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APPLICATION GUIDE FOR BIOSLURPING

VOLUME I SUMMARY OF THE PRINCIPLES AND PRACTICES OF BIOSLURPING

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VOLUME I – SUMMARY OF THE PRINCIPLES AND PRACTICES OF BIOSLURPING

1. Introduction

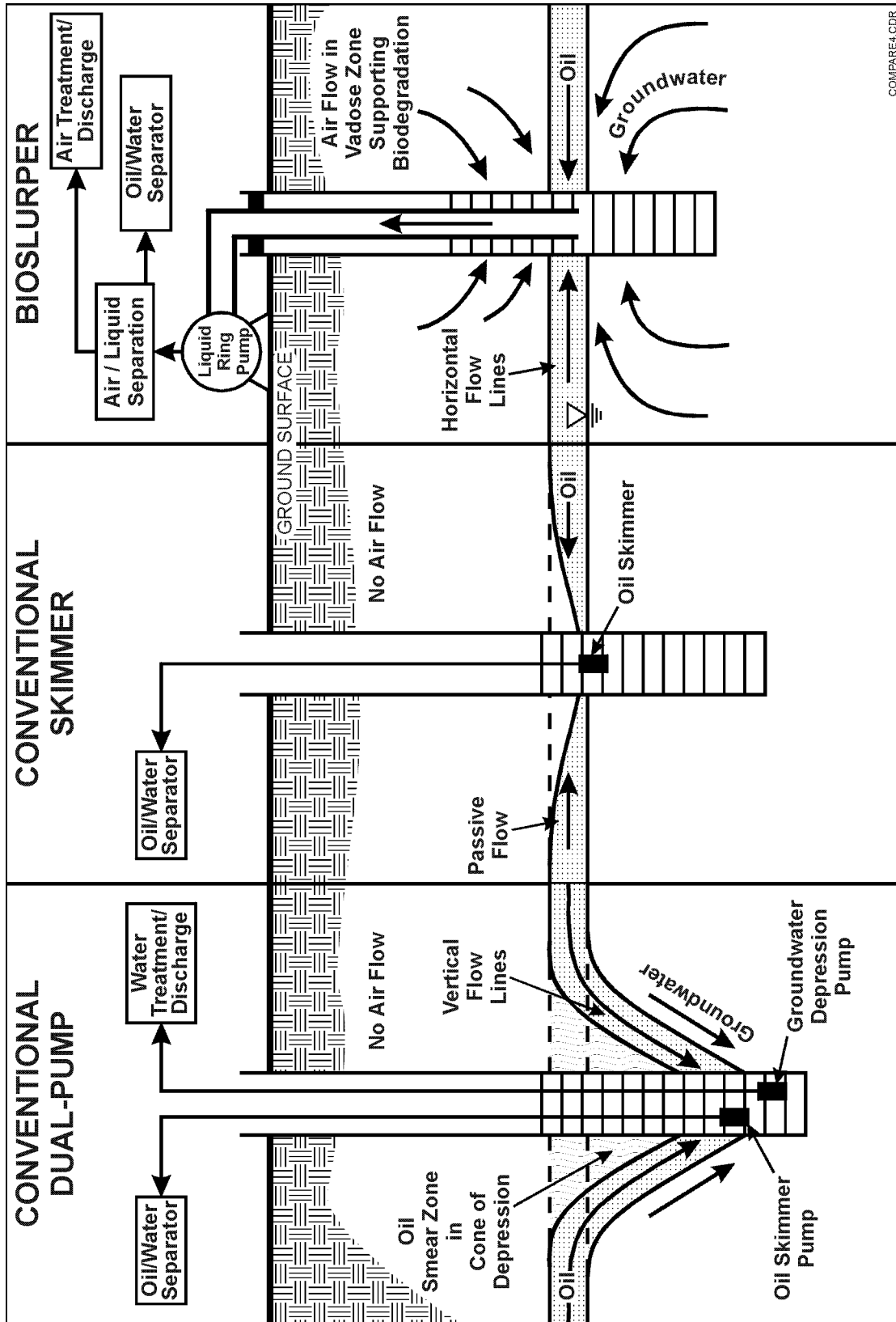
Under the Navy's Remedial Action Contract for Innovative Technologies (Contract No. N470895-D-0730), this Application Guide for Bioslurping was prepared by Battelle for the Naval Facilities Engineering Service Center (NFESC).

Volume I of the Application Guide for Bioslurping provides an overview and summary of Volume II of the Application Guide. Volume I provides principles and practices of bioslurping in an abbreviated fashion so that a remedial project manager (RPM) can make preliminary decisions rather quickly. By reading Volume I, RPMs may determine whether this technology is feasible for remediation of a site contaminated with light, non-aqueous phase liquid (LNAPL). Volume II of this document provides the reader with a detailed description of the bioslurper system, testing procedures, and system design, installation, operation, monitoring, and approach for site closure.

Leaks and spills from pipelines and underground and aboveground storage tanks at fueling terminals and service stations may result in extensive contamination to the aquifer and vadose (or unsaturated) zone beneath them. The leaked and spilled petroleum hydrocarbons, such as jet fuels, gasoline, diesel, heating oils, and crude oils, may pose direct and indirect safety hazards and cause adverse effects on human health and the environment. It is, therefore, desirable to remove free-phase and dissolved plumes and remediate the contaminated vadose zone, especially if the contaminated plumes are situated underneath densely populated areas.

After release, LNAPL migrates vertically through the vadose zone, where much of it may be left in the pore spaces due to surface tension. If the LNAPL volume is large enough, it will reach the saturated zone, spread laterally along the capillary fringe, and share pore spaces of the formation with groundwater and soil gas. The migration of LNAPL in the subsurface is dependent on the LNAPL volume released, the time duration of the release, the depth to the water table, properties of the LNAPL, properties of the geologic media, and subsurface flow conditions.

The LNAPL in the subsurface may be recovered using conventional extraction approaches, such as skimming, single-pump drawdown, and dual-pump drawdown, or using vacuum-enhanced recovery techniques. Bioslurping combines vacuum-assisted free-product recovery with bioventing and soil vapor extraction (SVE) to simultaneously recover free product and remediate the vadose zone. Figure 1 provides a comparison of drawdown, skimming, and typical bioslurping LNAPL-recovery systems. A bioslurper system withdraws LNAPL from the water table with soil gas and relatively small amounts of groundwater using the vacuum and airlift created by a single aboveground pump. The recovered free product then may be recycled. The groundwater and soil gas/vapor separated from the process stream may be treated (if necessary) and discharged. Vacuum-enhanced pumping, a common groundwater pumping method for construction dewatering, has been found to significantly increase LNAPL recovery when used to remediate petroleum hydrocarbon-contaminated sites (Beckett and Huntley, 1998; Parker, 1996; Reisinger et al., 1993). Using model simulations, Beckett and Huntley (1998) demonstrated an



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Figure 1. Comparison of Pumping, Skimming, and Bioslurping Methods for LNAPL Recovery

increase of nearly 100% when a vacuum was applied to the well head. Mathematical models comparing drawdown to bioslurping (Parker, 1996) have predicted that the free product mass removal rate would be three times as fast when using bioslurping. In addition, the models indicated that groundwater recovery rates might be seven times greater when the drawdown technology is used. In field operations at 16 sites, the bioslurper increased the LNAPL-recovery rate by 4 times over that of drawdown pumping and 7 times over that of skimming (Battelle, 1997). The increased recovery is due to increased hydraulic gradient (or hydraulic head difference between an extraction well and its surrounding strata) and aquifer transmissivity (or the rate at which fluid moves through a unit thickness of the aquifer). Vacuum enhanced pumping increases the transmissivity by promoting flow along more-permeable horizontal flow lines and by extracting the LNAPL along the zone of higher LNAPL saturation (and higher relative permeability). The increase in hydraulic gradient is caused by the formation of a cone of reduced pressure around the extraction well.

Extraction of soil gas through an extraction well will force atmospheric air to aerate the vadose-zone soil, thereby stimulating indigenous microorganisms to aerobically metabolize hydrocarbon contaminants in the soil. In general, biodegradation will take place as long as indigenous microorganisms are provided with an adequate supply of oxygen, and, perhaps, basic nutrients and moisture content (Leeson and Hinchee, 1997). Because the rate of biodegradation usually is dependent on the oxygen diffusion rate, acceleration of the oxygen transport process (through the movement of air) often is the most effective way to enhance vadose-zone bioremediation.

At sites where petroleum hydrocarbons possess relatively high volatilities (e.g., JP-4 and gasoline), SVE becomes another important process for contaminant removal during bioslurping. For example, removal of vapor-phase contaminants was as high as 980 lb/day at a gasoline-contaminated bioslurper site at Eaker Air Force Base (AFB) (Battelle, 1996). It must be noted, however, that although a portion of the released vapor was from the extracted soil gas, the majority might be from the volatilization of the extracted free product as it passed through the bioslurper system. Therefore, care should be taken when estimating the amount of soil gas recovered.

2. Site Characterization and Pre-design Studies

2.1 Background Data and Site Characteristics

Field tests are required to evaluate the feasibility of the bioslurping process and to generate the required data to design and install a full-scale system. Before testing, it is important to conduct a thorough review of site characterization data, including information sources describing when the release of LNAPL occurred, the quantity and type of the LNAPL released, measured LNAPL thickness in monitoring wells located in the area of concern, petroleum hydrocarbon levels in soils, areas/extent of contamination, and the site geology and hydrogeology. If the available information is limited, a site characterization program (including the installation of a number of monitoring wells) must be implemented to obtain the above data.

2.2 Pre-Design Studies

Proper delineation of the extent of contamination is important for the selection of the pilot test location and the implementation of a full-scale bioslurper system. Several tests usually are performed, including interface measurements, baildown tests, soil-gas surveys, and in situ respiration tests. The thickness and depth of the LNAPL layer are determined through interface measurements using an oil/water interface probe. The LNAPL thickness in a monitoring well is usually 2 to 10 times greater than that in the

formation. Baildown tests provide information regarding the mobility of LNAPL under passive conditions. At least two borehole volumes of the LNAPL should be removed from the well before measurement of the free-product recovery rate is begun.

A soil-gas survey and in situ respiration test may be necessary if remedial action objectives include addressing total petroleum hydrocarbons (TPH) in the vadose zone. The data from these tests and evaluations may be used to establish baseline levels for comparison with data generated throughout the remedial program. A soil-gas survey using a hand-driven stainless steel probe to obtain soil gas for O₂, CO₂, and TPH measurements provides information for locating the most contaminated areas of the LNAPL plume. Along with the soil-gas survey, in situ respiration tests indicate the biodegradation potential of the contaminants in the vadose zone. During testing, air containing 1 to 2% helium is injected into soil-gas monitoring points for 24 hours to fully aerate the soil. The soil gas is then measured for O₂, CO₂, and TPH, which, in turn, are used to estimate the degree of bioremediation occurring throughout the test duration.

In general, the extraction well for the pilot study should be located in an area with the greatest LNAPL thickness and near or in the wells displaying the most rapid LNAPL recovery during the baildown tests. The extraction well and monitoring points also may be located in areas with relatively low O₂ (i.e., < 5%) and relatively high TPH levels in the soil gas. As a rule of thumb, if a well does not produce > 0.005 gal/hr of LNAPL or at least two borehole volumes of LNAPL within a 12-hour period during the baildown test, LNAPL recovery from that well may not be economically feasible.

In addition to the tests described above, computer models, such as OILVOL (DAEM, 1997), may be used to delineate an LNAPL plume and estimate the total LNAPL volume. Note that the quality of the LNAPL volume estimate often depends on the quality of field and laboratory measurements for fluid levels, soil properties, and fluid properties. Therefore, care must be taken when performing these measurements. In addition, LNAPL is likely to exist as small pools or pockets as opposed to one large plume. It is important that reliable data are used when the LNAPL volume is estimated. An erroneous LNAPL volume estimate by computer models may lead to false expectations of the recoverable LNAPL volume.

Because of the inherent difficulties and potential errors associated with the volume estimation process, these volume estimates are not recommended. It is important to note that remedial objectives (ROs) should not be established to remove an estimated volume. The ROs should be based on employment of best available technology to remove the LNAPL source to the greatest possible practical extent.

3. Pilot-Scale Testing

3.1 Extraction Wells and Soil-Gas Monitoring Points

After selection of the well location, an extraction well and several soil-gas monitoring points are installed. Construction of the extraction well may have significant effects on the LNAPL recovery rate and LNAPL/groundwater and groundwater/soil-gas recovery ratios. For example, the extraction well usually is designed to possess a minimal length of well screen (e.g., 3 ft) both above and below the water table to exert maximum vacuum on the LNAPL layer, increasing the radius of influence with respect to the LNAPL while extracting the least amount of groundwater. However, the screened section should be long enough to cover the LNAPL layer, which may fluctuate with the water table due to climatic, seasonal, and tidal variations. In general, the screened section should extend from at least 1 ft below the lowest to 1 ft above the highest groundwater level. The drop tube usually is placed at the oil/water

interface. Even if the water table in the formation rises significantly, the fluid level in the well will be held constant by the extraction of groundwater. In contrast, the vacuum in the well tends to lift the groundwater level in the well if the water table subsides. Lifting of the groundwater level in the well, however, could create a mound around the extraction well, thereby driving the LNAPL away from the extraction well.

Soil-gas monitoring points are used for pressure measurements and soil-gas sampling and generally are installed at three or more depths and locations. The three monitoring points usually are located on a straight line radially out from the extraction well. The lateral spacing from the extraction well is determined based on the site geology and the depth to the top of the extraction well screen. Generally, the spacing decreases with increasing soil grain size but increases with increasing depth to the top of the well screen. Each monitoring point is screened at 1ft above the water table or liquid interface (the deepest screen), 3 to 5 ft below ground surface (bgs) (the shallowest screen), and in between (the intermediate screen). Ideally, the monitoring points would measure high TPH concentrations (e.g., > 10,000 ppmv) and low O₂ concentrations (e.g., < 5%). A background soil-gas monitoring point also is needed to establish background soil-gas concentrations.

3.2 Pilot-Scale Bioslurper System and Testing

Figure 2 presents the schematic of a typical trailer-mounted pilot-scale bioslurper system. The system consists of an extraction manifold, an equalization vessel, a liquid ring pump, an oil/water separator, a surge tank, and associated pipes, hoses, valves, gauges, and control panels. When required, the system also may include stack gas and/or water treatment equipment.

In most cases, a 7.5-hp liquid ring pump is used to extract LNAPL, groundwater, and soil gas. LNAPL is separated from groundwater by passing the oil/water mixture through the oil/water separator. If stable oil/water emulsions and floating solids (consisting of soil particles and LNAPL) are formed, a separator with coalescer packings and a cone-shape bottom should be used to allow LNAPL and floating solids to overflow the weir before being transferred to a fuel storage tank. The water from the oil/water separator may be disposed of to a sanitary sewer system, or further treated with organo-modified clay, activated carbon, and/or dissolved air floatation (DAF) to remove stable oil/water emulsions. The type of treatment is primarily dictated by the discharge limits. Depending on the regulatory requirements, the stack gas may be discharged directly to the atmosphere or treated with gas-phase activated carbon, catalytic or thermal oxidation, or by an internal combustion engine (ICE).

The bioslurper pilot test has been designed to determine the economic feasibility of LNAPL recovery at the test site. If the characteristics of the site or the contaminant profile significantly vary across the site, the pilot test should be performed at multiple wells to generate an accurate evaluation of the LNAPL-recovery potential of the site. During the test the trailer-mounted system is configured to operate in a simulated skimmer mode, simulated dual pump drawdown mode, bioslurping, and soil vapor extraction. The general sequence of testing is as follows: simulated skimming – 1 day, bioslurping – 4 days, simulated skimming – 1 day, and drawdown – 2 days. If the vapor phase mass removal rate of TPH is significant, an SVE test is warranted. It is important to follow the testing sequence in Table 1 by performing simulated skimmer testing before bioslurping and simulated dual-pump drawdown testing. The sequence will ensure minimum disturbance of the hydrogeologic conditions as the testing proceeds.

During bioslurper testing, LNAPL recovery rate and volume, groundwater recovery volume, stack gas, soil-gas, and vadose zone radius of influence (with respect to vacuum at various soil-gas monitoring points) are measured and/or monitored. At some period during the bioslurping portion of the pilot test

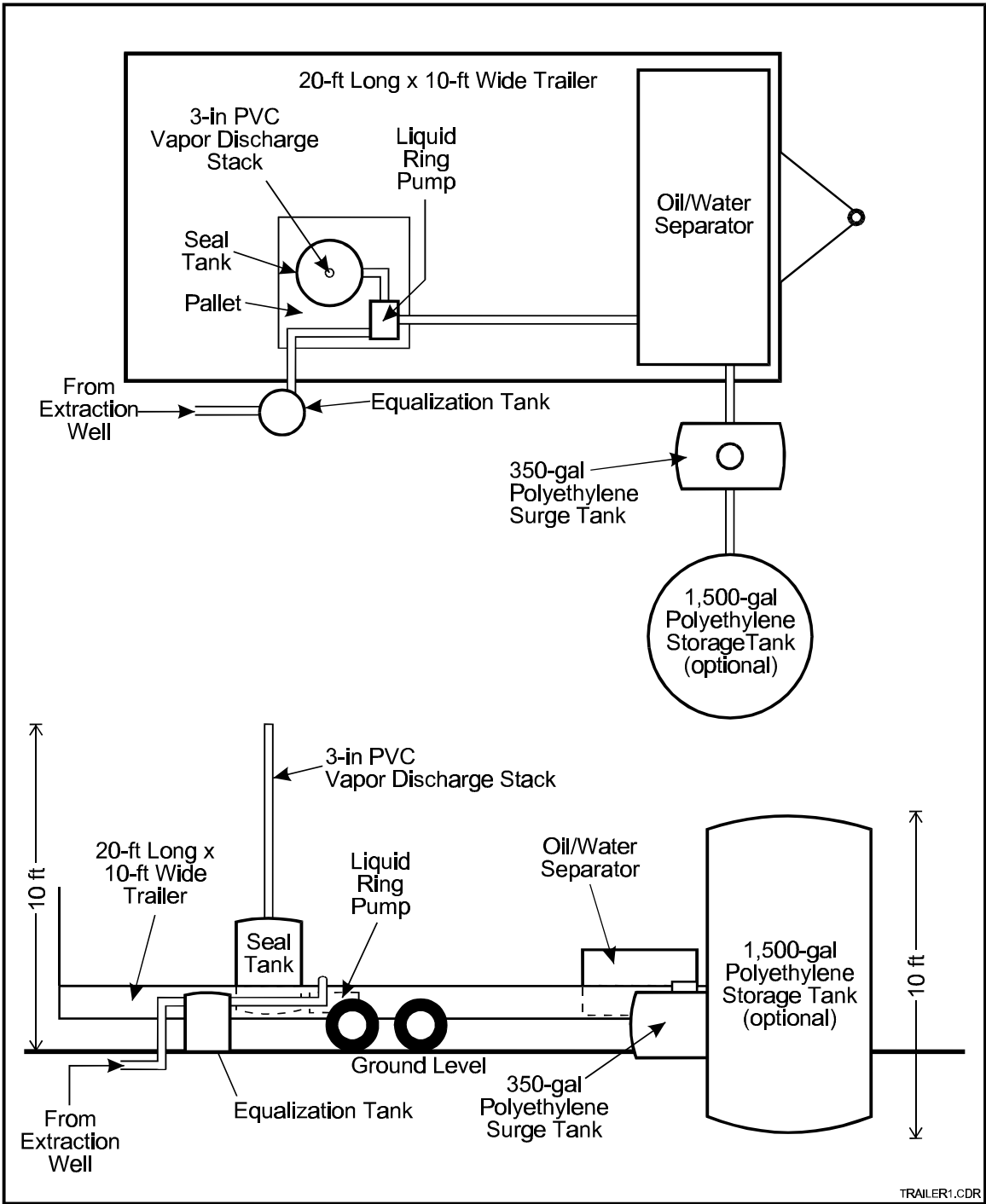


Figure 2. Trailer-Mounted, Pilot-Scale Bioslurper Unit

Table 1. Schedule of Activities

Pilot Test Activity	Test Duration
Mobilization	
Soil Characterization (if not already performed)	
Product/Groundwater Interface Monitoring	Depends on number of wells to be monitored
Baildown Tests	1 Day
Soil Gas Survey (limited)	1 Day
Simulated Skimmer Testing	2 Days
Bioslurper Testing	4 Days (Minimum)
Simulated Drawdown Testing	2 Days
Soil Vapor Extraction Testing (if indicated)	1 Day

useful data may be generated by reducing wellhead vacuum to a minimum level so that the airlift/vacuum is just great enough to extract fluids from the well. In addition, samples of soil gas, stack gas, process water, and LNAPL are collected at different time intervals for measurement of benzene, toluene, ethylbenzene, and xylenes (BTEX), TPHs, and various physical and chemical measurements. Meanwhile, the depth and thickness of LNAPL may be measured in the monitoring wells adjacent to the extraction well using in situ interface probes placed in tightly sealed monitoring wells under vacuum-enhanced conditions.

Combining with the field data collected during site characterization and pilot-scale testing, a more rigorous estimate of LNAPL radius of influence may be made using multi-phase computer simulations, such as MOVER (DAEM, 1998). The numerical simulators can incorporate hydrogeologic data, LNAPL distribution, and soil vacuum into a single model, allowing a more accurate estimate of LNAPL radius of influence. For full-scale implementation, the radius of influence of LNAPL, rather than that of soil gas, should be used as the basis for well spacing design. However, because computer simulations require specialized expertise, which is not necessarily available to the users of the bioslurping technology, it may be more cost-effective to use generalized rule of thumb to relate the observed field data to the actual LNAPL radius of influence. Further research in this area is currently underway at Battelle.

Data and information collected during the pilot-scale test should be evaluated to (1) determine the feasibility of the LNAPL source removal and vadose zone remediation, and (2) develop the approach for construction and implementation of a full-scale bioslurper system. Figure 3 presents a decision tree for determining the appropriate technology for full-scale implementation at the pilot test site. The data collected during the baildown tests performed during the site characterization provide an indication of whether free product is mobile at the site under passive conditions. If the baildown test suggests that free-product recovery is feasible, the technology that demonstrated the greatest LNAPL recovery rate during the pilot test likely will be used for full-scale site remediation. However, prior to implementing a full-scale system, the costs for stack gas and process water treatment should be evaluated.

If bioslurping is selected for site remediation, the information generated by the LNAPL extraction test may be used to design a full-scale system. Some of the most useful pieces of data are: LNAPL recovery rate, groundwater recovery rate and process water composition, stack discharge flowrate and composition, and whether floating solids or emulsions are formed. This information is required for sizing the full-scale system (e.g., pump capacities and sizes of oil/water separator and holding tank) and determining the requirement for oil/water separation and the need for stack gas or process water effluent treatment. Data generated during the pilot studies also may be used for discharge permit applications, if

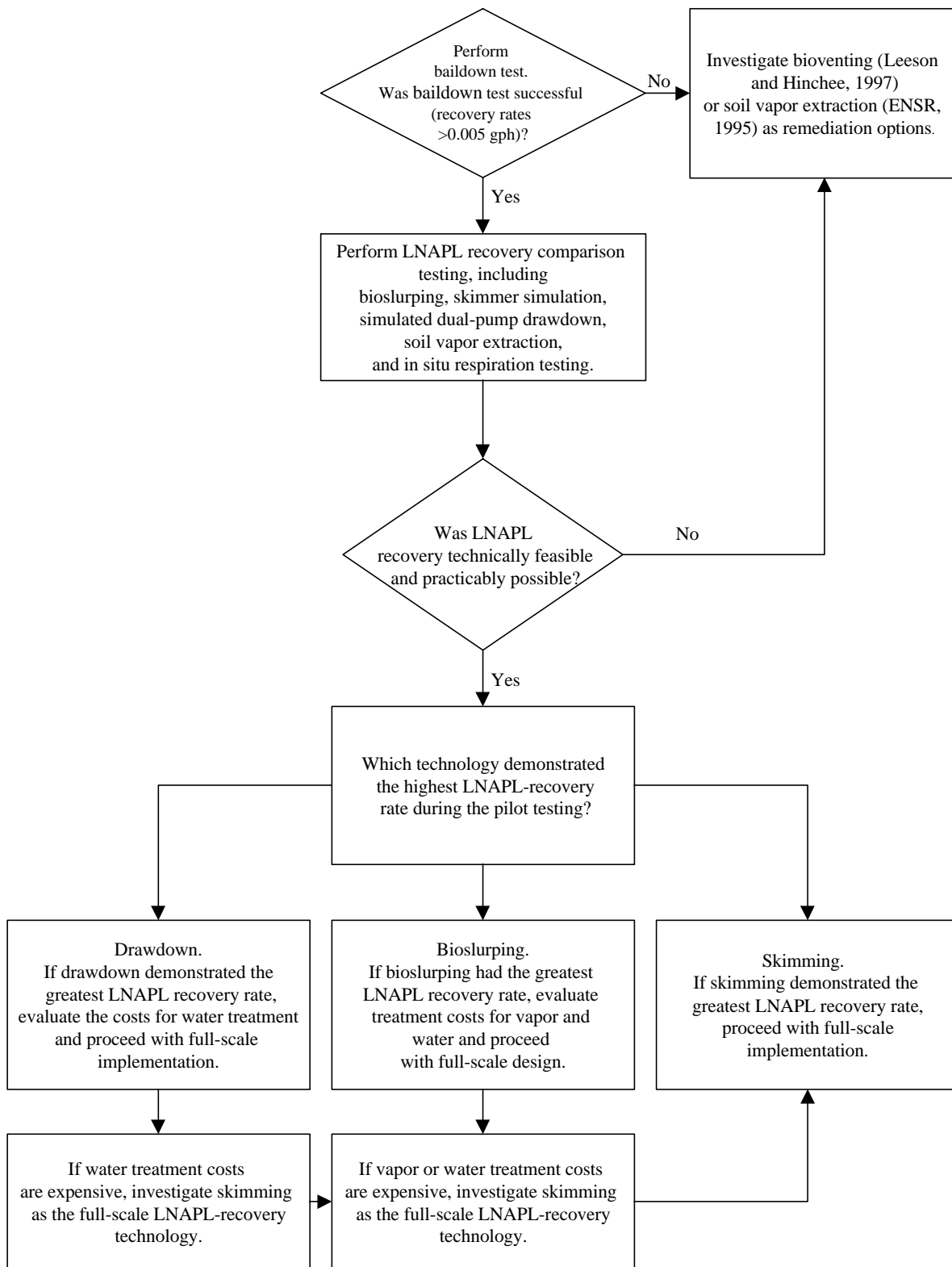


Figure 3. Decision Tree for Selecting an LNAPL-Recovery Technology

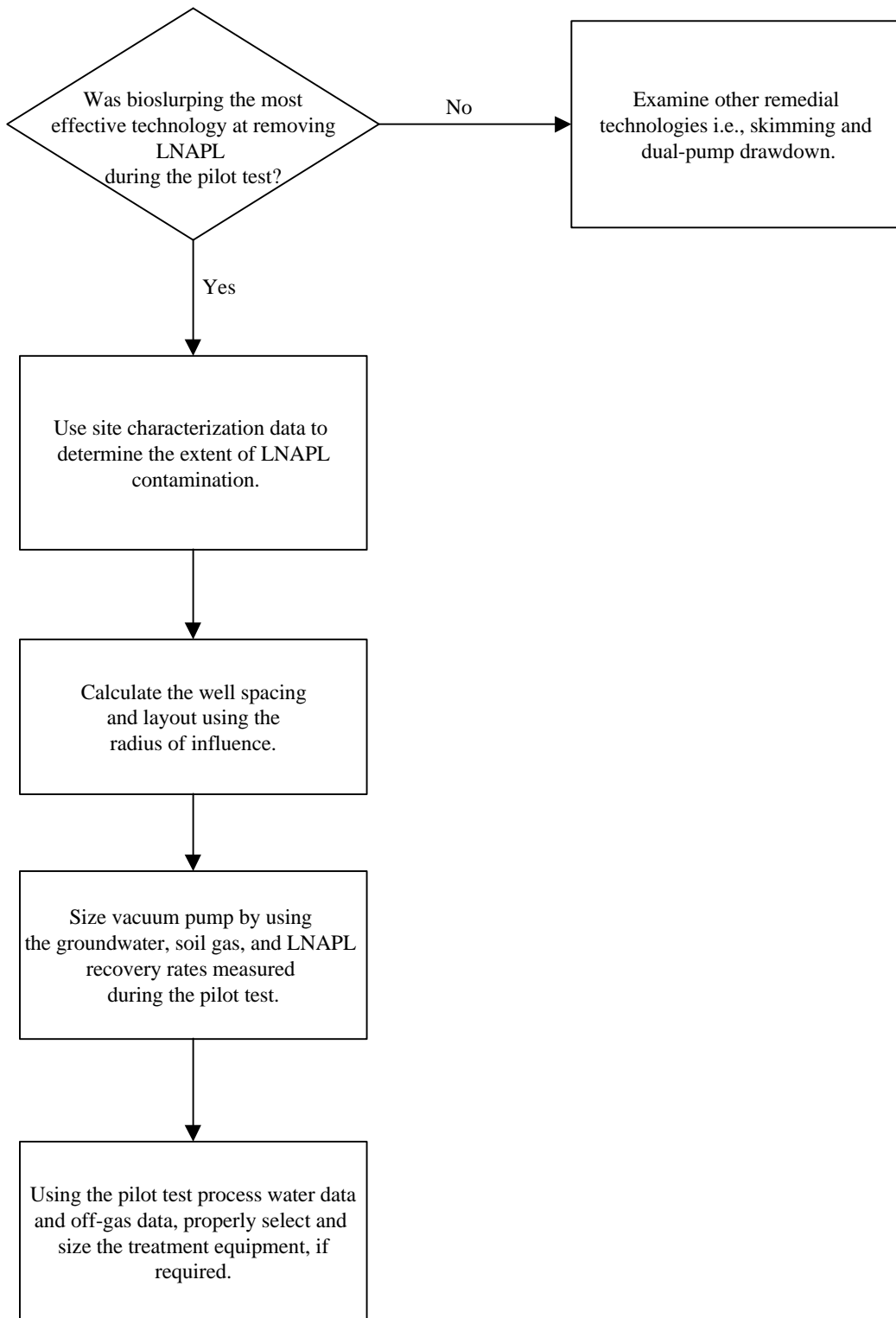


Figure 4. Stepwise Approach to Full-Scale Bioslurper Design

permitting is required. If stack gas and/or process water effluent requires treatment, composition and flowrate data must be used to obtain sizing, performance data, and cost information from various vendors and component suppliers for the full-scale treatment units.

The respiration tests provide data for the potential for bioremediation of the vadose zone.

4. Full-Scale Design and Implementation

Several components must be considered when designing a full-scale bioslurper system. These components include extraction well spacing and design, drop tube and extraction manifold sizing, liquid ring pump sizing, oil/water separation, stable emulsions treatment, stack gas treatment, safety switches and equipment, and miscellaneous design considerations (including noise abatement, traffic control, fluctuating groundwater table, and cold weather operation). Figure 4 presents a stepwise approach for designing a full-scale system. Improper sizing of the pumps, extraction manifold, or other materials may result if the if the order in the figure is not followed.

4.1 Well Spacing, Drop Tube, Extraction Manifold, and Liquid Ring Pump

Placing wells with proper spacing is important to ensure optimal LNAPL recovery and vadose zone remediation. The desired well spacing is determined by the LNAPL radius of influence estimated during the pilot testing. When the LNAPL radius of influence is not available, the soil gas radius of influence may be used as a contingency measure. Ideally, wells should be spaced in a configuration such that the distance between any two adjacent wells does not exceed the radius of influence. Optimization of the number and spacing of extraction wells will minimize both capital and operating and maintenance (O&M) costs. Minimizing the number of wells required to cover the LNAPL plume may be accomplished by installing the wells in a triangular array as depicted in Figure 5. The distance between any two adjacent extraction wells, L , is $1.732r$ where:

r = the radius of influence measured during the pilot test.

The bioslurper drop tube is designed to ensure that the superficial velocity of the LNAPL/groundwater mixture is low enough to maintain a pulsing or annular-type flow in the vertical tube. In general, a superficial air velocity of > 10 ft/sec would be adequate to maintain such a flow. Testing of bioslurper systems has demonstrated that the suction lift action is not very sensitive to operating conditions and that stable operations are easily maintained over a wide range of conditions.

Piping for the manifold must be selected so that the liquid velocity decreases sufficiently to avoid slug flow in horizontal piping. Pressure losses due to friction must be taken into account when designing a manifold system. Data for frictional loss in pipes can be found in engineering manuals or may be obtained from the pipe manufacturer. In general, a superficial liquid velocity of < 0.4 ft/sec would be adequate. The size of manifold piping near the liquid ring pump may increase as more wells are connected to the manifold. The manifold piping should be placed to avoid low points and should be sloped toward the liquid ring pump.

Liquid ring pumps have been used at most bioslurping pilot- and full-scale sites and are cost-effective for producing a liquid-extraction vacuum. The rule of thumb used by Battelle for sizing the pumps is to allow between $1/3$ and $2/3$ hp for each extraction well. However, the primary factor in sizing the pumps for a full-scale system is the volumetric flowrate of soil gas that extracts fluids from the wells through the

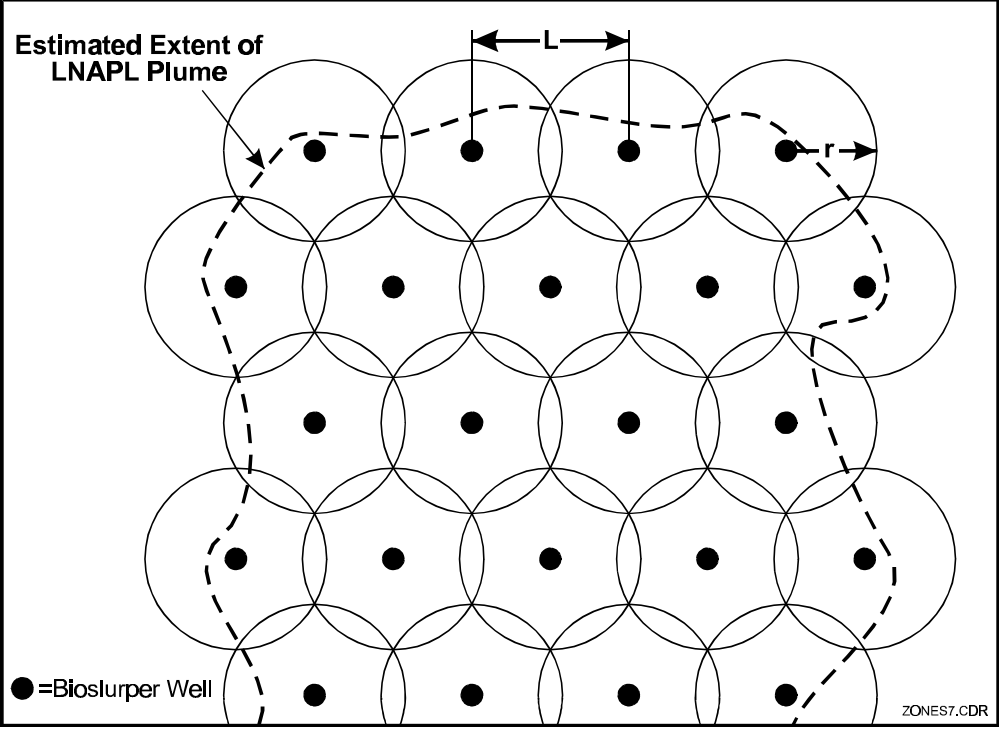


Figure 5. Recommended Extraction Well Layout

drop tubes. The flowrate measured during the pilot test is multiplied by the number of extraction wells required to cover the LNAPL plume to calculate the total soil-gas extraction rate during the pilot test. This total soil-gas extraction rate is then used with pump manufacturer's literature to determine the size of the pump. A minimum-sized pump may be calculated by multiplying the number of wells required to cover the site by the soil-gas extraction rate when the pump was operated at the lowest vacuum/air flowrate (measured during a pilot test) to lift water to the surface.

4.2 Water and Stack Gas Treatment

As discussed in Section 3, water separated by the oil/water separator may contain stable oil/water emulsions that must be further treated before final disposal. A number of techniques may be used to reduce the emulsion formation or treat the emulsions formed. Among the methods used to reduce emulsion formation are in-well oil/water separation using two drop tubes to separately extract LNAPL and groundwater, and separation using a knock-out tank before the LNAPL/groundwater/soil-gas mixture enters the liquid ring pump. Among the techniques used to treat emulsions are chemical treatment involving coagulation and flocculation, DAF, air stripping, carbon adsorption, and organo-modified clay adsorption. Treatment with coagulants and DAF has proven to be one of the most effective methods to control emulsions. However, this method involves significant capital and O&M costs. Organo-modified clay and carbon adsorption may be simpler and cheaper. However, when used for treating high concentrations of emulsified oil, the adsorption canisters must be replaced more frequently and the used canisters may be classified as hazardous wastes, thus increasing operation and disposal costs. Selection of appropriate treatment processes is based on the quality of influent water/emulsion, discharge limits, and cost.

Because bioslurper systems are often considered small emission sources, they may require stack gas treatment, depending on emission quantities and site-specific regulatory requirements. Selection of a vapor treatment system depends mainly on contaminant concentrations. For TPH concentrations ranging from 10 to 500 ppmv, activated carbon adsorption may be an option. For TPH concentrations ranging from 10 to 10,000 ppmv, vapor reinjection or biofiltration may be preferred. For stack gas with even higher concentrations, i.e., 500 to 100,000 ppmv, incineration or thermal destruction in an ICE would be an option.

4.3 Life-Cycle and Cost Analysis

The mass removal rate achieved by bioslurping and other LNAPL extraction technologies varies over time. Typically, a period of relatively rapid and steady mass removal is followed by a period of exponential decay. This reflects the relative availability of gross contaminant reservoirs compared to less accessible stores of contaminants. The duration over which the removal rate remains on the upper plateau depends on the gross quantity of readily available free product and on soil characteristics. The overall removal rate at a site is the sum of the removal rates observed in each individual extraction well during operation. Therefore, an operational strategy can be developed to maintain long-term extraction rates near initial conditions by extracting from wells that appear to be producing LNAPL. By eliminating the wells that contain and produce small quantities of LNAPL, the recovery ratio of groundwater to LNAPL decreases as well, thereby reducing the treatment costs for off-gas and process effluent.

The objective of life-cycle cost analysis is to determine the appropriate ratio between capital equipment and O&M commitments to achieve the greatest mass removal in the most cost-effective manner. Capital outlays can be underutilized at sites where the plateau period is brief because the purchased componentry is operated well below its design capacity for the majority of the operational period. Systems designed to

accommodate extraction rates near the maximum may achieve the desired mass removal in a shorter operational period.

A cost-effective approach is to design a system to perform at 40 to 60% of the expected maximum (initial) mass removal rate. With this approach, the lower mass removal rates are sustained near the capacity of the equipment for a longer period of time, making capital outlays more efficient. Another approach for cost-effective treatment of the vapor and process water from the bioslurper involves renting off-gas and water treatment equipment during the period of high mass removal. When the mass removal rates decrease, the treatment equipment may be returned. This approach also may be used when vapor-discharge permits are being obtained. Once the regulated discharge rates have been met and treatment is no longer required, the treatment equipment may be returned.

5. Site Closure

Development of an exit strategy and an approach for site closure is an integral part of the design and implementation of the bioslurping process. Figure 6 presents a generic decision diagram with an approach for site closure. Site closure requires review and understanding of applicable regulations and cleanup criteria/standards based on free-product levels in monitoring wells and/or contaminant levels in soil and groundwater. RPMs may modify the strategy to meet any other site-specific cleanup objectives. In general, the bioslurper system is operated until the LNAPL recovery diminishes. Because this condition may not be achieved simultaneously at all wells, the system may be operated until LNAPL recovery is significantly reduced (e.g., 20% of the original recovery rate). At this point, the system is turned off and each well is monitored over a limited time period for the presence of LNAPL. The system is restarted with only those wells that contain LNAPL. Additional wells may be installed in the surrounding areas to expedite the extraction process.

Meanwhile, the wells that do not have LNAPL may be operated in a "drawdown" mode for a short period (e.g., 1 week), to ensure the removal of any recoverable LNAPL captured in the saturated zone. When the LNAPL recovery is relatively low (e.g., 1-5 gal/week), the system is to be shut down and a long-term monitoring program is to be established to determine the status of the contaminated groundwater plume. If the plume is shrinking or stable, the site may be closed with limited long-term monitoring or no further action. Otherwise, other remediation techniques, such as natural attenuation, bioventing (if the vadose zone is a continuing source), and/or air sparging may be applied to the site to further control the plume.

6. Conclusions

Bioslurping has developed into a relatively mature technology for LNAPL recovery from contaminated aquifers. Although the process has been tested at the pilot scale at numerous sites and implemented at full scale at several sites, the factors affecting the system design and process performance have not been fully understood. The complexity of aquifer geology and hydrogeology, and of the various physical and chemical principles governing the extraction of LNAPL, groundwater, and soil gas, may have been contributing reasons. Nevertheless, bioslurping has been demonstrated as a viable technology to recover LNAPL and its overall performance has been shown by Battelle (1998) and other researchers to be superior to conventional skimming and drawdown technologies.

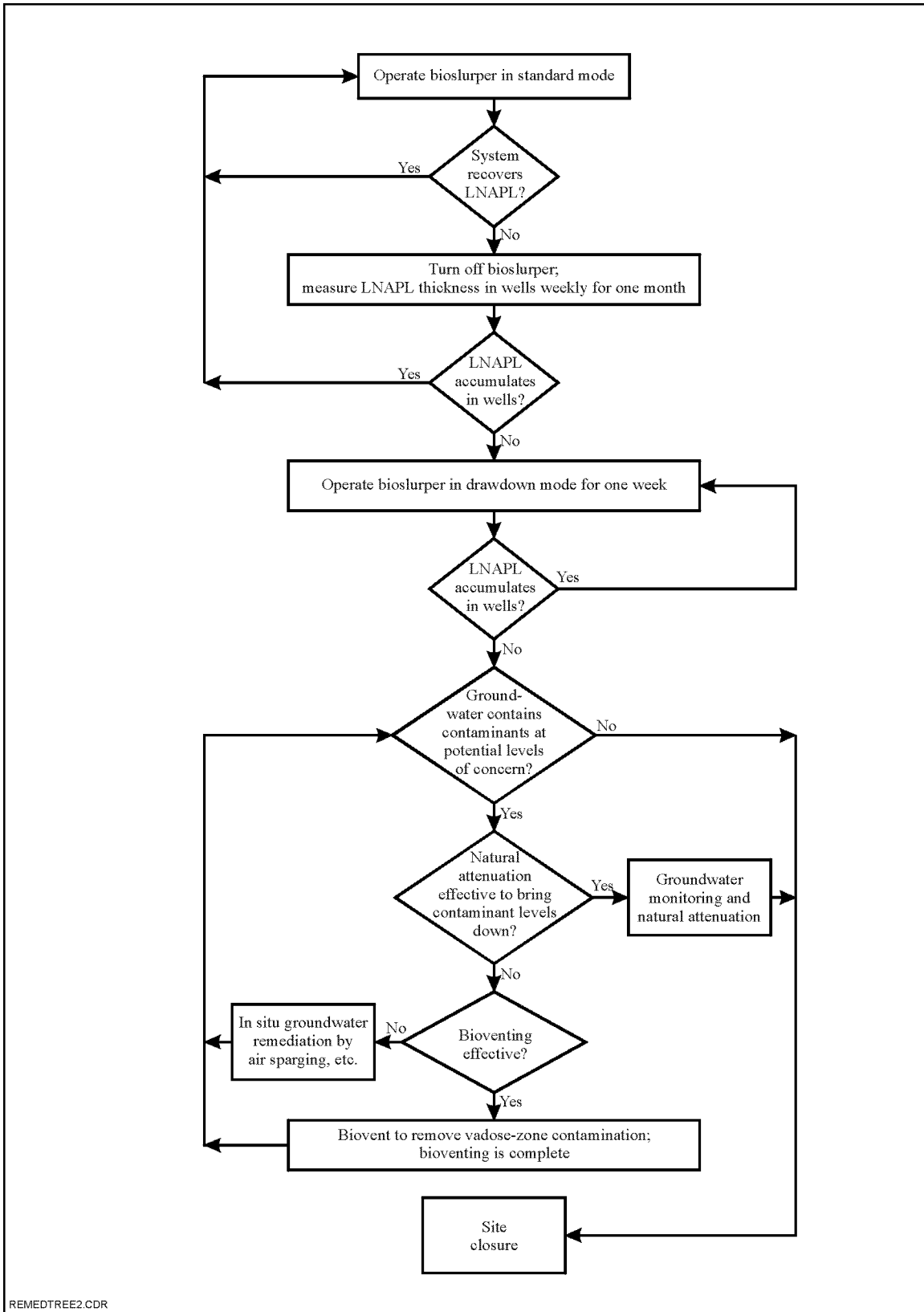


Figure 6. Generic Decision Diagram for Bioslurper Exit Strategy and Site Closure

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