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BEST PRACTICES MANUAL
FOR BIOSLURPING

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Prepared by

BATTELLE
505 King Avenue
Columbus, Ohio 43201

For submission to

Naval Facilities Engineering Service Center
1100 23rd Avenue
Port Hueneme, California 93043-4301

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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.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.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.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.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.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 TESTINGSection 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.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.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.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.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.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.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.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.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 INSTALLATIONSection 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.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.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.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

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.

Figure 3. Diagram of a Typical Soil Gas Monitoring Point

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.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.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.

Figure 4. Diagram of the Bioslurper Pilot Test System

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

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.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.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.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).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.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.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.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.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.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 IMPLEMENTATIONSection 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.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.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.

Table 2. Sampling and Analytical Methods

4.1.2   Soil Gas Survey.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 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.

Figure 6. Typical Setup for a Soil Gas Monitoring Point

4.1.3   LNAPL Thickness and Groundwater Level Measurements.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.

Figure 7. Diagram of the In Situ Interface Probe Setup

4.1.4   Baildown Tests.1.4Baildown 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).

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).

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

4.2   System Shakedown.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.

Figure 9. Bioslurper Pilot Test Shakedown Checklist

4.3   **Bioslurper System Startup.3**   **Bioslurper System Startup**

4.3.1   **Bioslurper Extraction Test.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).

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

4.3.2 **Bioslurper Radius of Influence.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.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.

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

4.4 **Process and Site Monitoring.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.)

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

Figure 11. Typical Record Sheets for Bioslurper Pilot Testing

4.4.1   Vapor Discharge Sampling and Analysis.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.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.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.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.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.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

$$C_6H_{14} + 9.5O_2 \rightarrow 6CO_2 + 7H_2O$$
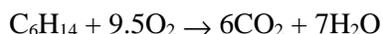
Based on this equation, on a weight basis, approximately 3.5 g of oxygen is required for every 1 g of hydrocarbon consumed. Therefore, the hydrocarbon degradation rate is approximately 0.29 times the oxygen utilization rate.

4.5   Data Reduction and Results Interpretation.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.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.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.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.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.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.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 INSTALLATIONSection 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.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.

Figure 12. Schematic of an Extraction/Treatment System to Treat an Oil/H₂O Emulsion

5.2   **Extraction/Treatment/Disposal System.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-

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.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.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.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).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.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.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 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.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.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.

Section 7.0: REFERENCES

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APPENDIX A

BIOSLURPING IMPLEMENTATION COST-ESTIMATING GUIDE