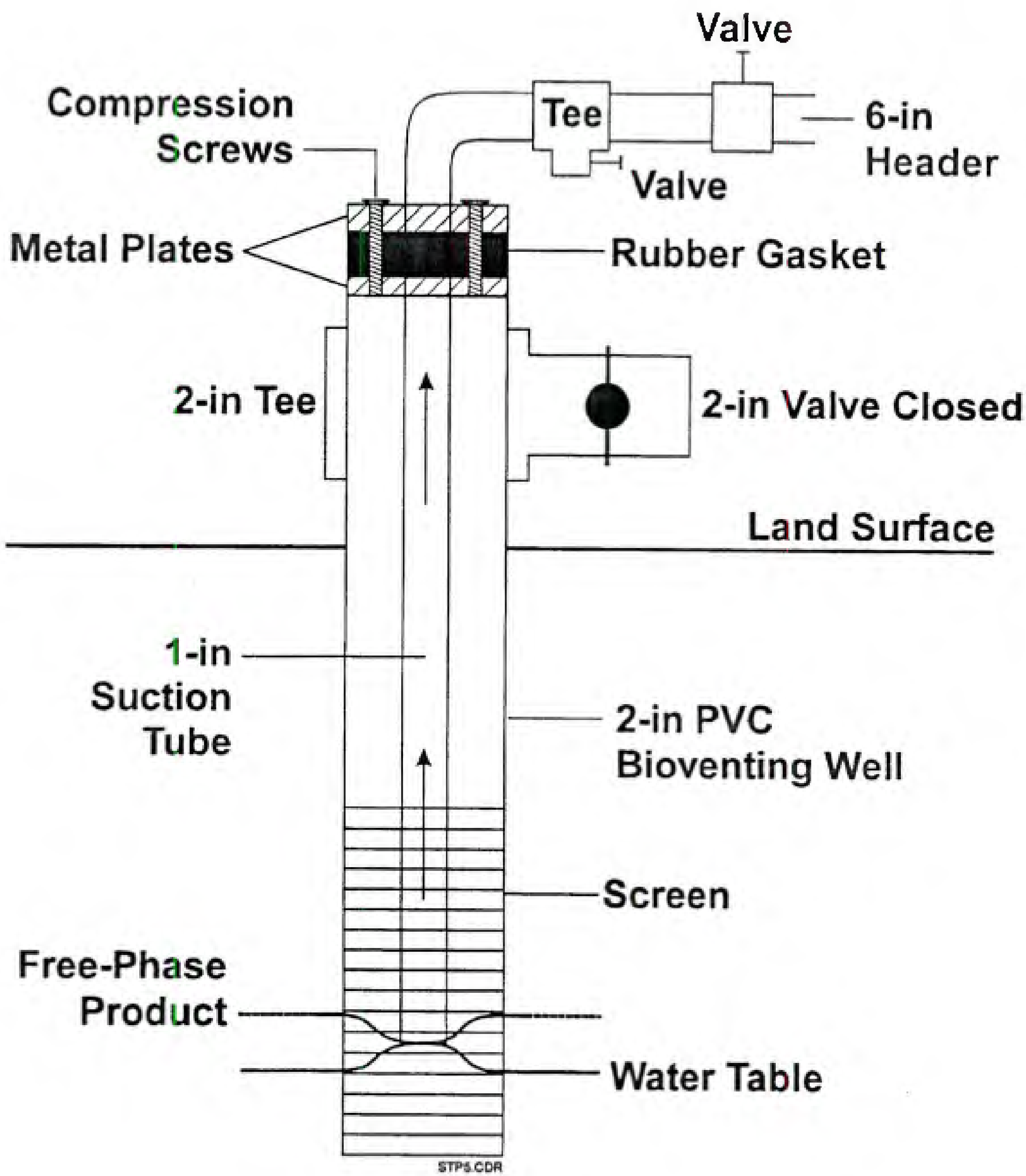

Figure 10. Slurper Tube Placement for the Bioslurper LNAPL Recovery Test

Table 3. Parameters to Be Measured for the In Situ Respiration Tests

Parameter/Media	Suggested Method	Suggested Frequency	Instrument Sensitivity (Accuracy)
Carbon dioxide/soil gas	Infrared adsorption method, GasTech Model 32520X (0 to 5% and 0 to 25% carbon dioxide)	Initial soil gas sample before pumping air, immediately after pump shutoff, every 2 hours for the first 8 hours, and then every 8 to 10 hours	0.2%
Oxygen/soil gas	Electrochemical cell method, GasTech Model 32520X (0 to 21% oxygen)	Same as above	0.5%
Total hydrocarbons (THC)/soil gas	GasTech hydrocarbon detector or similar field instrumentation	Initial soil gas sample before pumping air, then same as above if practical	1 ppm
Helium (optional)	Marks Helium Detector Model 9821 or equivalent	Same as for carbon dioxide	0.01%
Pressure	Pressure gauge (0 to 30 psia)	Reading taken during air injection	0.5 psia
Flowrate/air	Flowmeter	Reading taken during air injection	cfh

Biosluring Pilot Test
(Data Sheet 1)
Well Characteristics

Page ___ of ___

Site: ________________

Test Type (skimmer, bioslurper vacuum extraction, drawdown): ________________

Depth to Groundwater: ________ Depth to Fuel: ________ Depth of Slurper Tube: ________

Date at Start of Test: ________

Time at Start of Test: ________

Operator's Initials: ________

Date/Time	Well ID:			Well ID:			Well ID:		
	LNAPL Level	Water Level	Pressure (in H_2O)	LNAPL Level	Water Level	Pressure (in H_2O)	LNAPL Level	Water Level	Pressure (in H_2O)

Figure 11. Typical Record Sheets for Bioslurper Pilot Testing

Bioslurping Pilot Test
(Data Sheet 2)
Pilot Test Pumping Data

Page ____ of ____

Site: ______________________ Start Date: __________

Operators: __________________ Start Time: __________

Test Type: __________________ Well ID: __________

Depth to Groundwater: ________ Depth to Fuel: ________ Depth of Tube: ________

Date/Time	Run Time	Vapor Extraction: Stack Pressure (in. H_2O)	Vapor Extraction: Carbon Drums (in. H_2O)	Vapor Extraction: Flowrate (scfm)	Pump Stack Temp (°C)	Pump Head Vacuum (in. Hg)	Extraction Well Vacuum (in. H_2O)

Figure 11. Typical Record Sheets for Bioslurper Pilot Testing (Continued)

Bioslurping Pilot Test
(Data Sheet 3)
Fuel and Water Recovery Data

Page ____ of ____

Site: ____________________ Start Date: __________

Test Type: ________________ Operators: ____________________

Date/Time	Run Time	LNAPL Recovery (volume collected in time period)	Groundwater Recovery (volume collected in time period)

Figure 11. Typical Record Sheets for Bioslurper Pilot Testing (Continued)

4.4.1 Vapor Discharge Sampling and Analysis. At least two vapor samples for laboratory analysis should be taken for process monitoring during the bioslurper pilot test and analyzed for BTEX and TPH. Table 2 describes the vapor sampling and analysis methods. These samples are collected by connecting an evacuated 1-L, Summa polished air-sampling canister to the bioslurper vapor discharge stack. Prior to connecting the canister to the sampling line, a vacuum pump should be used to pull vapor from the bioslurper stack to ensure that the sample line is flushed with a representative vapor sample. Following flushing, the evacuated canister is connected to the sampling line, the valve is opened, and a vapor sample is pulled from the bioslurper discharge stack. The vacuum is displaced with the vapor sample until atmospheric pressure is reached. The vacuum/ pressure on each canister will be confirmed for each sampling event to ensure that the canister was received in an evacuated state and was completely filled during sampling.

4.4.2 Aqueous and LNAPL Effluent Analysis. At least two aqueous effluent samples should be collected from the bioslurper oil/water separator discharge during the pilot tests. The samples should be collected without leaving any head space in the 40-mL borosilicate glass volatile organic analysis (VOA) vials used for sample collection. The pH of the aqueous effluent samples should be adjusted with hydrochloric acid to a value of <2 to stabilize the organic species. The vials should be labeled, stored at 4°C, and shipped with the proper chain-of-custody forms for analyses. Analytical methods and relevant sampling information are summarized in Table 2.

LNAPL samples are to be collected from the bioslurper well immediately following the baildown test. A Teflon™ bailer is recommended for collecting a sample from the organic layer that recharges the well during the baildown test. The organic samples are transferred to glass vials, headspace free (5 mL to 10 mL), that are fitted with Teflon™-lined caps. No preservation is necessary for these samples. The vials should be labeled and shipped inside an outer shell to protect them from breakage or spillage. A sorbent material should also be used to package the vials inside the shell. These samples should be shipped either separately or in tightly sealed containers so that they do not compromise the nature of the other soil, groundwater, and soil gas samples. The analytical method and relevant sampling information are presented in Table 2.

4.4.3 LNAPL Recovery Rate/Volume. LNAPL will be transferred from the small holding tank on the pilot test trailer to a larger holding tank on the ground. LNAPL may be pumped with a hand-operated drum pump, and the recovery volume should be quantified using an in-line flow-totalizer meter calibrated in gallons.

During the pilot-scale bioslurper tests, the following procedure is recommended to monitor LNAPL recovery rates. LNAPL recovery volumes should be measured every 30 minutes for the first 2 hours of the test, every 2 hours for the next 10 hours, then every 12 hours until the test is complete. This procedure will make it easier to differentiate the initial slug of LNAPL recovered during the start of each test from sustainable LNAPL recovery.

4.4.4 Vapor Discharge Volume. The volume of vapor discharge can be quantified using a pitot tube (Annubar Flow Characteristics Model #HCR-15) flow indicator. The pitot tube is connected to a differential pressure gauge calibrated in inches of H_2O. The flowrate in cfm is determined by referencing the differential pressure to a flow calibration curve. The volume of vapor discharge can be calculated based on the average flowrate in cubic feet per minute (cfm) and the hours of operation. The mass of hydrocarbons extracted in the vapor phase will be based on the average concentration of the two vapor samples taken (see Section 4.5) and the volume of soil gas extracted.

4.4.5 Groundwater Discharge Volume. The groundwater extraction volume can be quantified using an in-line flow totalizer meter calibrated in gallons. The mass of petroleum hydrocarbons removed in the aqueous phase will be calculated based on the results of the effluent analysis (see Section 4.5) and the discharge volume.

4.4.6 Soil Gas Monitoring. Soil gas monitoring should be performed every 24 hours during the pilot tests. This in situ sampling is used to determine how the oxygen, carbon dioxide, and TPH concentrations vary with time. In addition, results of the in situ respiration test performed during the bioslurping tests will be used to estimate the oxygen utilization rate (see Section 4.5). The results are reported in percent oxygen utilized/day and can be used to estimate the mass of petroleum hydrocarbons biodegraded in mg/kg year. Using *n*-hexane as a representative compound for TPH, a stoichiometric equation describing hydrocarbon degradation may be presented as

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O$$

Based on this equation, on a weight basis, approximately 3.5 g of oxygen is required for every 1 g of hydrocarbon consumed. Therefore, the hydrocarbon degradation rate is approximately 0.29 times the oxygen utilization rate.

4.5 Data Reduction and Results Interpretation. Data and information collected during the pilot-scale tests should be evaluated to (1) determine the feasibility/effectiveness of bioslurping for source removal and site remediation, and (2) develop the approach for construction and implementation of full-scale bioslurping. Because of the limited experience in large-scale applications of this innovative technology, it has not yet been established how well the pilot test data correlate with the performance data of full-scale systems. The following sections present information on how the pilot test data can be used to develop a full-scale bioslurper system. As performance data from full-scale systems become available, such information can be used to develop bioslurper design criteria and to optimize the bioslurper operations.

4.5.1 Soil Characterization. By comparing the remedial objectives or appropriate cleanup goals with the levels of TPH and BTEX present in soil, the remedial investigator will be able to identify the areas of contamination (i.e., distribution of LNAPL) and estimate the quantity of soil requiring remediation. Also, based on the measured free-product thickness and soil characteristics, the volume of recoverable LNAPL can be roughly estimated. In addition, groundwater characteristics, such as hardness and turbidity, should be used to establish baseline conditions and to identify remedial needs based on the site-specific cleanup objectives. Soil physical characteristics are also important to understand how effective the bioslurping technology would be in remediating the site. Soils with high clay content may be difficult to aerate due to the inability to move air through the soil, particularly where the moisture levels are high. Similar restrictions would affect the migration and recovery of free product by bioslurping. Therefore, sites with high clay content may require more closely spaced bioslurper wells. Furthermore, extra time will be required for source removal and remediation of these soils.

4.5.2 Soil Gas Survey. The purpose of gathering soil gas data before the bioslurper pilot tests are performed is to locate areas where the addition of oxygen will most efficiently enhance fuel biodegradation. Low soil gas oxygen concentrations (e.g., $<5\%$) give a preliminary indication that bioslurper-induced aerobic biodegradation of fuel hydrocarbons is feasible at the site and that it is appropriate to proceed to bioslurper pilot testing. If the soil gas oxygen concentrations are high (>5 to 10%), yet contamination is present, other factors may be limiting biodegradation. The most common limiting factors are low moisture levels and high concentrations of TPH and BTEX (i.e., >10,000 ppmv).

Based on the results of the soil gas survey, the pilot test wells should be located where the oxygen concentrations are the lowest. For full-scale applications, it is useful to determine the entire aerial extent and depth of soils with an oxygen deficit (for practical purposes, less than 5% oxygen). However, the physical removal of LNAPL can occur independent of the biodegradation component of bioslurping, and vice versa.

4.5.3 LNAPL Distribution and Baildown Tests. LNAPL thickness and groundwater level measurements are used to select the locations of the bioslurper wells and determine the lengths of the bioslurper tubes, extraction wells, and screens. The bioslurper well(s) for the pilot test generally are installed at a location representative of the site characteristics with regard to LNAPL thickness, soil/soil gas contamination, and soil properties. A full-scale bioslurper well network should encompass primarily the area with free product with possible extension over the areas with light soil contamination (for remediation by bioslurper-induced venting and bioventing).

Baildown test results are used as baseline fuel recovery information. For example, the recovery rate in the pilot test well may be compared with the recovery rates during the implementation of the bioslurper tests.

4.5.4 Bioslurper Radius of Influence. In general, a higher vacuum can be created during the pilot tests because only one or two bioslurper wells will be used for these studies. During full-scale applications, the vacuum in the extraction system is expected to be low due to the soil gas flow from a large number of wells. Consequently, the bioslurper radius of influence during full-scale bioslurper application could be less than that observed during the pilot testing. Therefore, the full-scale system installation must be installed with a larger pump to achieve the radius of influence found during the pilot-scale testing (Section 4.3.2).

4.5.5 Bioslurper Extraction Tests. Bioslurper extraction pilot tests generate much of the information required to develop a full-scale system, such as the LNAPL recovery rate, groundwater discharge rate, composition of groundwater, limitations or potential concerns in separating oil from extracted groundwater (e.g., oil/water emulsion), vapor discharge volume and rate, and composition of vapors in the off-gas stream. All this information is required in sizing the full-scale system (e.g., pump capacities, sizing the oil/water separators and holding tanks) and determining the need for pretreatment of the extracted oil/water stream and for treatment of the off-gas stream or groundwater effluent. Data generated during the pilot studies can also be used for discharge permit applications, if permitting is required. If the off-gas stream and/or groundwater effluent requires treatment, composition and flow data should be provided to the appropriate vendors (e.g., GAC vendors) or component suppliers (e.g., ICE unit suppliers) to obtain sizing, performance data, and cost information for the full-scale treatment units.

4.5.6 In Situ Aeration/Respiration Testing. During the bioslurper pilot test, the soil gas composition is measured at the soil monitoring points. Along with the information on pressure radius of influence, soil gas data can be used to determine whether the oxygen levels and/or carbon dioxide levels have increased, indicating bioslurper-mediated aeration and/or enhanced microbial activity in the area of influence.

When the bioslurper extraction tests have been completed, the in situ respiration test can be performed. The soil gas data collected over time (after shutdown of the bioslurper test) can be used to establish the rates of oxygen utilization or carbon dioxide evolution. High oxygen utilization rates (e.g., >1%/day) are a good indication that bioslurper-mediated aeration would effectively improve microbial activity. If the oxygen utilization rates are low, yet significant contamination is present, other factors such as high clay content, low moisture content, nutrient limitation, and/or contaminant levels toxic to microorganisms may result in limiting biodegradation. Site-specific variables affecting microbial degradation should be identified to determine whether the conditions can be improved to implement enhanced bioremediation.

Section 5.0: DEVELOPMENT AND INSTALLATION

Upon completion of the feasibility testing, if it is found that the bioslurper system is a viable method of recovering the LNAPL and simultaneous in situ biodegradation of hydrocarbons in the vadose zone, then the full-scale bioslurper system can be installed. The full-scale system consists of extraction wells, piping/manifolds, valves, vacuum gauges, monitoring points, pumps, and an OWS. The following sections give a general description of the materials and equipment required to construct the full-scale system.

5.1 Extraction Wells. Proper well spacing is important to ensure that the optimum free-product recovery is achieved and that the entire site receives an oxygen-rich supply of air for enhanced in situ biodegradation of fuel hydrocarbons in the vadose zone. Additionally, the capital costs associated with full-scale implementation are directly related to proper well spacing (see Appendix A). The grid spacing of the wells is dependent primarily on the radius of influence. The radius of influence is based on the extent of the distribution of vacuum in the subsurface and is used to determine the well spacing. The recommended well spacing is such that half the distance between any two adjoining wells should not exceed the bioslurper radius of influence. Following are several specifications for constructing the full-scale bioslurper wells (see Section 3.1 for more details and Figure 2 for a typical bioslurper well):

1. The recommended diameter of the bioslurper wells is either 2 or 4 in., depending on the ease of drilling and the area and depth of the free-product plume (see Figure 2).

2. The bioslurper well may be constructed of schedule 40 PVC and should be screened with slot sizes in the range of 0.006 to 0.010 in.

3. Hollow-stem auguring is the recommended as the drilling method. Whenever possible, the diameter of the annular space should be at least two times greater than the vent well outside diameter and should be filled with silica sand or equivalent while being sealed from above with bentonite or grout (Figure 2).

4. The 1-in. PVC suction tube is sealed with a rubber gasket with metal plates (Figure 2). A soil gas monitoring port may be installed on the tube outside the well along with a valve.

The wells are connected to a central manifold by a series of pipes and tubing. Generally a main line is connected from the liquid ring pump to the manifold and secondary feeding lines are plumbed to groups or rows of wells as shown (Figure 12). Each main line or secondary line can be fitted with a valve, in line, so that one row of wells can be run at a time. At most sites a main line of 4-in. PVC pipe and secondary lines of 1-in. PVC pipe are adequate. The network of piping can be run aboveground or subsurface, depending on the site logistics and construction permits.

5.2 Extraction/Treatment/Disposal System. The system components/equipment associated with the extraction system generally include liquid pumps, pressure/vacuum gauges, valves, and pipes. Components of the treatment system primarily include an oil/water separator (OWS), holding tanks, and flowmeter. Depending on the characteristics of the fuel/water emulsion, some pretreat-

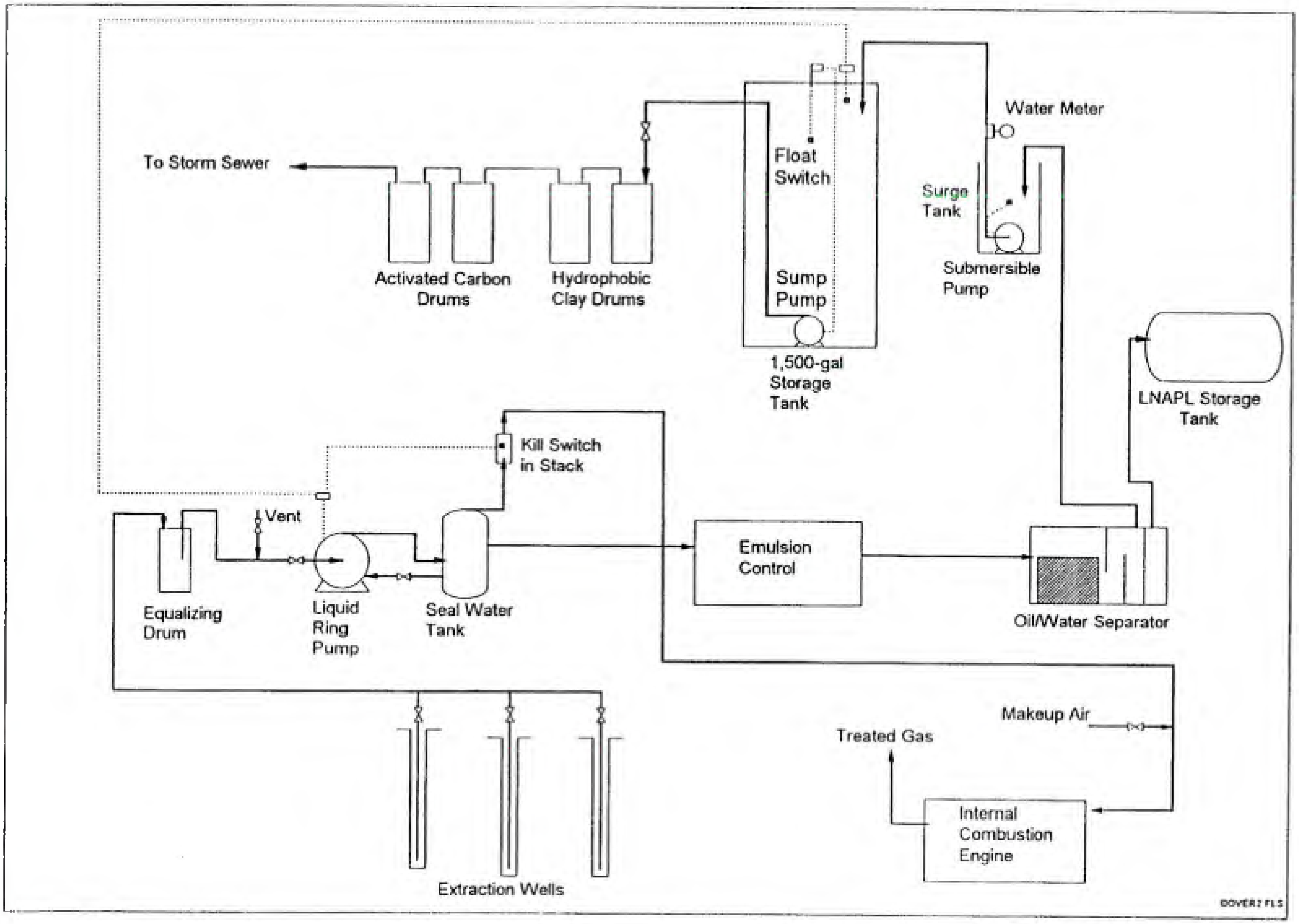

Figure 12. Schematic of an Extraction/Treatment System to Treat an Oil/H_2O Emulsion

ment by passing the emulsion through the holding tanks or through bag filters may be required to improve the performance of the OWS.

The bioslurper system generates both a point source vapor emission and an aqueous discharge. Petroleum hydrocarbon constituents will be present in each discharge at a rate in pounds per day (lb/day) related to the fuel type and the extraction rate. Depending on the discharge rate of petroleum contaminants in the off-gas, it may be treated to meet the regulatory requirements or discharged directly to the atmosphere with regulatory approval. The mass of hydrocarbons released to the environment as dissolved in the aqueous phase is expected to be lower than the mass released as vapors in the off-gas. Thus, the bioslurper aqueous effluent may be discharged to the sanitary sewer with prior approval from the regulatory authorities.

In some instances, the vapor and/or the aqueous effluent will require treatment before discharge, primarily due to the presence of benzene, which is present in relatively high concentrations in AVGAS and gasoline. Local/state regulatory requirements should be investigated prior to designing the treatment system.

5.2.1 Pumps. Liquid ring pumps are typically used to extract the fuel from the bioslurper wells. In addition, effluent transfer pumps may be required to facilitate the discharge of water separated from fuels.

5.2.1.1 Liquid Ring Pumps. Liquid ring pumps are generally recommended as bioslurper pumps because they have efficient pump curves (i.e., pump performance remains relatively uniform even at vacuums as high as 29 in. Hg), and they are total fluid pumps which are presumably explosion-proof. Varying conditions will require the use of different pump sizes at different sites. The use of multiple pumps at larger sites may also be required. The different liquid ring pump sizes available are 3 horsepower (hp), 5 hp, 7.5 hp, and 10 hp (Atlantic Fluidics Models A20, A75, A100, and A130, respectively). The pump size will depend on the number and the depths of the extraction wells. In general, a 10-hp pump can supply the necessary vacuum to about 30 bioslurper wells. However, if the contaminated soils are low in permeability, additional pumps will be required to achieve the ideal vacuum conditions.

5.2.1.2 Effluent Transfer Pump. The aqueous effluent from the OWS generally gravity-drains into an effluent transfer tank. A float-switch-activated transfer pump can be used to discharge the effluent to the appropriate receiving points. As discussed above, at some sites, groundwater may have to be pumped through a water treatment system (e.g., activated carbon canisters) prior to discharge. Effluent transfer pumps have a shelf life of more than three years and should serve adequately as fluid transfer pumps during the course of remedial activities.

5.2.2 Oil/Water Separator (OWS). The bioslurper system generates a liquid stream consisting of a mixture of LNAPL and groundwater. In most cases the LNAPL can be effectively separated from the aqueous phase by passing the liquid discharge stream through a gravity oil/water separator (OWS). Battelle uses a Megator Corp. OWS. The size and capacity of the OWS depend on the number of wells and the amount of liquid being extracted from the wells. For instance, a 10-gpm OWS may be sufficient for a site with 30 extraction wells, but a 20-gpm, or a 40-gpm OWS may be required at a larger site. The different OWS sizes available are 10-gpm, 20-gpm, 40-gpm, 60-gpm, 120-gpm, and 240-gpm. Recovered LNAPL gravity-drains into a small holding tank. Extracted groundwater gravity-drains into an effluent transfer tank.

If a fuel/water emulsion is expected or present, there are some pretreatment methods available. One method is the placement of bag filters ahead of the OWS. Another is to place a filter tank prior to the OWS. The filter tank should be equipped with the appropriate filter media (e.g., furnace filters, fiber filters, etc.) to remove any solid emulsion that is formed during fuel recovery operations. It will be necessary to change the filter used to ensure that fuel and water can flow freely through the system to prevent liquid backup and subsequent system shutdown. During pilot-scale testing it will be determined whether additional filter mechanisms are necessary to remove fuel/water emulsion formation for the full-scale installation.

5.2.3 Free Product Collection/Disposal. The LNAPL collected from the OWS can be placed in a storage tank until proper disposal of it is necessary. The LNAPL can be recycled for use in machinery; alternatively, arrangements should be made with a contractor for recycling, use for an alternative energy source, or disposal.

5.3 Monitoring Points. Soil gas monitoring points are used for pressure and soil gas sampling during full-scale testing. Generally, they should be positioned to allow monitoring of the in situ changes in soil gas composition caused by the bioslurper system. The recommended positions for the monitoring points are to place the majority within the bioslurper radius of influence, and to have two or three points outside the zone of influence as background points. It is most efficient if the points are placed between a set of four wells (Figure 13) and/or in highly contaminated soils within the free-product plume. At large sites, soil gas monitoring points can be placed more sparsely to avoid excessive data collection and reduce installation costs. The construction of the soil gas monitoring points for the full-scale system is the same as the construction of monitoring points for the pilot-scale testing (Section 3.2).

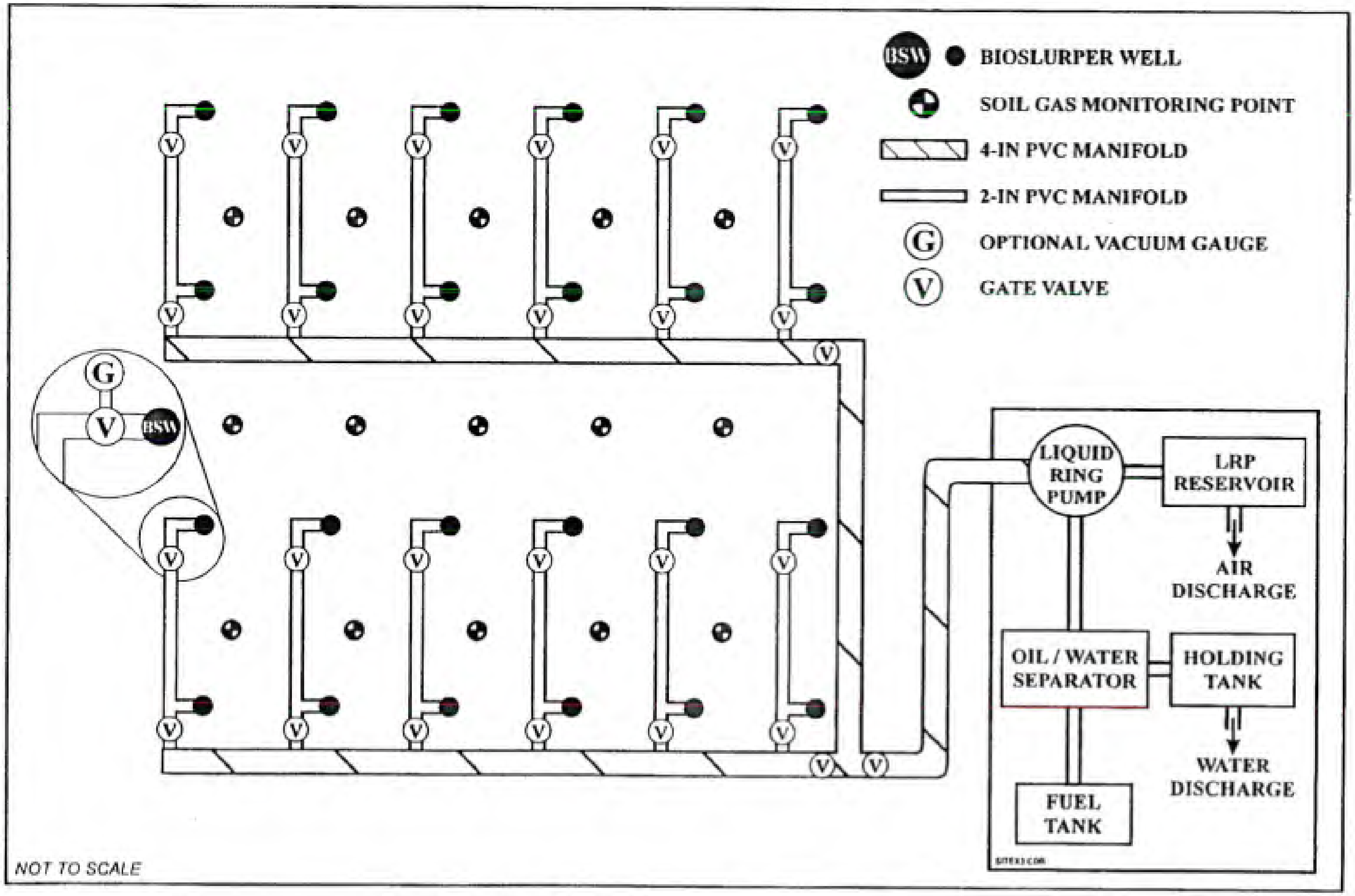

Figure 13. Schematic Layout of a Typical Full-Scale Bioslurper System

Section 6.0: SYSTEM OPERATION AND PERFORMANCE MONITORING

The operation of a bioslurper system generally starts with a shakedown test. Following system shakedown, the system is operated over a few days or even a few weeks under different configurations to determine effective operating conditions. System performance should be monitored closely during this initial stage, as well as during continuous operation.

A file containing the following items should be developed and made available at the site: (1) operating procedures for different equipment/system components, (2) equipment calibration procedures and frequency, and (3) health and safety plan.

6.1 System Operation. Prior to operation in continuous mode, a thorough startup/shakedown test is conducted to ensure that all system components are operating properly and that there are no leaks in the system. Components to be checked include the valves; pressure/vacuum gauges; liquid ring pump; aqueous transfer pump; vapor, fuel, and water flowmeter; oil/water interface probes; soil gas analysis instrumentation; emergency shutoff float switches in the OWS and in the effluent transfer tank; and any vapor/effluent treatment system components. A typical shakedown checklist is given in Figure 9.

Following shakedown, the baseline data for the site are collected. These data include the LNAPL thickness and depth to the groundwater table at each bioslurper well and the soil gas parameters including oxygen, carbon dioxide, and TPH. Then the openings of the bioslurper suction tubes at each well are placed at the LNAPL/water interface. The system is started by gradually opening all the valves at the wellhead seals. If the vacuum in each well is low (e.g., less than 5 feet of water vacuum), it may be necessary to operate only a few bioslurper wells at a time. Provision of adequate vacuum is required to ensure (1) effective pumping of LNAPL from the wells to the treatment system, (2) creation of a vacuum gradient that extends up to the radius of influence to promote LNAPL flow toward the bioslurper well, and (3) aeration of larger areas.

Sections of the well system can be operated sequentially over a 1- to 2-day period while other sections are shut down. The duration of the operating cycles will depend on the fuel recovery rates.

At locations where water table fluctuations are minimal or the soils have moderate to low permeability, it is likely that the vertical position of the slurper tube can essentially remain unchanged. However, in areas with high water table fluctuations, especially in high-permeability soils, the slurper tube may have to be adjusted from time to time to improve the fuel recovery and minimize the volume of groundwater extracted.

The length of time for remediation of soils using the bioslurper technology is difficult to estimate, but it is expected to be considerably shorter than the time required for remediation by conventional technologies such as skimming or drawdown pumping. Preliminary short-term test data suggest that the LNAPL recovery rate by bioslurping is over 5 times higher than the rate by skimming. The LNAPL thickness and recovery data collected during the operation of the system should be evaluated frequently to decide what areas served by the bioslurper wells have been effectively remediated, so that some wells can be closed and the extraction can be limited to those wells with residual LNAPL. By closing a particular well to the system, vadose zone soils will still be aerated by the surrounding wells, and the vacuum applied to the remaining wells will be increased. Before complete shutdown of the system, it is advisable to wait for a few weeks and sample the wells for free product. In addition, if soil remediation is not complete, the system should be switched over to run in the "bioventing" mode.

6.2 Performance Monitoring. During operation of the full-scale system, it is recommended that monitoring/analysis of the following be conducted:

- Vapor discharge
- Aqueous and LNAPL discharge
- LNAPL recovery volume/rate
- Vapor and groundwater discharge rates
- Aeration/respiration monitoring
- LNAPL levels and recovery rates in bioslurper wells.

Procedures and equipment used for the above analyses/measurements are given in Section 4.0 and Table 2. The frequency of analysis or measurement has to be determined on the basis of data needs. For example, requirements for measuring the vapor discharge rate and for groundwater analysis may be governed by applicable permits. Measurements of oxygen and carbon dioxide at soil gas monitoring points would indicate the effectiveness of aeration and microbial activity.

When the LNAPL extraction rates (as measured at the oil/water separator discharge) decrease, the system may be shut down and the rate of LNAPL recovery into the bioslurper wells measured. In addition, as the LNAPL thickness equilibrates, LNAPL levels should be measured to evaluate how the bioslurper system operation should be modified. For example, bioslurper treatment should be continued at wells with high recovery rates and/or comparatively high LNAPL, whereas treatment at wells with no LNAPL may be discontinued. The performance monitoring can be site specific and the operation and monitoring plans should be developed to meet the site-specific needs.

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APPENDIX A

BIOSLURPING IMPLEMENTATION COST-ESTIMATING GUIDE

CONTENTS

FIGURES

TABLES

Bioslurping Implementation
Cost-Estimating Guide

Section 1.0: INTRODUCTION

This bioslurping implementation cost-estimating guide is designed to provide reasonably accurate cost estimates of the application of bioslurping technology for the purposes of comparing costs to other feasible technologies. This guide is outlined according to the steps that would be followed to install, operate, and maintain a bioslurping remediation system. Each section has a descriptive text portion, a table of components and associated costs, and example calculations to estimate the costs of performing the described activity. The following topics are presented in Section 2.0:

- Construction of Mobile Pilot Unit (Section 2.1)
- Pilot-Scale Installation and Testing (Section 2.2)
- Full-Scale Installation and Testing (Section 2.3)
- Operations and Maintenance (Section 2.4).

Section 3.0 presents other costs associated with environmental remediation projects. Conclusions are stated in Section 4.0, and bibliographic data for references cited are presented in Section 5.0.

Section 2.0: BIOSLURPING INSTALLATION, OPERATIONS, AND MAINTENANCE

2.1 Construction of Mobile Pilot Unit

2.1.1 Description. Bioslurping field components typically are mounted on a flatbed trailer. Often site logistics are such that it is impossible to keep components in close proximity to the affected soils. By utilizing the mobile pilot unit bioslurper system, all field components and materials associated with the bioslurper can be kept up to 200 feet from the contaminated area. In addition, by having the bioslurper field components in a mobile pilot unit, they can be transported quickly and easily from one contaminated site to another. This approach to trailer construction minimizes the costs associated with field mobilization and implementation, and is essential to the overall cost effectiveness of the bioslurping technology.

2.1.2 Table of Components and Costs. Table A-1 presents the items mounted on the trailer that are used to conduct bioslurping at a contaminated location and the cost of each unit that is built onto the trailer.

2.1.3 Options. As can be seen in Table A-1, some of the components that are utilized on the bioslurper trailer are optional. The total cost to construct a bioslurper mobile trailer unit without any of the optional components is $30,175. This is the initial capital cost associated with implementing bioslurper technology. When all the optional system components and discharge filters are needed to utilize the bioslurping technology, the total capital cost to construct the mobile pilot unit is $34,432. When the internal combustion engine (ICE) is used as the off-gas treatment system, the total capital cost is $82,276. In the event that a local power source is not available, it will be necessary to equip the mobile pilot unit with a generator to supply the power required to run the bioslurper components. If connections to a local power source can be made, the capital cost to build the trailer can be maintained at the costs listed.

2.1.4 Calculation The following equation is the calculation for the total trailer cost to construct the bioslurper system with all the required and optional components and materials.

$$\mathbf{TT = Lr + Mr + Mo_1 + Mo_2\ (or\ Mo_3)} \quad (1)$$

Lr	=	Labor required to construct system trailer	=	$9,600
Mr	=	Materials required to construct system trailer	=	$20,575
Mo_1	=	Materials optional - Water treatment	=	$2,107
Mo_2	=	Materials optional - Off-gas treatment	=	$2,150
Mo_3	=	Materials optional - ICE off-gas treatment	=	$49,994
TT	=	**Total costs to construct mobile unit.**		

Through Construction of Mobile Pilot Unit the total costs (w/out options) are:

BIOM = TT = $ 30,175

Any one or all of the optional components can be included or excluded in the total trailer construction costs as required by site-specific requirements. When the ICE is used as the off-gas treatment for bioslurper emissions, it can augment the power needed to run the bioslurper system. The capital cost associated with the ICE unit is very high; however, the ICE is sometimes the most viable treatment option for the off-gas emissions. Site conditions and emissions regulations will dictate if the ICE should be used as the treatment option.

2.2 Pilot-Scale Installation and Testing

2.2.1 Description. The overall objective of pilot-scale installation and testing is to determine the feasibility of LNAPL recovery and the efficacy of full-scale bioslurping for LNAPL recovery. The approach of the pilot-scale installation and testing is to initiate pilot-scale bioslurping and to identify the variables that are critical in determining full-scale bioslurping feasibility. These variables include the rate of FPR, the ratio of FPR to extracted groundwater, the FPR radius of influence (the radius from which free product is mobilized to the bioslurper well), and the efficiency of the system to oxygenate subsurface soils.

If existing groundwater monitoring wells have been found to contain free product, the existing wells can be used to complete the pilot-scale testing of the bioslurping technology. However, if the information from the pilot-scale testing shows that the monitoring wells identified are unusable, it will be necessary to construct a groundwater monitoring well. Monitoring wells are required to measure the rate at which LNAPLs recharge and are made available for recovery. This is a critical test required to determine bioslurping feasibility. Soil gas monitoring points are used to assess whether bioslurping technology is efficient in cleaning the affected area. Soil gas samples collected from these monitoring points can be analyzed to give an indication of the level of residual-phase contamination remaining in the soil, and are collected during respiration tests in order to determine the rate of biodegradation occurring in the vadose zone. If existing soil gas monitoring points are not present at the site, it will be necessary to install three soil gas monitoring points in the affected area for the pilot testing. Table A-2 contains the costs associated with installing the necessary groundwater monitoring well and the soil gas monitoring points for pilot-scale testing.

The field materials required to examine the variables that are critical to successful implementation of a bioslurping operation are presented in Table A-3. These materials will be used again to examine the effectiveness of bioslurping operations during the full-scale implementation of the technology.

Any required permits must be obtained prior to implementing the pilot-scale installation and testing of the bioslurper technology. Typically, a digging permit is required whenever ground will be broken. Additionally, many locations will require that both water and air discharge permits be issued to operate a pilot-scale or full-scale bioslurper system. In the State of California, a site investigation permit must be issued before undertaking investigation activities at a contaminant site. Reasonable estimates of the air and water discharged by the bioslurper system can be made from soil gas and water contaminant measurements prior to test initiation (Battelle, 1995). The analytical results from the pilot-scale testing are used for the full-scale system discharge estimates.

Table A-1. Mobile Unit Construction Components and Costs

	Mobile Unit Components	Unit	Cost	Number	Total Cost	Vendor
Lr	Labor to Construct Bioslurper System	hr	$60.00	160	$9,600.00	Battelle
Mr	Trailer, Breaks, & Spare Tire	each	$1,954.00	1	$1,954.00	Rock's Trailer
	10-hp Liquid Ring Pump & Seal-Tank	each	$8,516.00	1	$8,516.00	Atlantic Fluidics
	10 gpm Oil/Water Separator	each	$3,544.00	1	$3,544.00	RC Olson
	210-gal Emulsion Tank w/cover	each	$583.04	1	$583.04	U.S. Plastics
	500-gal Polyethylene Storage Tank	each	$690.22	1	$690.22	U.S. Plastics
	Digital Flow Totalizer	each	$222.50	1	$222.50	Grainger
	Annubar Flow Sensor	each	$220.00	1	$220.00	W.R. Frew
	Sump Pump	each	$92.86	3	$278.58	Grainger
	Hand Pump	each	$106.65	1	$106.65	Grainger
	Gasoline Hose (3/4" X 12')	each	$36.00	1	$36.00	Grainger
	Camlock Fittings Part M+ F 1-1/2"	set	$16.34	15	$245.10	Pipe Valves
	Piggyback Float Switches	each	$30.60	5	$153.00	Grainger
	2" Transporter Tank Hose	per/ft	$3.67	225	$825.75	Fournier Rubber
	Level Control Switch	each	$34.35	3	$103.05	Grainger
	Quick-Connect Plugs	each	$6.41	10	$64.10	Forberg
	PVC 2" Ball Valve and Tee	each	$45.37	2	$90.74	Pipe Valves
	PVC 2" Coupler sch 40	each	$3.25	4	$13.00	U.S. Plastics
	PVC 2" Pipe sch 40	per/ft	$0.70	50	$35.07	U.S. Plastics
	Clear Pipe, Excelon	per/ft	$2.04	5	$102.00	U.S. Plastics
	Wellhead Seal, 4" OD, 2" ID	each	$28.40	2	$56.80	Boundary Waters
	K-type Thermocouple Plug M+ F	set	$5.56	4	$22.24	Instrument Lab
	Thermocouple Wire (type K) 125'	roll	$62.83	1	$62.83	L.H. Marshall
	Pressure Gauge 0-30 psi	each	$20.00	1	$20.00	Cole-Parmer
	Vacuum Gauge (high) 0-30" H_2O	each	$192.85	1	$192.85	Cole-Parmer
	Vacuum Gauge (low) 0-10" H_2O	each	$192.85	1	$192.85	Cole-Parmer
	Magnehelic Gauge 0-0.25" H_2O	each	$54.00	1	$54.00	Dwyer
	Magnehelic Gauge 0-0.50" H_2O	each	$47.00	1	$47.00	Dwyer
	Magnehelic Gauge 0-2.0" H_2O	each	$47.00	1	$47.00	Dwyer
	Magnehelic Gauge 0-10" H_2O	each	$47.00	1	$47.00	Dwyer
	Male Connector 68PL-4-2	each	$1.31	10	$13.10	Forberg
	Male Connector 4MSC4N-B	each	$1.52	10	$15.20	Forberg
	Qck-cnct F X 1/4" tube	each	$12.10	10	$121.00	Forberg
	Std Brass Valve Tags 1.5" Blk Flld	each	$1.30	1	$1.30	Seton
	Nylon Tubing 1/4" (natural)	50' pk	$19.25	50	$962.50	Cole-Parmer
	500-gal Steel Tank	each	$937.00	1	$937.00	Trombold Eqpt
Mo_1	1,500-gal Polyethylene Storage Tank	each	$825.98	1	$825.98	U.S. Plastics
	55-gal Drum Activated Carbon	each	$496.00	2	$992.00	Carbtrol
	PVC Check Valve 2"	each	$79.14	2	$158.28	U.S. Plastics
	1-1/2" Transporter Tank Hose	per/ft	$3.28	30	$98.40	Fournier Rubber
	Camlock Fittings Part M+ F 1-1/2"	set	$16.34	2	$32.68	Pipe Valves
Mo_2	55-gal Drum Activated Carbon	each	$496.00	4	$1,984.00	Carbtrol
	1-1/2" Transporter Tank Hose	per/ft	$3.28	30	$98.40	Fournier Rubber
	Camlock Fittings Part M+ F 1-1/2"	set	$16.34	4	$65.36	Pipe Valves
Mo_3	Internal Combustion Engine (ICE)	each	$49,994.00	1	$49,994.00	RSI International

(a) Terms in this column are defined on page A-2.

Table A-2. Pilot-Scale Test Drilling Task Costs

Pilot Test Drilling Task Description	Unit	Unit Cost
Mobilization to Site	L.S.	$400.00
6-1/4" HAS Drill	ft	$12.00
4-1/4" HAS Drill	ft	$7.00
4" PVC Screen	ft	$7.00
4" PVC Riser	ft	$5.50
4" PVC Slip Cap and Plug	set	$25.00
2" PVC Screen	ft	$5.00
2" PVC Riser	ft	$4.00
2" PVC Slip Cap and Plug	each	$15.00
Sand	bag	$9.00
Bentonite	bag	$12.50
Concrete mix	bag	$7.60
Hole Plug	bag	$14.00
Well Installation	hour	$100.00
Decontamination	hour	$100.00
Steam Cleaner Rental	day	$75.00
Steel Drums	each	$25.00
Per Diem	day	$130.00
Cost/ft Drilled for Monitoring Wells	$/ft + $100/well	$29.50/ft
Cost/ft Drilled for Soil Gas Points	$/ft + $100/point	$23.00/ft

PVC is polyvinyl chloride.

2.2.2 Tables of Components and Costs. Typically, a pilot-scale installation and test will utilize a single groundwater monitoring well and three soil gas monitoring points. Table A-2 is a listing of the costs associated with installing a single bioslurper well with a borehole diameter of 4 inches, and three soil gas monitoring points with borehole diameters of 2 inches. The 4-inch well diameter is used here because it is more expensive, and will yield a higher (more conservative) cost estimate. Depth to contamination is the variable which affects the cost to install bioslurper and soil gas wells. Deeper boreholes result in higher incurred costs for drilling. Examples of cost calculations are shown in Section 2.2.4 of this cost estimator. Table A-3 shows the costs for pilot-scale testing materials and analysis.

2.2.3 Options. The test wells, field materials, and analytical procedures that are required to conduct proper pilot-scale installation and testing are presented in Sections 2.2.1 and 2.2.2. Site-specific conditions drive decisions when dealing with contaminated sites, and details will vary. In most cases, existing monitoring wells with a known history of free product contamination can and should be used. If no suitable monitoring well or soil gas points are present, then the drilling costs associated with installing the needed wells would be incurred.

The bioslurper well must be established to facilitate the extraction of groundwater, free product, and soil gas through the subsurface to remediate the affected area. The well should be located as close to the center of the spill area as possible. The diameter of the bioslurper well can be either 2 or 4 inches and will depend on the ease of drilling and the area

Table A-3. Pilot Test Materials and Analytical Costs

	Pilot-Scale Materials/Analytical	Unit	Unit Cost	Number	Total Cost	Vendor
Lr(a)	Labor required to conduct the installation and testing	hr	$60.00	320	$19,200	Battelle
Mr	Interconnecting nipple hollow Ni pltd	each	$23.00	3	$69.00	KVA Associate
	Jar I-CHEM 250ml	12/case	$36.50	1	$36.50	VRW Scientific
	Jar I-CHEM 500ml	12/case	$44.60	1	$44.60	VRW Scientific
	GasTech GT105 test kit	each	$126.00	1	$126.00	Control Analytics
	Diluter kit OVA purchase	each	$750.00	1	$750.00	Hazco
	3-1/4" Basic soil sampling kit	each	$937.00	1	$937.00	EnviroTech
	Brass sleeves 2"X 6"	each	$2.10	4	$8.40	EnviroTech
	Plastic end caps 2"	each	$0.10	8	$0.80	EnviroTech
	Rotary electric hammer and adapter	each	$1,888.00	1	$1,888.00	KVA
	Soil probe Handi-jack and adapter	each	$301.15	1	$301.15	Battelle
	Interconnecting nipple solid S/S	each	$18.00	3	$54.00	KVA Associates
	Soil gas probe shaft section 3 ft	each	$255.00	4	$1,020.00	KVA Associates
	Thermocouple readout (Fluke 52)	each	$199.00	1	$199.00	Grainger
	GasTech 3250X CO2/O2	each	$3,700.00	1	$3,700.00	Control Analytics
	GasTech 3250X CO2/O2	each	$3,700.00	1	$3,700.00	Control Analytics
	GasTech GT105 O2-TPH	each	$1,548.75	1	$1,548.75	Control Analytics
	GasTech GT105 test kit	each	$126.00	1	$126.00	Control Analytics
	Oil/Water interface probe 100'	each	$1,990.00	1	$1,990.00	ORS Env. Equip.
	Regulator CGA 590	each	$245.00	1	$245.00	Liquid Carbonics
	1/3-HP compressor/vacuum pump	each	$228.00	3	$684.00	Grainger
	Stopwatch	each	$57.00	1	$57.00	Baxter
	Erlenmeyer 250 ml plastic flasks	each	$6.27	4	$25.08	U.S. Plastics
	Tedlar bags	10/box	$82.00	2	$164.00	VWR
	Helium gas cylinder	each	$100.00	1	$100.00	Liquid Carbonics
	Helium detector	each	$4,500.00	1	$4,500.00	Mark Products Inc.
	Tracetechtor, case, & Dilution	each	$2,075.00	1	$2,075.00	Gastech, Inc.
	Carbon dioxide, size s3 10% bal N2	each	$124.00	1	$124.00	Scott Specialty Gas
	Hexane, size s3 4800 in air	each	$124.00	1	$124.00	Scott Specialty Gas
	Oxygen, size s3 110% balance N2	each	$124.00	1	$124.00	Scott Specialty Gas
	Latex tubing 3/16" ID	100'	$45.56	1	$45.56	Baxter
	Plastic Disposable Bailers	each	$20.00	2	$40.00	Boundary Waters
ATr	Analysis- TPH and BTEX (soil)	each	$75.00	4	$300.00	Alpha Analytical
	Analysis - Bulk density (soil)	each	$10.00	4	$40.00	Alpha Analytical
	Analysis - Grain size (soil)	each	$50.00	4	$200.00	Alpha Analytical
	Analysis - Particle density (soil)	each	$50.00	4	$200.00	Alpha Analytical
	Analysis - Soil/Water (ASTM)	each	$14.00	4	$56.00	Alpha Analytical
	Analysis - Total porosity	each	$7.00	4	$28.00	Alpha Analytical
	Analysis - TPH and BTEX (water)	each	$75.00	4	$300.00	Alpha Analytical
	Analysis - TPH and BTEX (off-gas)	each	$135.00	3	$405.00	Air Toxics
	Analysis - TPH and BTEX (fuel)	each	$75.00	2	$150.00	Alpha Analytical
	Analysis - C-range compounds (fuel)	each	$50.00	2	$100.00	Alpha Analytical

OVA = organic vapor analyzer; S/S = stainless steel; TPH = total petroleum hydrocarbons; ID = inner diameter; BTEX = benzene, toluene, ethylbenzene, and xylenes; ASTM = American Society for Testing Materials.
(a) Terms in this column are defined on page A-7.

and depth of the contaminated volume. At most sites a 2-inch-diameter bioslurper well will provide the airflow needed to conduct the required test procedures. In addition, 2-inch-diameter wells cost less to install than the larger 4-inch-diameter wells, and frequently extract groundwater at a lower rate, thereby minimizing any water treatment costs that might be incurred during bioslurping. If a 4-inch-diameter well is desired, the cost of installation will exceed that of a 2-inch-diameter well only by the variable rate to use a larger drill auger. As is the case with the groundwater, free product often can be extracted at a higher rate when a larger-diameter well is employed. Site logistics should dictate what bioslurper well diameter should be used.

The soil gas monitoring point boreholes should be 2 inches in diameter. It is not necessary to drill the borehole any larger than the required 2 inches. For sites with shallow contamination and sandy soils, the soil gas monitoring points can be hand-augured, reducing drilling costs significantly. Additionally, some testing materials listed in Table A-3 are optional, i.e. they are not essential for completion of the pilot-scale testing. The cost of the analytical procedures presented in Table A-3 can be reduced further by limiting the number of tests performed and/or locating a testing facility that has lower costs.

2.2.4 Calculation. The following equation is the calculation of costs for the pilot-scale installation and testing of the bioslurper system.

$$\mathbf{PSI = Lr + Mr + ATr + MWi_o + SGPi_o + DC_o} \quad (2)$$

Lr = Labor required to conduct installation and testing
Mr = Materials required to conduct installation and testing
ATr = Analytical testing required to conduct installation and testing
MWi_o = Optional - Monitoring well installation
= [(Depth of MWs) × (#MWs) × ($/ft drilled)]
$SGPi_o$ = Optional - Soil gas point installation
= [(Depth of SGPs) × (#SGPs) × ($/ft drilled)]
DC_o(*) = Optional - Disposal costs of recovered fuel and extracted H_2O

PSI = Pilot-scale installation and testing costs

Through Pilot-Scale Installation and Testing the total costs are:

$$\mathbf{BIOM = TT + PSI}$$

(*) Disposal costs associated with the pilot-scale installation and testing are site specific. Depending on regulatory requirements and on-site disposal facilities, the DC_o will vary from site to site.

The following is an example problem involving the pilot-scale installation and testing of a bioslurper system at a petroleum-contaminated site and the calculation of costs for this problem.

Example Site X - Pilot-Scale Installation and Testing

The problem involves a fresh diesel fuel spill. The contaminated site is located in an area that has on-site treatment facilities and supplied power sources. It is estimated that the free product comprises about 10,000 gal of fuel over a 2,000-yd^2 area. The work proposal initiated dictates that a short-term bio-slurper pilot-scale installation and test be performed at the site to determine the feasibility of full-scale bioslurping to remediate the site. An existing monitoring well, MW-1, has been identified as having a known history of free-product thickness of 2 to 3 ft, and is in the center of the contaminant plume. It is proposed that this well be utilized to conduct the bioslurper pilot-scale testing. There are no soil gas monitoring points in the area of concern; therefore, three monitoring points will be constructed during the bioslurper installation. The monitoring points will be placed at distances of 5, 20, and 40 ft from MW-1. The regulatory guidelines for this site stipulate that extracted groundwater must be treated to less than 5 mg/L of total petroleum hydrocarbons (TPH) and less than 1 mg/L of benzene prior to release. Additionally, off-gas emissions are not to exceed 100 lb TPH per day. At contaminated sites comparable to this one, off-gas treatment has not been necessary. However, the extracted groundwater will be carbon treated to reduce contamination levels to below the regulatory requirements. Table A-4 details the capital and operating costs to conduct the short-term pilot-scale installation and test.

Table A-4. Example Site X - Pilot-Scale Installation, Testing, Capital, and Operating Costs

(Lr)	Labor cost to conduct the short-term pilot test (two workers/320 hr @ $60/hr)	=	$ 19,200
(Mr)	Materials cost to conduct the short-term pilot test	=	$ 24,807
(GWt,)	Capital cost of water treatment supplies, two 200-lb carbon drums, one 1,500-gal storage tank with accessories	=	$ 2,107
(SGPi,)	Capital cost to install three soil gas monitoring points to a depth of 15 ft [(15 ft)×(3 SGPs)×($23/ft)] + [(3 SGPs)×($100/SGP)]	=	$ 1,335
(ATr)	Capital cost to conduct the analytical testing, on four H_2O, three off-gas, four soil, and two fuel samples	=	$ 1,779
(PSI)	**Pilot-scale bioslurper system installation and testing costs**		**$ 49,228**
(TT)	**Total costs to construct the mobile unit**	+	**$ 30,175**
(BIOM)	**Total costs through the pilot-scale installation and testing stage at example site X**	=	**$ 79,403**

2.3 Full-Scale Installation and Testing

2.3.1 Description. From the data interpretation of the pilot-scale installation and testing, the decision whether to go to a full-scale (multiple bioslurper wells) bioslurping operation will be made. At sites where LNAPL recovery rates are high, usually greater than 1 gallon per day per well, full-scale bioslurping is a viable LNAPL recovery technology. At contaminated sites where full-scale implementation of bioslurping is utilized, the design, placement, and installation of the multiple bioslurper wells are the most critical factors in achieving successful remediation. From the data obtained during the pilot-scale operations, the zone of influence exerted by the bioslurper will be calculated. The radius of influence is the measurement of distance at which one bioslurper well will aerate the contaminated soils and mobilize the free-product and groundwater. To implement full-scale bioslurping, enough bioslurper wells need to be installed to ensure that the zones of influence encompass the entire contaminated area.

Figure A-1 depicts a typical layout of an affected area. R_{max} is the radius of influence calculated during the pilot testing. The bioslurper wells should be placed at a distance of $D \times R_{max}$, where D is the factor required by which the radius of influence is multiplied so that the individual wells' zones of influence overlap each other. D should not exceed the square root of 2 because D values greater than the square root of 2 will result in areas of contamination which are not influenced by the well configuration. The installation of extraction wells is the critical cost factor associated with installing a full-scale bioslurping operation because all materials (i.e. transporter hose, PVC-piping, etc.) used to operate the bioslurper system will be based on the number of wells that are installed. Also, the liquid ring pump size (number of horsepower) is determined by the number of wells installed. With an increasing number of wells, the amount of groundwater that might need to be treated also increases. Therefore, in order to minimize the cost to install the full-scale system, the number of wells installed must be minimized to cover only the contaminated area.

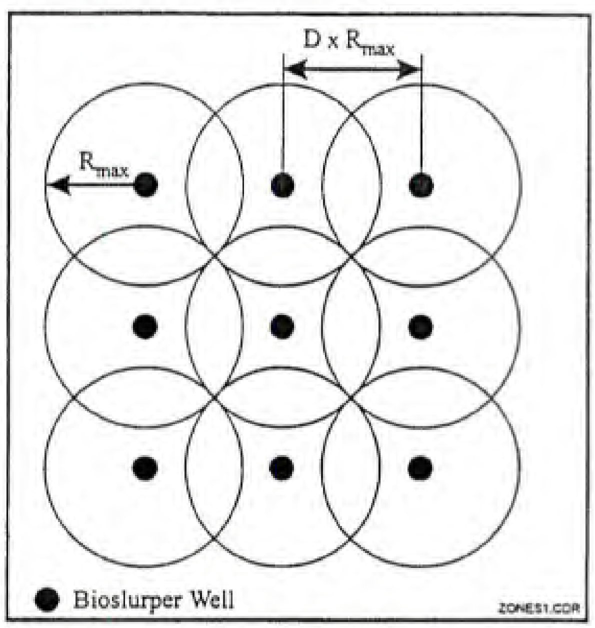

Figure A-1. Typical Layout of Monitoring Wells for Extended Bioslurper Testing

2.3.2 Tables of Components and Costs. Table A-2 in Section 2.2.2 presents the costs associated with drilling. As is the case with the pilot-scale installation and testing, the full-scale installation and operation are site specific. The costs to install the number of wells necessary to cover the entire contaminated area will vary depending on the site conditions and the volume of the contaminated soils and groundwater. The number of soil gas monitoring points to be installed for a full-scale bioslurper operation is dependent on the proximity of the wells to one another. If the radius of influence is high (greater than 50 feet), the number of soil gas monitoring points can be reduced from three per well to two or one per well. The soil gas monitoring points should extend radially out from the center of the plume, and at least two soil gas monitoring points should be located outside the contaminated area to monitor background conditions. Ideally, the number of soil gas monitoring points will be minimized to reduce installation costs. The monitoring points will be placed in such a manner that they will allow the system operators to gather accurate information about the effectiveness of the bioslurping technology to remediate the contaminated soils.

For the full-scale operation of the bioslurper system, the materials necessary to run the system are shown in Table A-3 in Section 2.2.2. The analytical procedures to be used in determining if the bioslurper is remediating the site are also shown in Table 3. The volume of fuel that is being recovered and the analytical test results will determine if bioslurping is remediating the contaminated site.

2.3.3 Options. The overall costs associated with remediating a contaminated site via bioslurping can be cost effective compared to costs for other remediation technologies. The site logistics necessary to substantially reduce capital costs are the availability of on-site-supplied power sources, wastewater treatment or sewage facilities, and off-gas venting of bioslurper emissions. If supplied power is available and treatment components are not required, the capital costs associated with installing a bioslurper system decrease drastically. For example, at a remote site where supplied power resources are unavailable, an electrical generator would need to be obtained, adding significantly to full-scale installation costs. By using on-site treatment facilities and power resources, the capital and operating costs can be reduced to make the bioslurper system the most effective and rapid remediation technology for LNAPL-contaminated plumes.

2.3.4 Calculation. The following is the calculation for the full-scale installation and testing costs. These costs are site specific.

$$\mathbf{FSI = Lr + Mr + ATr + MWi_o + SGPi_o + GWt_o + OGt_o} \qquad (3)$$

Lr	=	Labor required to expand to full-scale installation
Mr	=	Materials required to expand to full-scale installation
ATr	=	Analytical testing required to conduct full-scale installation
MWi_o	=	Optional - Monitoring well installation
	=	[(Depth of MWs) × (#MWs) × ($/ft drilled)]
$SGPi_o$	=	Optional - Soil gas point installation
	=	[(Depth of SGPs) × (#SGPs) × ($/ft drilled)]
GWt_o	=	Optional - Groundwater treatment
OGt_o	=	Optional - Off-gas Emissions treatment

FSI = Full-scale installation and testing costs

through Full-Scale Installation and Testing the total costs are:

$$\text{BIOM} = \text{TT} + \text{PSI} + \text{FSI}$$

The following paragraphs are a continuation of the problem involving the installation of a full-scale bioslurper system at the example petroleum-contaminated site.

Example Site X - Full-Scale Installation

During the pilot-scale testing, oil/water interface probe measurements in the existing monitoring well indicated that approximately 2.5 ft of floating free product is on the groundwater table. The depth to groundwater at the site is 12 ft and the soil is a fine sand with a horizontal hydraulic conductivity of 0.5 m/day. Recovery rates from the pilot-scale testing in the monitoring well mentioned were 1.2 gal/day. It is, therefore, recommended that full-scale bioslurping be implemented to remediate the contamination. The radius of influence of the bioslurper was calculated to be 36 ft. The soil analysis indicated that the soils in the unsaturated zone are smeared with free product (i.e. contain TPH and BTEX in mg/L levels). Figure A-2 depicts the contaminated area with nine installed bioslurper wells and the 21 soil gas monitoring points needed to encompass the entire site. From the water and off-gas emissions data it has been determined that it is not necessary to treat off-gas emissions; however, it will be necessary to treat the water extracted by the system prior to release. Because this is not a remote location, supplied power is available. All the bioslurper wells will be plumbed into a central manifold box, and the vacuum established in each well will be provided by a 10-hp liquid ring pump. Table A-5 presents the capital costs associated with expanding to a full-scale bioslurper system at this example site. The costs of the storage tanks and groundwater treatment materials are included in the materials cost.

Table A-5. Example Site X Installation Costs to Expand the Full-Scale Bioslurper System

(Lr)	Labor cost required to expand to a full-scale bioslurper system (2 workers/ 160 hr total @ $60/hr)	= $ 9,600
(Mr)	Materials cost to expand to a full-scale bioslurper system	= $ 15,222
(MWi$_r$)	Labor and capital cost to install 8 bioslurper wells to a depth of 15 ft [(15 ft)*(8 MWs)*($29.50/ft)] + [(8 MWs)*($100/MW)]	= $ 4,340
(SGPi$_r$)	Labor and capital cost to install 18 soil gas points to a depth of 15 ft [(15 ft)*(18 SGPs)*($23/ft)] + [(18 SGPs)*($100/SGP)]	= $ 8,010
(ATr)	Capital cost to conduct the analytical testing of 12 H_2O, 12 off-gas, 16 soil, and 12 fuel samples	= $ 8,816
(FSI)	**Total labor and capital costs to expand to a full-scale bioslurper system**	**$ 45,988**
(PSI)	**Pilot-scale bioslurper system installation and testing costs**	**+ $ 49,228**
(TT)	**Total costs to construct the mobile unit**	**+ $ 30,175**
(BIOM)	**Total costs through the full-scale installation stage at example site X**	**= $ 125,391**

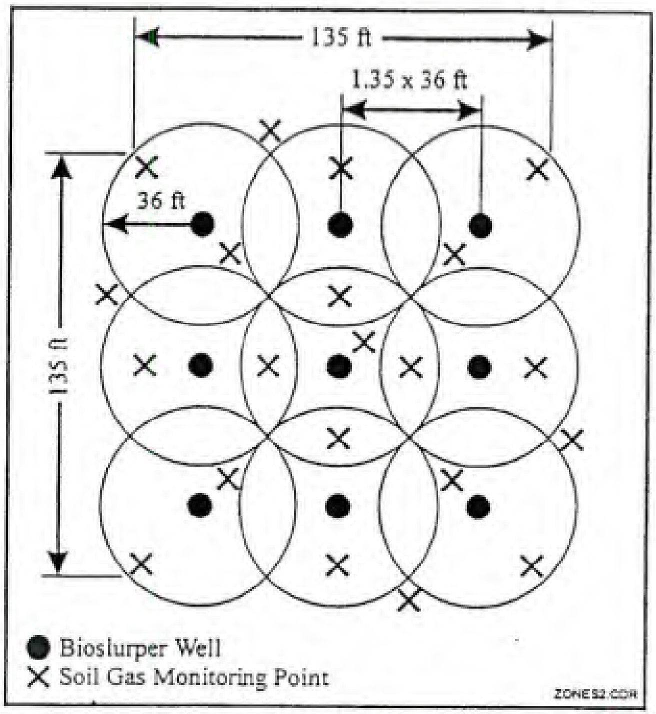

Figure A-2. Monitoring Well and Soil Gas Point Layout for Example Site X

2.4 Operations and Maintenance

2.4.1 Description. The operations and maintenance required to run the full-scale bioslurper system are minimal. The system requires only weekly on-site visits to collect the data critical in analyzing performance. On-site personnel also maintain the system. The personnel will be required to replace and repair any system component that malfunctions and/or fails. The bioslurper system is designed with components that have service lives of approximately 3 years. The liquid ring pump used to establish the vacuum gradient in the bioslurper wells has a service life of approximately 10 years, and should not need to be replaced; however, it may be useful to clean the pump head periodically to maintain the high level of efficiency that the pump needs to create the liquid vacuum. The other equipment components used with the bioslurper system has shorter shelf life and may need to be replaced before the site remediation is completed.

The primary duties of the on-site personnel will be to total the amount of fuel recovered, groundwater extracted, and off-gas emitted to the atmosphere per day. On-site personnel also will be responsible for ensuring that wastewater and off-gas discharges do not exceed any existing regulatory permit allowances.

2.4.2 Table of Operations and Maintenance Guidelines. Table A-6 presents the operational actions and maintenance requirements that on-site personnel will perform during bioslurper operations. The daily on-site involvement of site personnel will not be significant, unless there is a system component failure.

Table A-6. Operational Actions and Maintenance of the Bioslurper System

Frequency	Action
Weekly	Check system components to ensure normal operations Measure and record the fluid levels in each monitoring well Adjust the extraction tubes in each monitoring well to the measured oil/water interface Measure soil gas concentration in each soil gas point Measure water discharge flowrate Measure off-gas discharge flowrate
Monthly	Sample water discharge and ship for analysis Sample off-gas discharge and ship for analysis
As Required	Collect all relevant data to determine if the system is functioning at normal levels (pressures, temperatures) Record fuel recovered during operations and the proper removal of the fuel recovered to the disposal or recycling area

2.4.3 Options. To minimize the costs associated with maintaining the bioslurper system, it is essential that mechanically inclined staff be available on site to identify, replace, and repair any system component malfunctions. It is also important to use technical staff with field expertise to ensure proper data collection of the critical parameters that define the bioslurper's effectiveness in remediating the site. By separating the functions with two staff members, the labor time required for the bioslurper operations and maintenance can be minimized to highly cost-effective levels.

2.4.4 Calculation. The following is the equation used to calculate the total operations and maintenance costs associated with implementing the bioslurper system for extended testing.

$$\mathbf{OMT = Lr + Mr(*) + KWr + DCr} \qquad (4)$$

Lr = Labor required to conduct operations and maintenance
Mr(*) = Materials required to conduct operations and maintenance
KWr = Power required to run the generator and other components
DCr(*) = Disposal and discharge costs required to remove recovered fuel and extracted H_2O

OMT = Total operations and maintenance costs

$$\mathbf{BIOM = TT + PSI + FSI + OMT}$$

(*) Operations and maintenance costs are site specific. They will be based on the total costs incurred with repairing and/or replacing materials associated with maintaining the bioslurper system in a normal operational status and the disposal costs to remove recovered fuel and extracted water.

Referring back to the example problem described in Section 2.3.4, the operations and maintenance costs incurred during the past month of operation in remediating this type of contaminated site are presented in the following paragraph and table. This is not a reflection of every site, and depending on site conditions and system component malfunctions, the monthly operating and maintenance costs will vary.

<u>Example Site X - Operations and Maintenance costs</u>

No instrumentation failures occurred during the first 4 months of system operation. However, during the fifth month of full-scale operation at site X, one wellhead seal cracked and one water tank sump pump failed. Weekly data measurements and analytical samples have been recorded and shipped. The replacement materials were purchased and installed during the weekly routine checkups of the system. During the fifth month of operation, 550 gal of fuel was recovered, and 402,000 gal of water was extracted. The disposal costs for removing fuel from the site are $2.90/gal. From the results provided by the pilot-scale testing at this site it has been determined that the two carbon canisters used in series to treat extracted water will need to be replaced on a monthly basis. Monthly sampling of the discharge water and off-gas emissions will be made to ensure that regulatory guidelines are not exceeded. The system wastewater is pretreated with the activated carbon and discharged at a cost of $5.00/1,000 gal.

Table A-7. Example Site X Monthly Operations and Maintenance Costs

(Lr)	Labor costs required to operate and maintain the bioslurper system (2 workers/32 hr/week @ $60/hr)	=	$ 1,920
(Mr)	Material costs required to operate and maintain the bioslurper system	=	$ 1,114
(DCr)	Disposal and discharge costs required to remove ten 55-gal drums of fuel and discharge 402,000 gal of treated wastewater	=	$ 3,605
(KWr)	Power costs required to operate and maintain the bioslurper system (38,000 kWh/month @ $0.10/kWh)	=	<u>$ 3,800</u>
(OM_m)	**Total monthly operations and maintenance costs at example site X**	=	**$ 10,439**
(OMT)	**Total yearly operations and maintenance costs at example site X**		**$ 125,268**
(FSI)	**Total labor and capital costs to expand to a full-scale bioslurper system**	+	**$ 45,988**
(PSI)	**Pilot-scale bioslurper system installation and testing costs**	+	**$ 49,228**
(TT)	**Total costs to construct the mobile unit**	+	**<u>$ 30,175</u>**
(BIOM)	**Bioslurper installation, operations, and maintenance total costs at example site X**	=	**$ 250,659**

Section 3.0: OTHER COSTS

The cost of implementing a bioslurping system is presented in the previous sections. This section includes approximate costs for other items such as design, work plan preparation, and post-remediation/closure sampling. These costs can vary significantly depending on the site conditions and the local, state, and/or federal regulatory requirements. As such, unit costs presented here should be revised for each site.

3.1 **Design Costs.** The costs associated with designing a bioslurper system vary with factors such as formation heterogeneity, natural and man-made obstacles, climate, and local regulatory requirements. Typically, engineering design costs represent approximately 15% to 20% of the cost of installed system components, however, site-specific complications must be considered. For the example Site X in this document, the expected design costs would be around $19,000 using a design factor of 15%. The calculation is shown in the following equation:

$$\textbf{Design Costs} = [(TT) + (PSI) + (FSI)] \times DF \qquad (5)$$

where TT, PSI, and FSI have previously been defined and DF is the design cost factor, will yield a reasonable estimate that can be increased further by complicating factors at the user's discretion.

3.2 **Documentation Costs.** Documentation costs also will vary greatly with local regulatory agency requirements. Typically, the cost for the preparation of a Health and Safety Plan is about $10,000. Development of a pilot-scale work plan may cost about $10,000. Preparation of a full-scale Remedial Action work plan for regulatory approval may cost approximately $25,000. If a Quality Assurance Program Plan (QAPP) or a Contractor Quality Control (CQC) Plan is required, it usually can be written for $5,000 to $15,000. Project Final Reports describing the methods, materials, data analysis results, and conclusions can be written for $20,000 to $50,000 depending on the scope of the project.

Summarizing, documentation costs can reasonably be expected to vary greatly depending on the local physical and regulatory requirements. For the example Site X described previously, documentation costs are assumed to be $70,000.

3.3 **Site Closure (Sampling and Analysis) Costs.** After routine free product recovery rate and soil gas monitoring results indicate that bioremediation rates and residual contamination concentrations have been minimized, soil samples can be collected and analyzed to demonstrate site cleanup. The number of samples to be collected depends on the site size and heterogeneity as well as the local regulatory requirements. It is assumed that a one-soil-sample-per-50 ft grid over the site will be adequate to characterize the soil at closure. At Site X in the aforementioned examples, the 2,000-yd^2 (18,000-ft^2) site would require approximately 16 soil samples analyzed for TPH and benzene, toluene, ethylbenzene, and xylenes (BTEX) for closure characterization. At a cost of $100 per TPH and BTEX sample (Table 3), the analyses would cost $1,600. Sample collection and shipping costs must be added to this figure. It is assumed that for Site X, $3,000 would cover final soil sample collection and analysis. As already stated, soil formation heterogeneity and local regulatory requirements can increase closure sampling and analysis costs significantly.

3.4 Contingency Costs. It is reasonable to expect that unforeseeable circumstances will arise in any project which may add to the total project cost. Health and safety issues, scope increases, climatic interference, vandalism, regulatory delays, and equipment manufacturing errors are only some examples of factors that can add cost to a well-planned project. To cover these costs, a contingency factor ranging from 10% to 20% typically is used. Again referring to example Site X, assuming a factor of 10%, the contingency cost of the installation, operation, and maintenance would be $25,000.

3.5 General and Administration, Overhead, and Fee. Each contracting company applies these charges to different categories of project costs. The labor rates in this bioslurping costs estimator are assumed to be fully burdened values already containing these fees. Application of other overhead and administrative inflation factors must be computed according to contractor-specific methods.

<u>Example Site X (Summary) - Other Costs</u>

The total cost for implementing bioslurping (installation, operations, and maintenance) at Site X has been determined to be $250,659. This value can be increased by the other costs described above to yield a total bioslurping project cost:

BIOM	=	$ 251,000
Design Costs	=	$ 19,000
Documentation Costs	=	$ 70,000
Closure Costs	=	$ 3,000
Contingency Costs	=	$ 25,000
TOTAL	=	**$ 368,000**

Section 4.0: CONCLUSIONS

This cost estimator is designed to provide readers with a set of useful guidelines that will enable them to make sound decisions in costing and implementing bioslurper technology at a petroleum-contaminated site. By utilizing the information provided, readers will be able to make an informed decision as to whether or not bioslurping would be a cost-effective and rapid technology to use in remediating the contaminated area. The costs presented in the tables of this document reflect the market price of the materials sold by the listed vendors as of May 1996. The drilling costs given in Table 3 are estimates made from previous quotations of several drilling contractors. The drilling costs will vary depending on the location of the affected area. Mention of manufacturer and trade names does not constitute endorsement of said product by Battelle or the Naval Facilities Engineering Service Center. Table 8 provides the final costing factors associated with designing, documenting, implementing, and closing a full-scale bioslurping project.

Table A-8. Bioslurping Project Costs

BPC	=	**TT + PSI + FSI + OMT + DDCC**
	=	**BIOM + DDCC**
TT	=	Total costs incurred to construct system trailer with optional materials included
PSI	=	Total costs incurred to conduct pilot-scale installation and testing
FSI	=	Total costs incurred to expand to a full-scale installation
OMT	=	Total costs incurred to operate and maintain the system in a normal operational mode
DDCC	=	Design, documentation, site closure, and contingency costs
BPC	=	**Bioslurping project costs**

Section 5.0: REFERENCE

Battelle. 1995. *Test Plan and Technical Protocol for Bioslurping*. Prepared for U.S. Air Force Center for Environmental Excellence, Brooks Air Force Base, TX.

APPENDIX B

ACRONYMS AND ABBREVIATIONS

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ACRONYMS AND ABBREVIATIONS

AFCEE	U.S. Air Force Center for Environmental Excellence
ASTM	American Society for Testing and Materials
AVGAS	aviation gasoline
BTEX	benzene, toluene, ethylbenzene, and xylenes
cfm	cubic feet per minute
CQC	Contractor Quality Control
FPR	free-product recovery
GAC	granular activated charcoal
hp	horsepower
ICE	internal combustion engine
ID	inside diameter
JP	jet propulsion (fuel)
LNAPL	light, nonaqueous-phase liquid
LRP	liquid ring pump
MDL	minimum detection limit
mgd	millions of gallons per day
MW	monitoring well
NFESC	Naval Facilities Engineering Service Center
O&M	operations and maintenance
OD	outside diameter
OWS	oil/water separator
ppmv	part(s) per million by volume
psia	pound(s) per square inch absolute
PVC	polyvinyl chloride
QAPP	Quality Assurance Program Plan
SGP	soil gas point
THC	total hydrocarbons
TPH	total petroleum hydrocarbons
VOA	volatile organic analysis; volatile organic analyzer
VOC	volatile organic carbon