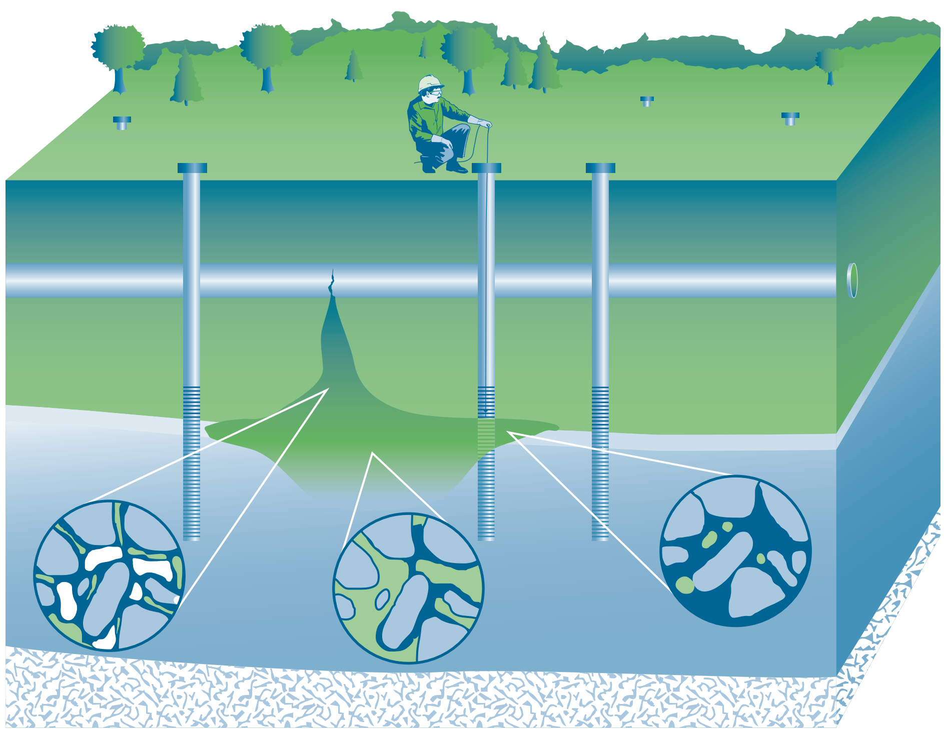
Technical/Regulatory Guidance

Evaluating LNAPL Remedial Technologies for Achieving Project Goals



December 2009

Prepared by
The Interstate Technology & Regulatory Council
LNAPLs Team

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LNAPL-2

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EXECUTIVE SUMMARY

Light, nonaqueous-phase liquid (LNAPL) management (LNAPL assessment and remediation) presents some of the greatest challenges to corrective action and cleanup at petroleum manufacturing, storage, and handling facilities such as refineries, bulk product terminals, gas stations, airports, and military bases. Once in the subsurface, LNAPLs can be difficult to adequately assess and recover and thus can be a long-term source of

- risk and exposure issues (e.g., vapor, groundwater and soil contamination)
- acute-risk concerns (e.g., explosive conditions)
- LNAPL mass concerns (e.g., regulations that require recovery of “free-product,” “free-phase hydrocarbon,” or “liquid-phase hydrocarbon”; for aesthetics or mass reduction reasons; or for potential LNAPL migration)

Over the past few decades, LNAPL remedial technologies have evolved from conventional pumping or hydraulic recovery systems to a variety of innovative, aggressive, and experimental technologies. Thus, selecting the LNAPL remedial technology best suited for an LNAPL site can be daunting. Further, not all LNAPL sites pose the same concerns and risks and, therefore, may not warrant the same level of management. The simple concept is to first identify the specific concerns the particular LNAPL site conditions pose and then set a course of LNAPL management that specifically addresses those concerns. When those concerns are abated, unless other concerns arise, the LNAPL management effort has succeeded.

This guidance provides a framework to help stakeholders select the best-suited LNAPL remedial technology for an LNAPL site and will help the regulator and others understand what technologies apply in different site situations. Seventeen LNAPL remedial technologies are considered in this guidance, some of which are more innovative or less proven as an LNAPL remedial technology than others. The framework advocates selecting LNAPL remedial technologies to achieve specific LNAPL remedial objectives that are set to address the specific LNAPL concerns identified at the LNAPL site. This guidance also discusses regulatory practices which may foster better completion of LNAPL remediation, including the important step of developing an adequate LNAPL conceptual site model to guide the setting of LNAPL remedial objectives and remedial technology selection. It is anticipated that use of this guidance will facilitate regulatory oversight of LNAPL remediation, streamline remedial technology selection and regulatory approval, enhance communication between stakeholders, and facilitate closure of LNAPL remediation projects.

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1. INTRODUCTION

Light, nonaqueous-phase liquid (LNAPL) management (LNAPL assessment and remediation) presents some of the greatest corrective action and cleanup compliance challenges to petroleum manufacturing, storage, and handling facilities such as refineries, bulk product terminals, gas stations, airports, and military bases. Once in the subsurface, LNAPLs can be difficult to adequately assess and recover and thus can be a long-term source of

- risk and exposure issues (e.g., vapor, groundwater and soil contamination)
- acute-risk concerns (e.g., explosive conditions)
- LNAPL mass concerns (e.g., regulations that require recovery of “free-product,” “free-phase hydrocarbon,” or “liquid-phase hydrocarbon”; for aesthetics or mass reduction reasons; or for potential LNAPL migration)

State and federal regulations typically well address LNAPL risk and exposure issues and acute risk concerns, generally referred to herein as “composition” concerns, as such risks are driven by the chemical composition of the LNAPL. What is typically not well addressed in state and federal regulations, however, is the concern related to presence of LNAPL mass or degree of LNAPL saturation, generally referred to herein as LNAPL “saturation” concerns. Other than the common “recover LNAPL to the maximum extent practicable” requirement, most state or federal regulatory programs address saturation concerns on a site-specific basis, and few specifics are provided.

Not all LNAPL sites, however, pose the same concerns and, therefore, may not warrant the same level of management. Figure 1-1 presents an LNAPL management paradigm. The simple concept is to first identify the specific LNAPL composition and saturation concerns the particular LNAPL site conditions pose, if any. Next, apply the appropriate LNAPL remedial technology(ies) to abate those concerns. After all are addressed and any necessary actions with long-term stewardship are completed, the site should be eligible for no further action (NFA) status, if such status is applicable.

Fortunately, over the past few decades, LNAPL remedial technologies have evolved from conventional pumping or hydraulic recovery systems to a variety of innovative, aggressive, and experimental technologies that address the mobile and residual LNAPL fractions, as well as volatile and dissolved-phase plumes. Unfortunately, determining the appropriate level of LNAPL management and choosing among the large number of available LNAPL remedial technologies to provide that level of LNAPL management can be a significant challenge.

The Interstate Technology & Regulatory Council (ITRC) LNAPLs Team formed in 2007 to develop a suite of guidance documents and training to address emerging LNAPL concepts and remedial technology solutions. Specifically, the LNAPLs Team developed this technical/ regulatory guidance document (guidance) to provide a framework that helps to systematically

- set appropriate LNAPL remedial objectives for potential composition and saturation LNAPL concerns
- inform stakeholders of the applicability and capability of 17 different LNAPL remedial technologies that are currently available
- select which remedial technologies will best achieve the LNAPL remedial objectives for an LNAPL site, in the context of site and LNAPL conditions and the LNAPL remedial objectives

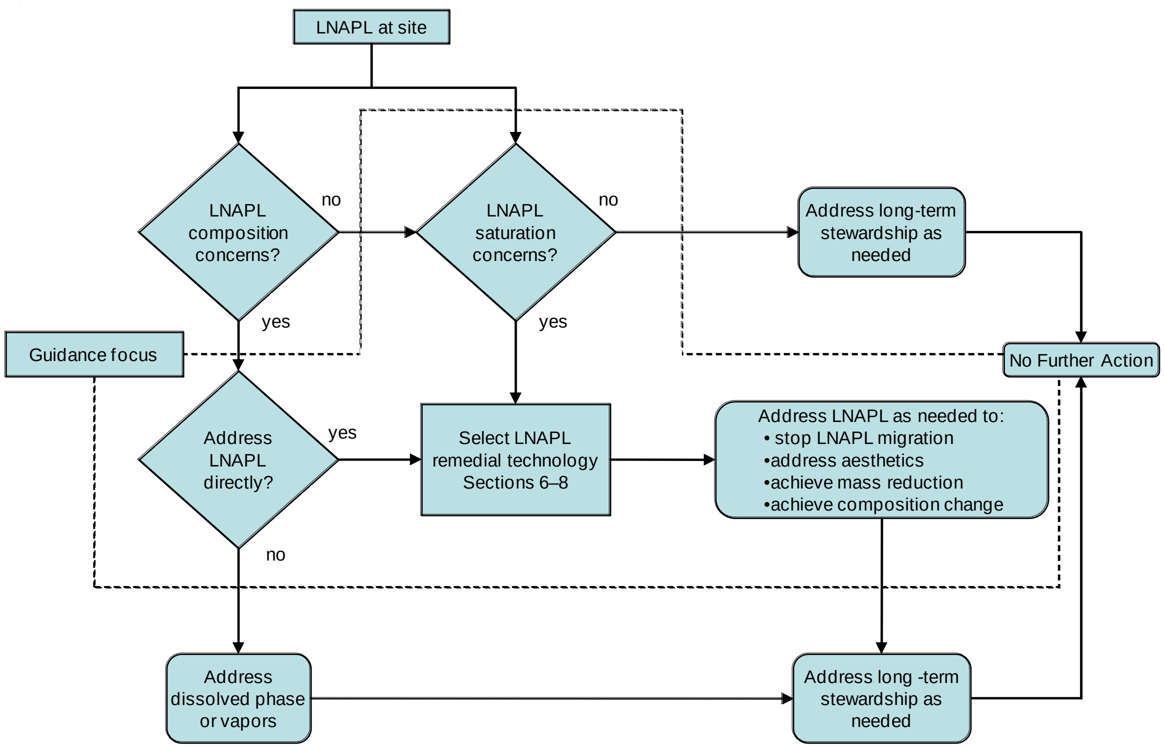


Figure 1-1. Generalized LNAPL management overview and focus of this guidance document.

This guidance complements other products developed by the LNAPLs Team (Section 1.1).

1.1 About the ITRC LNAPLs Team

ITRC is a state-led organization that promotes innovative solutions for a variety of environmental issues. Teams are formed to develop technical/regulatory guidance documents and training to facilitate regulatory acceptance and sound implementation of new and innovative technologies and environmental techniques. The ITRC LNAPLs Team is, as are all ITRC teams, a balanced mix of environmental professionals representing state and federal government, industry, environmental consulting, and public stakeholders. The LNAPLs Team has included state regulators from Arkansas, Delaware, Georgia, Kansas, Missouri, Montana, Pennsylvania, South Carolina, Texas, Utah, Virginia, and Wyoming. Federal government partners include the Environmental Protection Agency (EPA) and the Department of Defense. The team also includes some of the top engineers, hydrogeologists, and scientists from the petroleum industry and environmental consulting.

The LNAPLs Team was formed to continue work started by the EPA Remediation Technologies Development Forum's (RTDF) NAPL Cleanup Alliance. That RTDF effort was disbanded in 2006 due to a lack of funding. The RTDF group was motivated and wanted to continue the work started, which fit perfectly into the ITRC structure. The RTDF group also comprised representatives from industry, industry groups, federal and state government, environmental consultants, and academia. The ITRC LNAPLs Team is composed of many of these original RTDF members and many new non-RTDF members. Many members of the LNAPLs Team also participated on ASTM's *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface* (ASTM 2007). ITRC LNAPLs Team products should be used in conjunction with the ASTM and RTDF products.

During 2008 the LNAPLs Team produced a two-part Internet-based training (IBT) on LNAPL "basics." Part 1, *An Improved Understanding of LNAPL Behavior in the Subsurface—State of Science vs. State of Practice,* explains how LNAPLs behave in the subsurface and examines what controls their behavior. Part 2, *LNAPL Characterization and Recoverability—Improved Analysis: Do you know where the LNAPL is and can you recover it?,* addresses LNAPL characterization and conceptual site model development as well as LNAPL recovery evaluation and remedial considerations. The LNAPL Team strongly recommends availing of the trainings as part of using this guidance. The IBT courses are available online (www.clu-in.org/live/archive) at no cost.

In 2009, the LNAPLs Team also issued a technical overview document: *Evaluating Natural Source Zone Depletion at Sites with LNAPL* (NSZD document). The NSZD document explains how LNAPL source zones naturally deplete through volatilization and dissolution and provides tools and techniques for quantifying these depletion rates. NSZD evaluations may provide a baseline against which to compare the effectiveness of current remedial strategies or for estimating the sustainability of such rates for long-term predictions.

1.2 Purpose

The purpose of this guidance is to provide a framework that uses LNAPL conceptual site model (LCSM) information to identify appropriate LNAPL remedial objectives and systematically screen LNAPL remedial technologies to identify technology(ies) best suited to achieve those objectives. The purpose of this document is not, however, to define when LNAPL remediation is warranted or to dictate the selected LNAPL remediation technology(ies). Those decisions are made in the context of regulations, policy, and other factors that are outside the scope of the framework and this guidance. If LNAPL remediation is warranted, the user is encouraged to use the framework steps in an iterative fashion as warranted, until the optimum LNAPL remedial technology(ies) is/are identified.

This guidance may be used for any LNAPL site regardless of size and current or future site use. The guidance may also be used not only in implementing an initial remedial strategy but also in evaluating an LNAPL remedial strategy previously deployed at a site. Remedial technologies will continue to improve, and newer technologies will be available in the future. The grouping and principles included in this document may be applied to new technologies. As discussed further in the guidance, users should adequately evaluate and research technologies identified using this framework for a particular site before deployment.

1.3 Issues Addressed in this Technical/Regulatory Guidance Document

This guidance addresses the issues of setting LNAPL remedial objective(s) and selecting the appropriate LNAPL remedial technology(ies) to achieve the objectives, both of which must be consistent with site understanding yielded from an adequate LCSM. This guidance also addresses the issue of setting the performance metrics by which remedial objective(s) achievement will be measured. In addition, the guidance addresses some issues that historically have resulted in ineffective LNAPL management.

Every state regulatory agency has a backlog of LNAPL sites that are not effectively approaching an end point (e.g., NFA), and this guidance can be used to evaluate the effectiveness of a currently deployed technology. It recommends four fundamental steps in developing an appropriate LNAPL remedial strategy to move LNAPL sites toward an end point. These steps should be completed *prior* to implementing a remedial strategy and reevaluated throughout the process as additional information becomes available. These steps are as follows:

1. Adequately characterize the site according to the complexity of the problem, including the development, use, and refinement of an LCSM.
2. Establish appropriate and *achievable* LNAPL remedial objectives for the site.
3. Develop an LNAPL remedial strategy designed to achieve the LNAPL remedial objectives.
4. Establish an acceptable outcome if the LNAPL remedial objectives are met (i.e., closure, NFA, release of liability, long-term monitoring, etc.)

Failure to complete any one of the steps may result in a failed and/or costly and ineffective remedial attempt. As simple as this seems, however, these steps are not always completed, and consequently, many LNAPL remedial projects have failed. The reasons for failure include insufficient LNAPL characterization leading to an inadequate site understanding (an inadequate LCSM); nondefined, unclear, or arbitrary remedial objectives (e.g., removal of LNAPL to sheen, or 1/8-inch thickness in a monitoring well); and poor selection or design of remedial strategies (perhaps due to an insufficient LCSM). In fact, in a state survey conducted by the LNAPLs Team (78 respondents from 38 states) nearly 50% responded that LNAPL remedial decisions were made using inadequate LCSMs.

The guidance also addresses the issue of determining the “maximum extent practicable.” This guidance advocates ending historic “poor” practices, some of which have become commonplace and have resulted from the “recover LNAPL to the maximum extent practicable” requirements. For example, setting an arbitrary maximum allowable in-well apparent LNAPL thickness (e.g., LNAPL $\leq$1/8 inch) as a remedial objective ignores site conditions, LNAPL type, and subsurface characteristics and may have limited or no correlation with LNAPL mobility, recoverability, or dissolved-phase groundwater or vapor-phase soil gas concentrations. Also, implementing a series of ineffective or inappropriate remedial approaches until all options have been exhausted to achieve “maximum extent practicable” is a poor practice.

Instead, this guidance advocates setting sound LNAPL remedial objectives, consistent with an LCSM and regulatory requirements; using a systematic, science-based approach to select the most suitable LNAPL remediation technology(ies); and then implementing the technology(ies) to the fullest benefit.

1.4 Organization

Sections 1 and 2 of this guidance identify the LNAPL regulatory problem and describe the scope of this guidance. The user of this guidance should read these sections at least once but will likely primarily use Sections 3–9, which are more tool based and process oriented.

Sections 3 and 4 discuss key LNAPL terminology and concepts from the IBT and reinforce the importance of a sound LCSM to identify LNAPL concerns. Understanding these terms and concepts is crucial for identifying applicable and achievable LNAPL remedial objectives and effectively applying the remedial selection framework. The remainder of the guidance focuses on the remedial technology screening and selection process. A summary of this process may be found in Section 5; however, each step is described in detail individually in Sections 6–8. Of particular value to the user is a series of three tables (Series A, B, and C tables) for each technology addressed in this guidance. The tables are presented in Appendix A, and the use of the tables is explained later in the guidance.

The LNAPLs Team hopes this guidance will encourage and help regulatory agencies to reevaluate their current policies and procedures relating to LNAPL management if current ones are failing.

1.5 Limitations

The 17 LNAPL remediation technologies addressed herein are the technologies the LNAPLs Team has experience with. Other technologies may also be applicable. The concepts and tools addressed herein, however, can also be used to screen those other technologies.

Dissolved- and/or vapor-phase concentrations may necessitate LNAPL remediation; however, this guidance focuses primarily on the LNAPL body, or “source zone.” Dissolved and vapor-phase issues have been adequately addressed through other documents and programs, such as ITRC’s vapor intrusion technical/regulatory guidance and numerous risk-based corrective action (RBCA) projects and programs. It is important to note, however, that although this guidance focuses primarily on the LNAPL body, compositional objectives (i.e., dissolved phase and vapor phase) may be used as LNAPL remedial objectives. Further, the focus of the guidance is on LNAPL in porous media—it does not specifically address LNAPL in fractured media, but technology considerations may also be generally applicable to fractured media.

Finally, as with all remedial decision-making processes, this guidance advocates pragmatic thinking, flexibility, involvement of qualified professionals, and cooperative team work. Plainly put, the optimum solution with LNAPL is rarely cleaning up every last drop, nor is it leaving it all in the ground when there is no human health risk. Even when there is no human health risk, there are commonly other considerations, such as liability, long-term stewardship, reduced monitoring, or reduced potential for LNAPL migration.

The key is to use a sound understanding of LNAPL to establish science-based, achievable objectives and to select the most pragmatic approach for achieving such objectives. Although this guidance may be used for any set of objectives, including those of states that do not embrace risk-based approaches because of water resource "nondegradation requirements," it is most likely to be useful where there is some regulatory flexibility. For example, if all LNAPL in a nondegradation-policy state must be recovered to background conditions, a greater LNAPL remedial time frame may be allowed to achieve that objective in low-risk settings (i.e., where receptors are protected). Such regulatory flexibility may make a wider range of LNAPL remedial technologies applicable to the site.

2. LNAPL REGULATORY CONTEXT AND MANAGEMENT

Historically, regulatory agencies have required removal of LNAPL to the "maximum extent practicable" (MEP) largely due to a provision in the Code of Federal Regulations (40 CFR §280.64) pertaining to underground storage tanks (USTs). Interpretation of MEP was left to the "implementing agency," most commonly the states and tribal territories. As a result, MEP has been interpreted many different ways, from no interpretation to a maximum allowable LNAPL thickness in a monitoring well (e.g., sheen or 1/8-inch thickness). LNAPL thickness-in-a-well requirements are sometimes written into state statutes and define when active LNAPL remediation efforts may be discontinued at a site. This approach often leads to perpetual LNAPL pumping (quite typically more groundwater than LNAPL is removed) and/or monitoring, even if the LNAPL body has been rendered immobile.

LNAPL removal to the "maximum extent practicable" will, in most cases (except for complete removal by excavation), leave some LNAPL behind in the subsurface. According to EPA (1996, p. IV-2): "Engineered systems are designed for use within discrete operating ranges, and no one recovery system will be optimally suited for all hydrocarbon release sites. It is also important to realize that only a portion of the total volume of the LNAPL release will be recoverable. Even under ideal conditions a significant proportion of the free product will remain in the subsurface as immobile residue."

Considerable effort in recent years has been directed at defining a decision-making framework for remediation of sites containing LNAPL, including protocols, technical information, and guidance that either directly advocate or establish such framework or address key concepts that could be used in the context of risk-based decision making (e.g., see API 2004, ASCWG 2006, EPA 2005a, EPA 2005b, ASTM 2007, TCEQ 2008, and WDC/WDNR 2008). A common element of these protocols is a framework where remedial objectives, together with remediation goals, end points, or performance metrics, are defined as part of a comprehensive LNAPL management strategy. The strategy is founded on a scientifically sound understanding of LNAPL behavior, potential risk, and a technical understanding of LNAPL remedial technology applicability and other relevant factors. This approach contrasts with historical approaches based on unclearly defined or qualitative goals; arbitrary LNAPL thickness goals; and/or an inadequate understanding of LNAPL characteristics, behavior, and remedial technologies.

While significant advances have been made in the development of protocols, the methods for identifying and quantifying appropriate LNAPL remedial objectives and end points that are based on and consistent with the LNAPL and site conditions remain largely unclear and inconsistent.

Until recently, within most regulatory environments, the technical factors that control LNAPL recovery and mobility have not been evaluated, and risk-based approaches to define LNAPL remedial objectives for free-phase LNAPL have not been considered. Examples of new paradigms for LNAPL management include that of Delaware, which defines LNAPL as "mobile," "free," or "residual" and provides an avenue for the responsible party to petition for a practicability determination (Fischer 2008). Texas has developed a comprehensive risk-based framework for nonaqueous-phase liquid (NAPL) management and a five-step process to address the rule requirements (TCEQ 2008).

Some states (e.g., Arkansas, Delaware, Texas, Wisconsin) are recognizing that understanding LNAPL behavior and recoverability allows for more realistic remedial objectives and better solutions. LNAPL remedial objectives can be crafted within existing regulatory frameworks to offer risk-based protective measures and define specific achievable and realistic MEP goals. LNAPL recovery objectives may include recovery to residual LNAPL saturation, recovery until LNAPL removal is not effective, or recovery until LNAPL plume expansion or migration has stopped.

State Survey Results

While developing this document, the LNAPLs Team sent a survey to regulators in all 50 U.S. states to learn how each state handles LNAPL management issues, remedy selection, and site closures. Seventy-eight regulators from 38 states responded, along with representatives from the Department of the Navy. The majority of state LNAPL programs fall under the jurisdictions of underground and aboveground storage tank sections or branches.

Most states manage their LNAPL sites through a combination of statute, regulation, policy, and guidance documents. In some states, if LNAPL problems occur at a site regulated under multiple regulatory branches (USTs, Resource Conservation and Recovery Act), then LNAPL remedial requirements may vary. Approximately, 35% responded that their actual practice for LNAPL remediation requirements was simply "MEP"; 25% responded "risk based and site specific." Alternatively, only one responded that the state LNAPL remediation requirement is "recover to sheen," 11% responded with a measurable amount, and 5% responded with "remove all detectable levels." Grouping the MEP and risk-based responses as site-specific requirements and grouping the "sheen," "measurable amount," and "removing all" as direct-measurement requirements, over 60% of the responses are site specific, and only 18% are direct measurement.

When asked what condition must be met to terminate active remediation systems, 40% responded that "all measurable LNAPL must be remediated," 40% responded that a "long-term monitoring plan" must be in place, 23% said engineering controls must be in place, 37% said institutional controls must be in place, and 26 % responded more than one of these (monitoring and engineering and/or institutional controls) was required.

Some states interpret that they are bound by statute to remove all LNAPL based on a law or policy stipulating nondegradation of waters. These states typically require active LNAPL recovery until LNAPL is no longer detected in a monitoring well. However, some states (e.g., California, Wyoming) enforce the statute with a more flexible management policy if potential receptors are protected. With respect to long-term management of the site, some degree of treatment or monitoring may be required, regardless of the time frame, until restoration of the surface or groundwater resource is attained. The California State Water Resources Control Board (SWRCB) has adopted Resolution No. 92-49, which does not require that the requisite level of water quality be met at the time of case closure. A case may be closed if the level will be attained within a reasonable period of time. The determinations of what constitutes a reasonable period of time to attain water quality objectives and the level of petroleum hydrocarbon constituents allowed to remain in the groundwater are based on the evaluation of all relevant factors, including but not limited to the extent and gravity of any threat to public health and the environment during the time period required to meet water quality objectives. The SWRCB has reviewed 16 petitions for closure since 1998, and 14 of these cases were closed (www.swrcb.ca.gov/water_issues/programs/ust/publications/closure_orders.shtml).

In recent years, approaches have been developed that place greater emphasis on risk considerations, as well as other defined non-risk-based objectives. Considerable effort in recent years has been directed at defining a decision-making framework for remediation of sites containing LNAPL, and this guidance provides such a framework.

3. KEY TERMINOLOGY AND CONCEPTS

The terminology and concepts presented in this section are critical for understanding an LNAPL site, setting appropriate and realistic LNAPL remedial objectives, and using this guidance to select appropriate LNAPL remedial technologies to achieve the remedial objectives.

3.1 Keys Terms

capillary pressure. The pressure difference between the nonwetting phase (e.g., LNAPL) and the wetting phase (e.g., groundwater) in a multiphase system such as in an LNAPL-groundwater system.

in-well LNAPL thickness. The observed thickness of LNAPL in a monitoring well, which relates to the pressure and spatial distribution of LNAPL in the subsurface (see Appendix D). In-well LNAPL thicknesses in monitor wells vary with changes in groundwater elevations.

LNAPL. A light, nonaqueous-phase liquid (e.g., petroleum oil, gasoline, diesel fuel) that has a density less than water (density < 1.0 g/cm^3) and is immiscible with water.

LNAPL control. Application of a technology that stabilizes an LNAPL body or impedes LNAPL migration without reliance on mass recovery or phase change.

LNAPL management. Assessment of LNAPL body conditions and LNAPL remediation as warranted.

LNAPL mass recovery. Application of a technology that physically removes LNAPL without significant reliance on phase change.

LNAPL phase change remediation. Reliance on or application of a technology that indirectly remediates the LNAPL body via recovery and/or in situ destruction/degradation of vapor or dissolved-phase LNAPL constituents.

LNAPL remedial objective. The LNAPL condition to be achieved by the remedial strategy or action that constitutes the end of LNAPL management for a specific LNAPL concern. When the objective is achieved, the LNAPL concern(s) necessitating LNAPL management has been eliminated. Because more than one LNAPL concern may need to be addressed to render the site protective, multiple objectives may be established so that the different LNAPL concerns are abated.

LNAPL remediation. Application of an LNAPL mass recovery, phase-change, and/or mass control technology to achieve a saturation and/or composition LNAPL remedial objective.

LNAPL remediation goal. A measurable, agreed-upon LNAPL remedial technology–specific end point selected to meet the associated LNAPL remedial objective. The goal depends on the site conditions and technology selected for the site.

LNAPL saturation. The LNAPL-filled fraction of the total porosity (e.g., 10% LNAPL saturation means 10% of the total porosity is filled with LNAPL).

migrating LNAPL. An LNAPL body that is observed to spread or expand laterally or vertically or otherwise result in an increased volume of the LNAPL extent, usually indicated by time-series data (Figure 3-1). Migrating LNAPL does not include LNAPL that appears in a well due to a dropping water table.

mobile LNAPL. LNAPL that exceeds the residual saturation. Includes migrating LNAPL, but not all mobile LNAPL is migrating LNAPL (Figure 3-1).

performance metric. The measured data or demonstrated change in site condition(s) capable of indicating progress toward and achievement of a remediation goal. This is the value or condition that is tracked to measure progress of a technology toward the end point.

phase change. Natural or induced partitioning of LNAPL constituents from the LNAPL phase to a sorbed, vapor, or dissolved phase within the soil solids, soil air, or groundwater, respectively.

pore entry pressure. The capillary pressure that must be exceeded before a nonwetting fluid (e.g., LNAPL) can invade pore space saturated with a wetting fluid (e.g., water).

residual LNAPL saturation. The range of LNAPL saturations greater than zero LNAPL saturation up to the LNAPL saturation, at which LNAPL capillary pressure equals pore entry pressure. Includes the maximum LNAPL saturation, below which LNAPL is discontinuous and immobile under the applied gradient (Figure 3-1).

Some terms introduced in this section have synonyms or have been used in different contexts in other works. The use of multiple terms to refer to one thing, a single term defined in multiple ways, and use of undefined terms has added some unfortunate confusion to the LNAPL field. Table 3-1 illustrates the terminology inconsistency and provides a cross-reference for key terms used in this guidance.

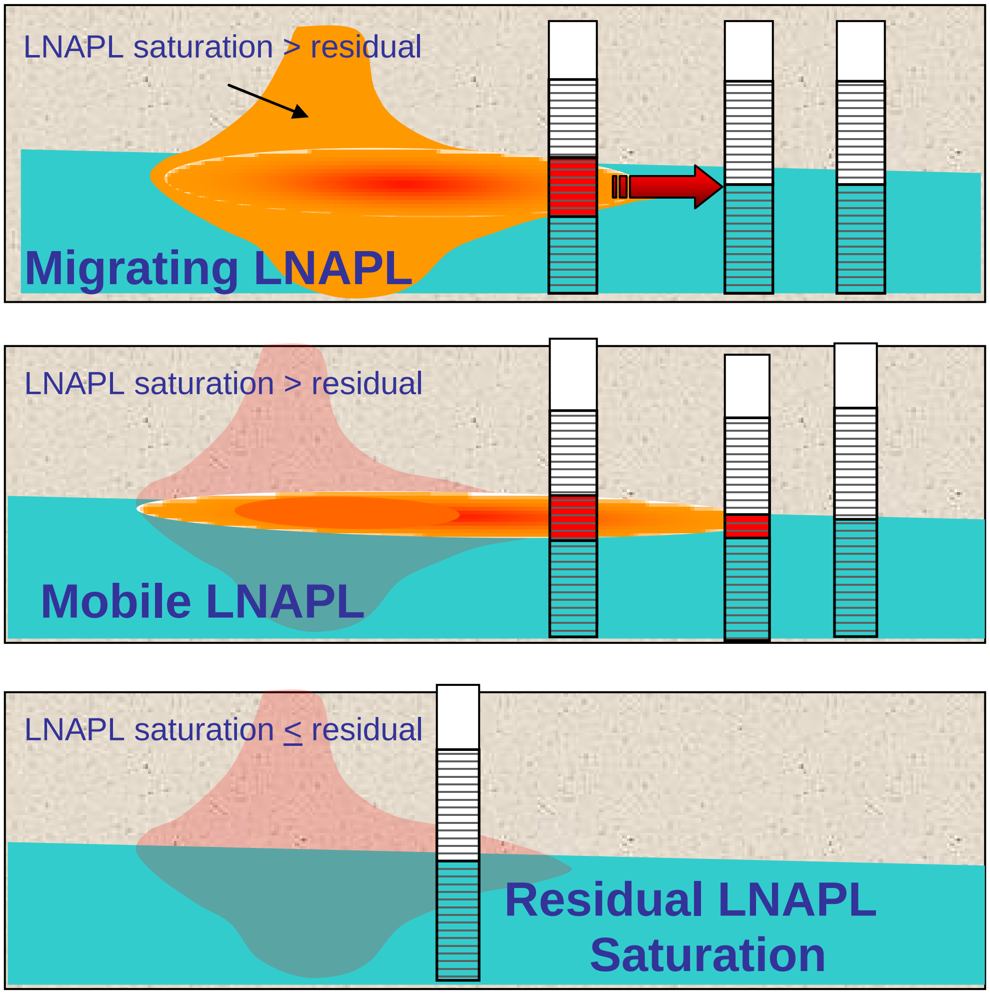


Figure 3-1. Three LNAPL conditions. The upper pane illustrates a situation before the LNAPL release is stopped. The LNAPL body is migrating due to the LNAPL head. LNAPL will continue to migrate laterally until the release is stopped and the LNAPL head dissipates. The middle pane illustrates a situation where the LNAPL release has been stopped and the LNAPL head has dissipated. LNAPL accumulates in a well installed in the LNAPL body, but the LNAPL is no longer migrating (spreading) laterally. The lower pane illustrates the situation where LNAPL is at residual saturation. LNAPL will not accumulate in a well installed in the LNAPL body unless the water table drops and LNAPL trapped below the water table can flow into the well.

Table 3-1. LNAPL terminology cross references

ITRC LNAPL-2 (this guidance) **LNAPL:** "A light, nonaqueous-phase liquid (e.g., oil), that has a density less than water (density < 1.0 g/cm^3) and is immiscible with water."	**40 CFR §280.64** (for UST sites)	Free product	---
	ASTM E2531-06 (ASTM 2007)	LNAPL	"a light nonaqueous phase liquid having a specific gravity less than one and composed of one or more organic compounds that are immiscible or sparingly soluble in water and the term encompasses all potential occurrences of LNAPL (for example, free, residual, mobile, entrapped)"
	EPA 510-R-96-001 (EPA 1996)	Liquid-phase hydrocarbons	"(residual and free) that are less dense than water are also referred to by the acronym LNAPL"
	EPA 540-S-95-500 (EPA 1995a)	LNAPL	"light nonaqueous phase liquids (LNAPLs) which have densities less than that of water"
ITRC LNAPL-2 **In-well LNAPL thickness:** "The observed thickness of LNAPL in a monitoring well, which relates to the pressure and spatial distribution of LNAPL in the subsurface (see Appendix D). In-well LNAPL thicknesses in monitor wells vary with changes in groundwater elevations."	**40 CFR §280.64** (for UST sites)	Thickness of free product observed or measured in wells	---
	ASTM E2531-06 (ASTM 2007)	---	---
	EPA 510-R-96-001 (EPA 1996)	Thickness of product in a well	"A commonly measured field parameter is the thickness of product in a well; however, this thickness is usually much greater than the true thickness of free product in the aquifer. This exaggeration is most pronounced in media with strong capillary effects (e.g., fine grained silts and clays) and least pronounced in media with weak capillary effects (e.g., sands and gravels). Exhibit III-12 illustrates this effect; however, the exhibit is not intended to be used to estimate the amount of free product at a particular site. This effect obviously is of great practical significance in the design of a free product recovery system."
	EPA 540-S-95-500 (EPA 1995a)	Apparent LNAPL Thickness	"The LNAPL thickness measured in a monitoring well has been reported to typically exceed the LNAPL-saturated formation thickness by a factor estimated to range between approximately 2 and 10 (Mercer and Cohen, 1990). Due to this difference, the LNAPL thickness measured in a monitoring well has been referred to as an apparent thickness (Figure 10)."

ITRC LNAPL-2 **Residual LNAPL Saturation**: "The range of LNAPL saturations greater than zero LNAPL saturation up to the LNAPL saturation, at which LNAPL capillary pressure equals pore entry pressure. Includes the maximum LNAPL saturation, below which LNAPL is discontinuous and immobile under the applied gradient (Figure 3-1)."	**40 CFR §280.64** (for UST sites)	Free product	---
	ASTM E2531-06 (ASTM 2007)	---	---
	EPA 510-R-96-001 (EPA 1996)	Residual-phase hydrocarbons	"Refers to separate phase liquids in the subsurface that are not present in an amount sufficient for them to flow readily into wells or excavations. In this situation, the petroleum hydrocarbons represent a separate residual phase, but not a "free product" phase. Residual phase hydrocarbons typically do not extend great lateral distances from the source of the release, and they tend to be relatively nonmobile."
	EPA 540-S-95-500 (EPA 1995a)	Residual saturation	"The saturation level where a continuous NAPL becomes discontinuous and is immobilized by capillary forces is known as the residual saturation (Sr)."
ITRC LNAPLs-2 **Mobile LNAPL:** "LNAPL that exceeds the residual saturation. Includes migrating LNAPL, but not all mobile LNAPL is migrating LNAPL (Figure 3-1)."	**40 CFR §280.64** (for UST sites)	Free product	"At sites where investigations under §280.62(a)(6) indicate the presence of free product, owners and operators must remove free product to the maximum extent practicable as determined by the implementing agency."
	ASTM E2531-06 (ASTM 2007)	Free LNAPL	"LNAPL that is hydraulically connected in the pore space and has the potential to be mobile in the environment."
	EPA 510-R-96-001 (EPA 1996)	Free product or free phase	---
	EPA 540-S-95-500 (EPA 1995a)	Potentially Mobile	---
ITRC LNAPLs-2 **Migrating LNAPL:** "An LNAPL body that is observed to spread or expand laterally or vertically or otherwise result in an increased volume of the LNAPL extent, usually indicated by time-series data (Figure 3-1). Migrating LNAPL does not include LNAPL that appears in a well due to a dropping water table."	**40 CFR §280.64** (for UST sites)	Free product	"Conduct free product removal in a manner that minimizes the spread of contamination into previously uncontaminated zones by using recovery."
	ASTM E2531-06 (ASTM 2007)	Mobile LNAPL	"free LNAPL that is moving laterally or vertically in the environment under prevailing hydraulic conditions."
	EPA 510-R-96-001 (EPA 1996)	Free product or free phase	---
	EPA 540-S-95-500 (EPA 1995a)	Mobile LNAPL or migrating LNAPL	---

3.2 Key Concepts

The following concepts are integrated into the framework and tools presented in this guidance, critical to understanding the logic used in the development of the tools, and key to appropriate application of this guidance. This guidance assumes the reader has attended both ITRC LNAPLs IBT courses and has become familiar with the concepts introduced in that training. The training courses are available online (www.clu-in.org/live/archive) at no cost.

3.2.1 Key IBT LNAPL Concepts

The key LNAPL concepts from the IBTs as applicable to this guidance are summarized below.

3.2.1.1 LNAPL Distribution

- LNAPL does not float on the water table in a uniform, high-saturation, "pancake"-like layer.
- The LNAPL is distributed above, at, and below the water table at saturations that vary vertically.

3.2.1.2 LNAPL Saturation

- Even when LNAPL is observed in monitoring wells, the soil pores are never 100% filled with LNAPL. The LNAPL saturation depends on the geology, LNAPL fluid properties, and release dynamics.
- LNAPL cannot be fully removed from soil by hydraulic recovery. The lowest saturation theoretically attainable by hydraulic recovery is residual saturation.

3.2.1.3 Residual LNAPL Saturation

- Residual LNAPL saturations are different for saturated and unsaturated zones. Other things being the same, unsaturated zone saturations are generally lower.
- Seasonal water table fluctuations can continually change the extent of the unsaturated and saturated zones, causing the LNAPL to redistribute vertically. Consequently the amount of mobile LNAPL changes, but the total LNAPL volume is unchanged.
- Residual LNAPL saturation is not a single number, but a range of saturations.

3.2.1.4 Mobile LNAPL

- LNAPL is considered mobile when it will accumulate in wells, assuming that the wells are properly constructed and located.
- LNAPL is mobile when LNAPL saturation is greater than the residual saturation.
- Mobile LNAPL is potentially hydraulically recoverable, but recoverability depends on several factors (see Section 3.2.1.8).

3.2.1.5 Migrating LNAPL

- LNAPL is migrating when it can be observed to move over time (i.e., expanding footprint).

- Migration of LNAPL cannot occur unless LNAPL is present within the mobile range of LNAPL saturations.
- LNAPL bodies with a terminated or finite source eventually stop migrating.

3.2.1.6 Mobile LNAPL vs. Migrating LNAPL

- Not all mobile LNAPL necessarily migrates, but LNAPL must be mobile in order to migrate.
- Multiple lines of evidence may be needed to make the distinction between mobile and migrating LNAPL.
- Reduction of LNAPL saturation to the residual range is not necessary for arresting LNAPL migration.

3.2.1.7 In-Well LNAPL Thickness

- For the same LNAPL in-well thickness, the volume of LNAPL per unit area of the formation can be different; it is generally higher in coarse-grained soils than in fine-grained soils.
- Due to the dependence of LNAPL thickness on geology and water-table fluctuations, caution should be exercised in using it as a sole metric for recoverability and migration.

3.2.1.8 LNAPL Transmissivity

- LNAPL transmissivity is an indicator of the formation to transmit LNAPL to a well.
- LNAPL transmissivity depends on soil type, LNAPL type, LNAPL saturation, and thickness of mobile LNAPL.
- Since LNAPL transmissivity is related to all key variables (see above) that can affect recoverability, it is a better metric than the conventionally used metric of in-well thickness.
- The higher the LNAPL transmissivity, the higher the LNAPL recoverability.

Insights into LNAPL Transmissivity as a Performance Metric

Beckett and Lundegard (1997) proposed that appreciable quantities of LNAPL cannot be recovered and that there is little migration risk associated with a well with an LNAPL transmissivity (Tn) of 0.015 ft^2/day. However, ITRC LNAPL Team members' experience indicates that hydraulic or pneumatic recovery systems can practically reduce Tn to values between 0.1 and 0.8 ft^2/day. Sites in state regulatory programs in California, Kentucky, and Florida have been closed or granted no further action after developing comprehensive LCSMs and operating recovery systems, followed by demonstrating lack of LNAPL recoverability (irrespective of in-well LNAPL thickness) remaining. The Tn values at these sites were estimated to be between 0.1 and 0.8 ft^2/day. Lower Tn values can potentially be achieved, but technologies other than hydraulic and pneumatic recovery technologies typically need to be employed to recover additional LNAPL. Further lowering of Tn is difficult and can be inefficient; that is, it can take very long to marginally reduce Tn without much benefit in terms of reduction of LNAPL mass, migration potential, risk, or longevity. A site in Virginia was granted closure after it was demonstrated that the recoverability could not be significantly reduced by multiphase extraction technology below the current status. Tn values occurring at this site were below 0.1 ft^2/day. Tn is a relatively new metric; further study and experience may refine this Tn range.

3.2.1.9 Concentrations in Groundwater and Vapor

- Most hydrocarbons are multiconstituent mixtures (e.g., gasoline, diesel), the exception being single-constituent LNAPLs (e.g., benzene).
- Concentrations in groundwater and/or vapor depend primarily on LNAPL composition. They have limited dependence on LNAPL saturation.
- Degree of LNAPL saturation has an effect on the longevity of the groundwater/vapor impacts.

3.2.1.10 Saturation vs. Composition

- Saturation reduction can be a key objective for a migrating plume.
- Composition change can be a key objective where groundwater and vapor concentrations are to be reduced.
- Where LNAPL migration is not an issue but LNAPL is mobile, LNAPL saturation reduction should be evaluated in terms of added net benefit.

Additional discussion pertaining to concepts stated in Sections 3.2.1.9 and 3.2.1.10 is presented below.

3.2.2 Other Key LNAPL Concepts

The following concepts are not a focus of the LNAPLs IBT courses but are important to understanding this guidance.

3.2.2.1 LNAPL Constituent Partitioning

Partitioning refers to the transfer of chemical mass into other phases adjacent to the LNAPL body. One relevant pair of phases, for example, is LNAPL and groundwater. The dissolved concentration of an LNAPL constituent in groundwater, according to Raoult’s Law, is the product of its concentration in the LNAPL (mole fraction) and the aqueous solubility of the pure LNAPL constituent and is not based on the saturation of LNAPL in the pore space. For example, if benzene is present in gasoline at 0.5% by weight (0.62 mole %), its effective solubility (equilibrium groundwater concentration) is approximately 11 mg/L (Scenario A, Figure 3-2). If the benzene concentration in gasoline were halved to 0.25% without any measurable reduction in LNAPL saturation (e.g., by soil vapor extraction [SVE]), the corresponding effective solubility would also be halved to about 5.5 mg/L (Scenario C, Figure 3-2).

On the other hand, if the LNAPL saturation were halved with no change in LNAPL composition (e.g., by hydraulic recovery), the dissolved benzene concentration in groundwater would be virtually identical. In this case, however, the longevity of groundwater impacts (Scenario B, Figure 3-2) would reduce some, as the total mass of benzene would be halved also. Similar relationships exist for other constituents in different pairs of phases, for example, LNAPL and soil gas (vapor pressure and mole fraction), groundwater and soil gas (Henry’s Law). In summary, the composition of LNAPL and not its mass (or saturation level) is the primary control for concentrations in adjacent phases (groundwater and soil gas).

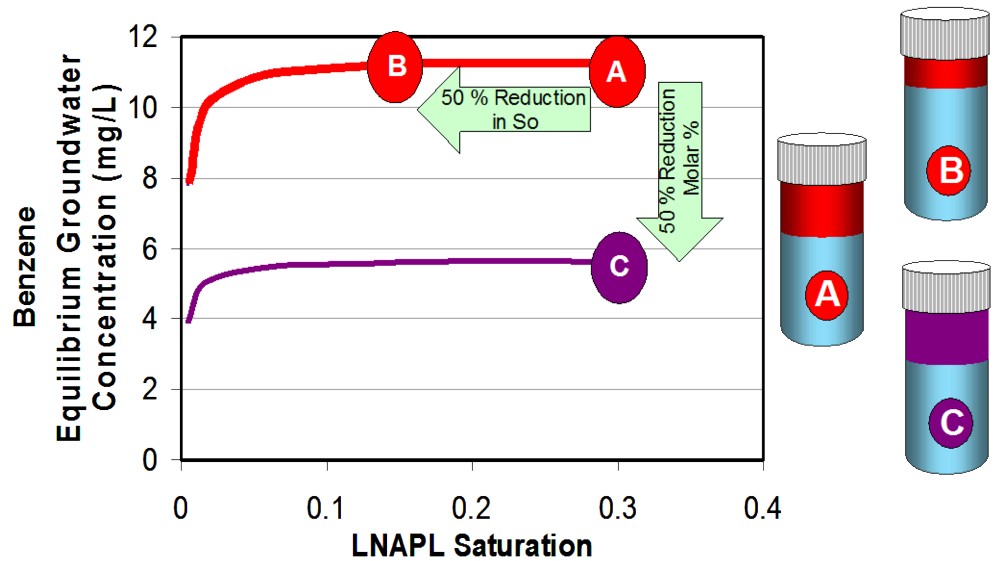


Figure 3-2. Comparison of LNAPL mass or saturation (So) reduction (A to B) and LNAPL composition reduction in constituent concentration in LNAPL (A to C) on dissolved benzene concentrations in groundwater. (Courtesy of S. Garg, Shell, 2009)

3.2.2.2 LNAPL Source Longevity

LNAPL source longevity for a specific LNAPL constituent is the time over which the constituent will potentially exist in the environment at concentrations of concern (e.g., longevity of benzene in groundwater from a gasoline LNAPL body—the lower-solubility fraction of LNAPL may still remain once the benzene is dissolved out). For a given site, LNAPL type, and hydrogeology, the longevity of a constituent in groundwater depends primarily on the length of the source zone and the LNAPL saturation within that zone, while its concentrations depend on the composition of the LNAPL.

Figure 3-3 conceptually illustrates the effect of partial LNAPL mass removal on the LNAPL constituent concentrations in a monitoring well positioned downgradient of the source area and screened completely across the initial thickness of LNAPL impacts. The LNAPL body is multiconstituent and uniform. The various cases are simulated for conceptual purposes with several assumptions (e.g., plug flow through the source, equilibrium dissolution, no contribution from the unsaturated zone and no biodegradation or other losses). In reality, these conditions are rarely met, but the concepts conveyed regarding the relative significance of LNAPL composition and saturation are applicable for decision making.

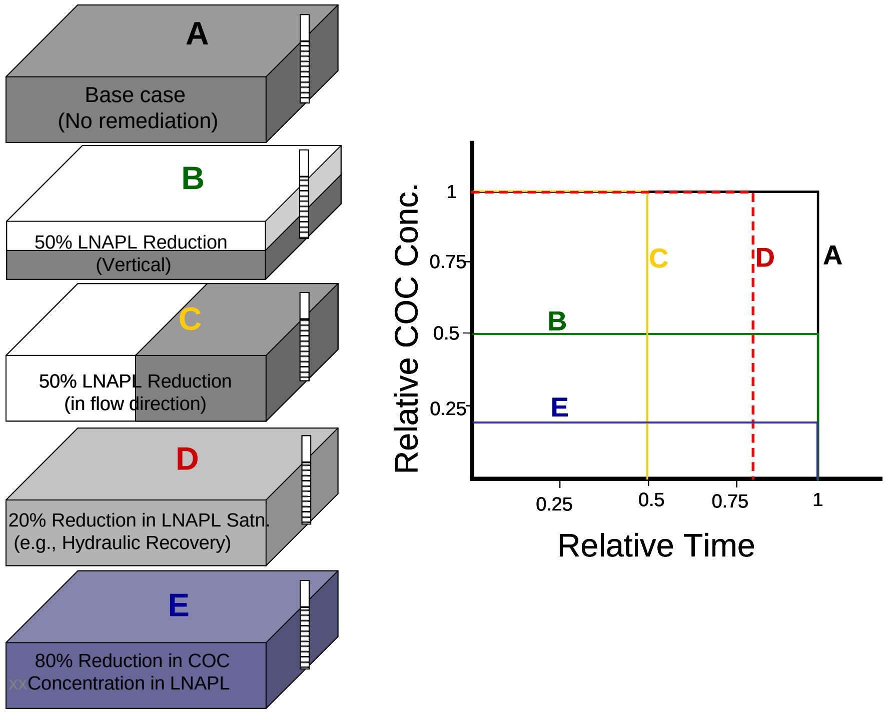


Figure 3-3. Conceptual effect of partial mass recovery on LNAPL constituent plume concentrations and longevity in a monitoring well positioned downgradient from the LNAPL source. Groundwater flow direction is from left to right. The figure assumes plug flow through the source, equilibrium dissolution, and no biodegradation. (Courtesy of S. Garg, Shell, 2009)

Case A: In this base case, where no active remediation is performed, the constituent dissolves into the groundwater until it is completely dissipated from the LNAPL. The groundwater constituent concentration and time to total depletion of the constituent in the other cases are normalized to those for Case A. For example, a relative time of 0.5 indicates that the constituent will completely dissolve away in one-half the time when compared to the base case. Similarly, a relative concentration of 0.5 indicates that the groundwater constituent concentrations in the monitoring well will be one-half of that in the base case.

Case B: In this case, the LNAPL source has been partially cleaned up vertically (e.g., partial excavation through a uniformly impacted LNAPL source). Since the well is screened across the entire thickness of the original LNAPL impacts, the constituent concentration in the monitoring well is reduced by one-half due to dilution. However, since the LNAPL source length is not changed, there is no reduction in the longevity of the groundwater impacts. Another example of this case could be the preferential or selective cleanup of only the coarse-grained layers at a site with interbedded geology.

Case C: In this case, the LNAPL source has been partially removed in the direction of groundwater flow (e.g., the upgradient one-half of the LNAPL source has been excavated, but the other one-half remains due to lack of access for excavation). The groundwater constituent concentrations in the monitoring wells are unchanged, but their longevity is reduced by one-half since twice as many source pore volumes are flushed from the source in the same amount of time, resulting in the constituent washing out earlier.

Case D: The theoretical end point of hydraulic recovery is residual saturation. Case D represents a scenario where 20% of the LNAPL is removed (reduced LNAPL saturation) via hydraulic recovery, resulting in a corresponding 20% reduction in time (or pore volumes) for complete dissolution of the constituent.

Case E: In this case, the constituent is preferentially removed from the LNAPL (e.g., via air sparging). For simplicity, it is assumed that there is no effect on any of the other LNAPL constituents and that the change in LNAPL saturation is negligible. Drawing from the earlier discussion on partitioning, there is a proportional decrease in groundwater constituent concentration. However, there is no change in the LNAPL source length or the LNAPL saturation; hence, the time required for complete dissolution of the constituent is unchanged.

4. CONSIDERATIONS/FACTORS AFFECTING LNAPL REMEDIAL OBJECTIVES AND REMEDIAL TECHNOLOGY SELECTION

The LCSM is the body of information describing aspects of the LNAPL and site setting necessary to satisfy the LNAPL remedial objectives (see ASTM 2007 for additional detailed discussions of the development and use of the LCSM). The LCSM is similar to a conceptual site model, which includes the source, pathway, and receptors, but the emphasis in the LCSM is on the source component (i.e., the LNAPL). Hence, the additional information to consider when mobile LNAPL is present include the following:

- Is there an ongoing LNAPL release?
- What is the LNAPL spatial distribution (i.e., the description of the LNAPL body)?
- Are there risk and exposure issues attributed to the presence of the LNAPL?
- Are there potential explosivity issues associated with the LNAPL?
- What are the LNAPL-specific regulatory requirements?
- What is the LNAPL recoverability?

The risk and exposure issues are typically evaluated through a risk assessment, which evaluates potential exposure and toxicity concerns associated with the presence of LNAPL. Specifically, the risk assessment qualifies and/or quantifies risks associated with potentially completed exposure pathways relating to the LNAPL. If there is a potentially completed exposure pathway (current or future) that results in an unacceptable risk, then the site is deemed to have a risk-based LNAPL concern and an associated LNAPL remedial objective. For example, a site may present an unacceptable risk if the LNAPL migrates to a different location with a sensitive receptor. Another example would be if the LNAPL results in dissolved- or vapor-phase LNAPL constituents that present unacceptable risks to sensitive receptors.

Another potential concern is site topography. Sites with significant topographical changes may present additional migration issues in the form of large LNAPL gradients and/or LNAPL seeps.

Groundwater pumping or site development excavations may also result in large LNAPL gradients and potential for LNAPL migration.

4.1 The LCSM "Science"

The LCSM may comprise some or all of the following scientific and technological information (hereinafter referred to as the "science"):

- site setting (historical and current)—includes land use, groundwater classification, presence and proximity of receptors, etc.)
- geological and hydrogeological information/setting
- LNAPL physical properties (density, viscosity, interfacial tensions, vapor pressure) and chemical properties (constituent solubilities and mole fractions)
- LNAPL body spatial distribution (vertical and horizontal delineation)
- LNAPL mobility and body stability information
- LNAPL recoverability information
- associated dissolved-phase and vapor-phase plume information
- LNAPL natural depletion processes

The level of detail required for a given LCSM is site specific and based on the complexity of environmental conditions at each site, the regulatory framework, and the overall LNAPL site management objectives. In certain situations, where the size of the LNAPL body is relatively small and a presumptive remedy such as soil excavation is adequate to satisfy the LNAPL remedial objectives, the LCSM may be limited, with a primary focus on LNAPL delineation or spatial distribution. In other situations, where a presumptive remedy such as excavation is not feasible, the LCSM needs adequate detail, particularly in terms of hydrogeology and LNAPL spatial distribution and mobility. With the distribution and mobility aspects understood, the recoverability aspects become more straightforward to select and manage.

LNAPL mobility and body stability are typically evaluated using various lines of evidence, including the following:

- historical data (e.g., depth to LNAPL/water levels, in-well thicknesses, evidence of LNAPL migration, stable or shrinking dissolved-phase plume associated with LNAPL, etc.)
- site-specific laboratory data (e.g., total petroleum hydrocarbons [TPH] profiling, LNAPL saturations in soil cores, etc.)
- analytical and/or numerical modeling results
- LNAPL risk assessment issues (including the consideration of both current and potential future site conditions)
- combinations of the above

LCSM Update and Evaluation

As the project progresses, the current LCSM should be regularly reevaluated in light of additional site/LNAPL data assessment, pilot test data, remedial technology performance metrics, and monitoring data. A complete and up-to-date LCSM allows the best possible decisions about application and operation of remedial technologies to be made (see ASTM 2007).

The extent to which one particular line of evidence may be needed for the LCSM depends on the other available lines of evidence. For example, at a site where there are little or no historical data or where the data sets are extremely sparse, there will be a stronger need for site-specific laboratory data (i.e., the need for extensive sampling and data collection), possibly supplemented with modeling to characterize LNAPL mobility and body stability issues. (In such data-limited situations, modeling may be difficult or particularly unreliable and need to be verified with subsequent data collection.) Conversely, at a site with an abundance of historical data covering the full range of water table fluctuations, there will likely be less need to engage in a comprehensive laboratory program or modeling effort to complete the LCSM.

Associated dissolved-phase and vapor-phase information can provide additional lines of evidence pertaining to the overall stability or instability of the LNAPL body. For example, a stable dissolved-phase plume also suggests that the LNAPL body is stable (i.e., not expanding or moving with time). Conversely, a migrating dissolved-phase plume may suggest that the LNAPL body is not stable. It should be noted that this guidance does not describe the methods and approaches for evaluating the distribution and mobility of dissolved and/or vapor-phase plumes. These phases are addressed in other guidance documents. Rather, the discussion regarding dissolved and vapor phases herein pertains to the assessment of the LNAPL body or source zone.

ASTM 2007 advocates development of an LCSM to evaluate LNAPL sites in a manner consistent with the RBCA process (see ASTM 2002 and 2004 for more information about the RBCA process). ASTM identifies three tiers of LCSMs based on site complexity: Tier 1, Tier 2, and Tier 3 (with site complexity and LCSM requirements increasing with increasing tier level). Generally speaking, the LCSM for a given site is deemed adequate (in terms of level of detail) when the collection of additional information regarding the site/LNAPL will not enhance decision making associated with the LNAPL remedial objectives. Table C-1 in Appendix C identifies example components associated with Tier 1, Tier 2, and Tier 3 LCSMs. Ultimately, however, the judgment of the environmental professional (e.g., environmental consultants, regulators, site owners) must be used to assess whether sufficient information has been gathered to make appropriate remediation decisions.

Although the LCSM is used as the scientific basis for all LNAPL remedial and/or management decisions and strategies, other considerations and factors must also be evaluated during the remedial technology screening and selection process. These other considerations/factors are discussed in following subsections.

4.2 LNAPL Remedial Objective, Remediation Goal, and Performance Metrics: Purpose and Relationship to LNAPL Remediation

The technology selection framework sorts the 17 LNAPL remediation technologies considered in this guidance by LNAPL remedial objective, LNAPL remediation goal, and performance metrics. This section describes the interrelationship among these three concepts. The text box on the next page illustrates the concepts by example, and the concepts are used in the screening tool presented in Section 6.

LNAPL Remedial Objectives, LNAPL Remediation Goals, and Performance Metrics

Step 1: Identify LNAPL concerns and set an LNAPL remedial objective for each concern:
For any one LNAPL occurrence, multiple LNAPL concerns may be identified. An LNAPL remedial objective is set to address each concern. For example:

- **Concern 1:** LNAPL present in a monitoring well. **Objective:** Reduce LNAPL mass.
- **Concern 2:** LNAPL is source of dissolved plume. **Objective:** Abate accumulation of dissolved-phase concentrations from LNAPL source.
- **Concern 3:** LNAPL migrating. **Objective:** Terminate LNAPL migration and reduce potential for LNAPL migration.

Step 2: Set LNAPL remediation goals for each LNAPL remedial objective:
For example, for the concerns LNAPL remedial objectives above:

- **Objective 1, Goal 1:** Recover LNAPL mass to MEP with dual-pump liquid extraction.
- **Objective 2, Goal 2:** Abate generation of dissolved-phase impacts with removal of soluble phase with ISCO.
- **Objective 3, Goal 3:** Abate LNAPL migration by sufficient physical removal of mobile LNAPL mass with dual-pump liquid extraction.

Step 3: Set performance metrics for the LNAPL remediation goal:
For each LNAPL remediation goal, there may be more than one potential performance metric. For Technology Option 1: select one or more.

- **Goal 1 and 3 Metric:** LNAPL transmissivity. **End point:** LNAPL transmissivity decreased to practical limit of hydraulic recovery.
- **Goal 2 Metric**: Stable dissolved plume. **End point:** Stabilized dissolved-plume concentrations and regulatory standards met at compliance point.

4.2.1 LNAPL Remedial Objective

To begin proper management of an LNAPL site, one must first determine the problems or concerns that the LNAPL poses at the site. A complete site characterization and LCSM will help to identify these concerns. Once the concerns are identified, appropriate "LNAPL remedial objectives" are set to eliminate the LNAPL concerns at the site. If there are three LNAPL concerns at the site, then an LNAPL remedial objective is set to eliminate each of the three LNAPL concerns at the site. Table 6-1 lists example LNAPL remedial objectives. The LNAPL remedial objectives are generally categorized in Table 6-1 as saturation, or composition-based, remedial objectives. For completeness, LNAPL aesthetics-based remedial objectives are also included in Table 6-1 but are not further discussed in this guidance. These saturation and composition categories are used to organize the technology selection process.

4.2.2 LNAPL Remediation Goal

As stated previously, this guidance provides an LNAPL technology selection framework to systematically evaluate 17 different LNAPL remediation technologies to select the technology(ies) best suited to address the particular LNAPL site conditions. The technology selection framework sorts the technologies into three groups (Section 3.2.2), each reflective of how the technologies in the group remediate LNAPL:

- LNAPL mass recovery (e.g., excavation or dual-pump liquid extraction)
- LNAPL mass control (e.g., physical containment or LNAPL soil stabilization)

- LNAPL phase change (e.g., air sparging/soil vapor extraction [AS/SVE], in situ chemical oxidation [ISCO])

One, two, or all three of the technology groups may be able to achieve the LNAPL remedial objective(s), but the different technology groups use different techniques. Therefore, in the context of an LNAPL technology group, the LNAPL remedial objective is stated as an "LNAPL remediation goal" to specify the condition or end point to be achieved by the technology group to satisfy the LNAPL remedial objective. Table 6-1 lists example LNAPL remediation goals for the example LNAPL remedial objectives.

4.2.3 Performance Metrics

For each LNAPL remediation goal, one or more "performance metrics" are defined. Performance metrics are measurable characteristics that relate to the remedial progress of a technology in abating the concern. The different LNAPL remediation technologies function differently (e.g., excavation vs. cosolvent flushing), and therefore, the performance metrics used to demonstrate progress toward and achievement of the LNAPL remediation goal depend on the technology used. Ideally, each performance metric has a predetermined value that describes when the technology has reached the limits of beneficial application. That is the end point metric for the technology chosen. Table 4-1 lists example performance metrics for the example LNAPL remediation goals.

Table 4-1. Example performance metrics

Example performance metrics	Description/comments
LNAPL transmissivity	Hydraulic recovery is likely ineffective for plumes exhibiting low LNAPL transmissivity.
LNAPL/water recovery ratio	Ratio of unit volume of LNAPL recovered per unit volume of water. Decreasing ratio indicates decreasing recovery effectiveness.
LNAPL/vapor recovery ratio	Ratio of unit volume of LNAPL recovered per unit volume of vapor. Decreasing ratio indicates decreasing recovery effectiveness.
Limited/infrequent in-well LNAPL thickness	Stated LNAPL thickness goal or LNAPL thickness typically not observed in monitoring well under average site conditions. Indicative that LNAPL is not consistently recoverable and the majority of remaining impacts are residual; excavation may be the only potential option.
Decline curve analysis	Analysis of unit volume of LNAPL recovery or recovery rate per unit time. Declining curve indicates decreasing recovery effectiveness (e.g., decline curve analysis indicates that based on the LNAPL recovered the remaining LNAPL is either small or the time to recover relative to the remaining volume may be impractical).
Unit cost per gallon LNAPL recovered	Increasing cost/gallon LNAPL recovered indicates decreasing cost-effectiveness (cost may not always be in line with regulatory rules; however, in certain circumstances this metric can be useful).
Soil concentration/soil concentration profile	Soil concentrations in LNAPL area at regulatory criteria, or desired soil concentration profile demonstrated.
LNAPL recovery rate vs. estimated LNAPL flux	The recovery system either diminishes the driving LNAPL gradient and/or achieves a higher recovery rate than estimated by flux migration across the width of the LNAPL body front.
LNAPL saturation profile	Comparison of saturations before and after treatment to demonstrate reduced saturations.

Example performance metrics	Description/comments
LNAPL body footprint stabilized	Will technology counter existing LNAPL driving gradient and/or capture migrating LNAPL? Comparison of LNAPL plume footprint before and after treatment to demonstrate nonincreasing footprint size.
Dissolved-phase plume stabilized	If exhibited, then it is an indication of a stable LNAPL body.
No first LNAPL occurrence in downgradient well	LNAPL never enters a monitoring well installed outside of LNAPL body.
Soil concentration for soil stability	Concentrations reduced to the regulatory limit.
Soil concentrations	Concentrations reduced to the regulatory limit.
Dissolved-phase concentration	Concentrations reduced to regulatory standard at a compliance point.
Vapor-phase concentration	Concentrations reduced to regulatory standard at a compliance point.
LNAPL composition	Reduced mole fraction of volatile or soluble LNAPL constituents.

4.3 LNAPL Remedial Technologies

Many LNAPL remedial technologies exist, each with unique applicability and capability. Some are capable of achieving a greater degree of LNAPL removal than others. One should consider, however, that an increasing capability (aggressiveness) of LNAPL remediation may also increase costs or remedial time frames nonlinearly. Additionally, some technologies are more innovative than others, and while innovation should be encouraged, those technologies may have limited application at the field scale and therefore represent a lower degree of certainty as to their effectiveness and costs. Ideally, the degree of LNAPL remediation is commensurate with that warranted to satisfy applicable risk or non-risk-based federal and state regulations and overall project objectives.

The selected LNAPL remedial technology should align with the particular LNAPL remedial objective and LNAPL remediation goal. As indicated by the different nature of LNAPL remediation goals and performance metrics discussed in the previous section, different LNAPL remedial technologies have different applicability and capabilities. Mismatching an LNAPL remedial objective and technology does not work. While there may be other categories for different remediation types and variations on the types, for the purposes of this guidance, the LNAPL remedial technologies are divided into three basic groups:

- LNAPL mass-recovery technology
- LNAPL mass-control technology
- LNAPL phase-change technology

The three technology groups are intended to help associate a technology with the general context of how that technology remediates the LNAPL. Further, the three technology groups illustrate how a remedial technology can be used in the context of the LNAPL remedial objectives and remediation goals. A specific technology, however, may not necessarily be a pure end member of the technology group to which it is assigned. For example, phase-change remediation technologies inherently reduce LNAPL saturation but via an intermediate process of partitioning the LNAPL to another phase (LNAPL volatilization to the vapor phase, LNAPL dissolution to the dissolved phase), rather than direct bulk removal as in the case of hydraulic recovery (e.g., skimming).

The technologies are assigned to a technology group based on the primary mechanism by which they address LNAPL and whether they are used primarily to address saturation or composition objectives, not by their secondary or coincidental effects. In instances where they equally address saturation and composition objectives, they are identified as both LNAPL mass-recovery and LNAPL phase-change technologies. The applicable technology type is stated for each of the 17 technologies considered in this guidance as the technology is introduced in Table 5-1. Table 5-2 indicates whether the technology can be applicable to a composition objective, saturation objective, or both. In this regard, there may appear to be an inconsistency with Table 5-1, but the LNAPLs Team chose to acknowledge the secondary or coincidental benefits in Table 5-2, with the primary mechanism highlighted.

4.3.1 LNAPL Mass-Recovery Technology

LNAPL mass-recovery technologies directly recover LNAPL via physical removal in the case of excavation or hydraulic recovery (e.g., LNAPL pumping or skimming). Hydraulic recovery may be pursued with or without flow augmentation by using remedial techniques that reduce LNAPL viscosity or interfacial tension (e.g., surfactants or solvents), thereby enhancing LNAPL flow. LNAPL mass-recovery technologies address saturation-based LNAPL remedial objectives. With the exception of excavation, which can achieve complete LNAPL removal, subject to logistical and practical limits, LNAPL mass recovery using pumping or skimming technologies is limited to reducing LNAPL saturation to residual saturation. At residual saturation, LNAPL will not flow and, therefore, hydraulic recovery is no longer possible (see Section 3.2.1.8 for other discussion regarding the limit of hydraulic recovery). Some technologies, however, change the LNAPL properties and enhance hydraulic recovery, further reducing the residual LNAPL saturation. Given limitations subsequently described in this guidance, however, at the limit of hydraulic recovery technologies, some LNAPL will remain at saturations above residual. LNAPL mass-recovery technologies are the most frequently used technologies for LNAPL remediation. Appropriate design and implementation of such systems is commonplace, and their costs and technical limits are generally well understood. LNAPL mass-recovery technologies are discussed in Section 5.

4.3.2 LNAPL Phase-Change Technology

LNAPL phase-change technologies do not directly remove LNAPL from the environment as is the case for LNAPL mass-recovery technologies. Instead, LNAPL phase-change technologies exploit the tendencies of LNAPLs to partition to other phases by increasing the rates of volatilization or dissolution of the LNAPL constituents by different means. Those LNAPL constituents are then degraded or captured in the vapor or dissolved phase and removed from the environment. As the LNAPL constituents are removed from the LNAPL, the composition of a multiconstituent LNAPL is changed by loss of the LNAPL constituents that readily degrade, volatilize, or dissolve from the LNAPL. LNAPL phase-change technologies are thus primarily applicable to composition-based LNAPL remedial objectives. With LNAPL phase change comes some saturation reduction (e.g., SVE for gasoline LNAPL can reduce bulk LNAPL saturation). These technologies may therefore have some secondary application for saturation-based LNAPL remedial objectives.

LNAPL phase-change technologies are not limited by residual LNAPL saturation because they do not depend on the presence of mobile LNAPL. Some LNAPL phase-change technologies are more elaborate to design and implement than LNAPL mass-recovery technologies, and their costs and limits may be not be as well understood as those of LNAPL mass-recovery technologies. Thus, LNAPL phase-change technologies may be more costly to design and deploy, but strategic/targeted application may minimize such limitations and possibly shorten the overall LNAPL remediation life cycle. For example, to achieve a remedial objective of LNAPL recovery to saturations less than residual, it might be more appropriate to hold off deployment of the LNAPL phase-change remedial technology until after an LNAPL mass-recovery technology has reached its recovery limit or an LNAPL remediation goal is reached that is set to transition between the two technologies. LNAPL phase-change technologies are identified in Section 5, but some may also be identified as LNAPL mass-recovery technologies, depending on how the technology is deployed.

4.3.3 LNAPL Mass-Control Technology

LNAPL mass-control technologies stabilize a migrating LNAPL by reducing the LNAPL saturation via blending a binding agent with the LNAPL zone (mixing technologies) or by physically blocking LNAPL migration (containment technologies). Such technologies alone may satisfactorily meet the remedial objective or can be used in combination with LNAPL mass-recovery or LNAPL phase-change technologies. Additional long-term operation and maintenance and stewardship requirements may also be warranted, depending on site conditions and property use. Specifically, LNAPL mass-control technologies are primarily suited for saturation-based LNAPL remedial objectives by limiting mobility or eliminating migration. The containment technologies are limited in applicability to LNAPL saturations in excess of residual saturation, since at residual saturations the LNAPL body is, by definition, immobile. In some instances, mixing technologies may also reduce cross-media impacts (e.g., recharge infiltration and leaching through the LNAPL zone) since some binding agents (e.g., Portland cement) can reduce the soil permeability of the LNAPL zone or degrade the volatile or soluble LNAPL constituents. LNAPL mass-control technologies are identified in Section 5.

4.4 Other Considerations/Factors that Affect Remedial Alternatives

Other considerations/factors may need to be assessed in conjunction with the LCSM to establish the true LNAPL concerns for the site, identify applicable LNAPL remedial objectives, and evaluate potential remedial/management strategies:

- LNAPL regulatory requirements
- additional considerations (business, stakeholder, community, etc.)

LNAPL concerns and associated LNAPL remedial objectives may be associated with regulatory requirements or additional considerations such as business plans, stakeholder concerns, and community issues. Stakeholders often have valuable information about site characteristics and history that can enhance the evaluation process and improve the quality of remediation and monitoring decisions. Sampling, evaluation, and deployment decisions need to take into account the current usage of the site and businesses' and community's planned or potential future use of the site. Table 4-2 lists common stakeholder interests, in no particular order of importance.

Table 4-2. Example of stakeholder interests (modified from EPA 2005b)

Stakeholder	Interests
Facility owner	• Protect human health and the environment • Achieve regulatory compliance • Use risk-based techniques • Minimize/eliminate disruption of operations • Minimize costs • Reduce long-term treatment and liabilities
Regulatory agencies	• Protect human health and the environment • Protect groundwater resources • Achieve regulatory compliance • Eliminate off-site impacts • Involve stakeholders • Maintain reasonable schedule • Obtain reimbursement for oversight costs
Other stakeholders (local/county agencies, property owners, special interest groups, etc.)	• Protect human health and the environment • Optimize zoning • Maximize tax revenues • Accelerate remediation schedule • Maximize quality of life • Protect groundwater resources • Protect property values • Preserve land use options

Some regulatory agencies adopt an RBCA approach where the regulatory requirements are directly connected to the identified site risks (i.e., the objective of the regulatory requirement is to mitigate the identified unacceptable risk). Other regulatory requirements/drivers are based on statutes and policies and not necessarily connected to site-specific risk issues.

Some states recognize that the best practices to implement for a particular site or portion of a site, based on a scientific understanding of LNAPL behavior and recoverability, do not necessarily satisfy statutes, regulations, and policies. Some states use the site engineering and chemical data to determine or evaluate the appropriate LNAPL remedy end points that should be applied to a particular site, without constraint of conflicting statutes, regulations, or policies.

Wisconsin uses primarily three assessment parameters: soil type, LNAPL fluid properties, and apparent LNAPL thickness in monitoring wells (WDC/WDNR 2008). Data associated with these parameters are used to evaluate whether LNAPL is migrating or stable and whether the LNAPL volume is significant. This type of evaluation is used to determine whether recovery actions are warranted. Assessment data and some form of feasibility testing are used to identify a remedy and establish credible expectations of the remedy during the selection process. This process and results are compared to risk factors and receptors if the data and testing suggest that active LNAPL recovery is not practicable. If there are no receptors, the overall risk is low, and future conditions are unlikely to change, then exhaustive testing of unproven technologies may not be warranted, and the focus is shifted to other remedies, such as excavation (if practical) or passive management alternatives (limited groundwater monitoring) if the dissolved-phase plume associated with the LNAPL is not expanding or threatening potential receptors.

Other states address the human health and environmental concerns associated with LNAPL releases by integrating risk-based decision making into the LNAPL management process (TCEQ 2008). LNAPL remediation goals are specifically defined end points that offer risk-based protective measures and define specific readily achievable MEP recovery goals. LNAPL recovery goals typically include recovery to residual LNAPL saturation, recovery until effective LNAPL removal is exhausted, or recovery until LNAPL migration has halted. Additionally, the Texas guidance clarifies when LNAPL recovery is required and when a control-based alternative may be available.

States such as Wyoming, bound by statute to enforce LNAPL remedial options based on nondegradation of state waters, typically require active LNAPL recovery until LNAPL is no longer detected in a monitoring well. Some of these states, however, enforce the statute with a more flexible management policy if potential receptors are protected. With respect to long-term management of the site, some degree of treatment or monitoring is required regardless of the time frame, until restoration of the groundwater resource is attained.

4.5 Integration of the LCSM and LNAPL Remedial Technology Selection

The science and other considerations need to be evaluated concurrently, in a parallel manner, to ensure that the basic framework for the LCSM has been developed to the appropriate extent for the given site, and is acceptable under the applicable regulatory program. Once the framework has been developed, the LCSM continues to evolve through an iterative refinement process until the final LNAPL remedy has been selected and evaluated for the site. Hence, the process begins with a simpler LCSM and may move to a more complex analysis as dictated by the site requirements, costs, uncertainties, and judgment of the stakeholders.

The LCSM provides the information necessary to determine whether or not LNAPL remediation is warranted, and if it is warranted, the basis for LNAPL remediation (e.g., concern, portion/condition of LNAPL body needing remediation, and urgency). As stated earlier, the decision to require or conduct LNAPL remediation is outside the scope of this guidance. The LCSM information is integrated into the LNAPL remedial selection process as presented in Sections 6–8. Section 5 provides an overview of the LNAPL remedial technology selection process.

5. LNAPL REMEDIAL TECHNOLOGY SELECTION PROCESS OVERVIEW

The following sections of this guidance explain the remedial technology selection process. The process is illustrated in Figure 5-1 as a somewhat stepwise, linear process; however, remedy selection is seldom linear. The focus, therefore, should not be *when* (i.e., in what sequence) each of these sections is addressed but rather that they *are* addressed, *sufficiently*. If they are, then the regulating authority can be confident that an optimum remedial strategy is being proposed, and the proposing entity can be confident that the proposal is likely to be effective and ultimately approved.

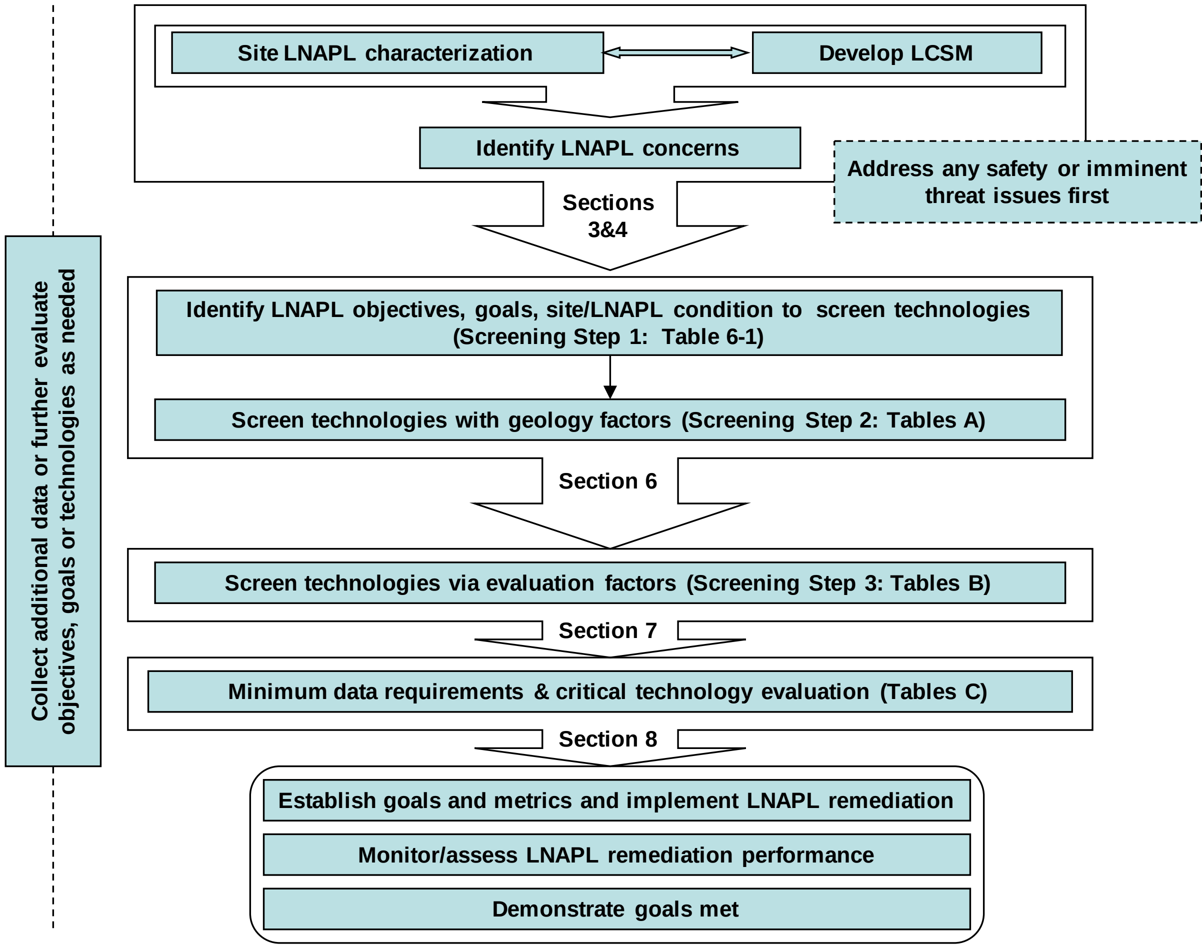


Figure 5-1. LNAPL technology screening, selection, and implementation overview.

As seen in Figure 5-1, after LCSM development and identifying the LNAPL concerns and LNAPL remedial objectives, Section 6 begins the remedial technology screening process. Table 5-1 summarizes the 17 technologies addressed in this guidance. As stated earlier, these are the technologies the LNAPLs Team has most experience with, and some are more innovative or have a more proven LNAPL remediation track record than others. Table 5-2 summarizes information about each of the technologies. Table 5-2 is intended to be used not for remedy selection but to gain basic information about the technologies. Because of the number of potential technology candidates and the wide array of applicability of the technologies, selection of an appropriate technology is multifaceted. A good selection process considers the LNAPL remedial objectives in light of the overall site objectives, LNAPL remediation goals, site conditions, LNAPL type, and other factors. Sections 6–8 of this guidance establish an LNAPL remedial technology selection framework and present screening process steps to simplify and streamline the LNAPL remedial selection process. At each step additional site information/data may be needed to refine the LCSM to complete the steps. To assist with this stepwise screening process, Appendix A provides a series of three tables (A-, B-, and C-series tables) on each of the 17 technologies considered in this guidance that correlate with Sections 6, 7, and 8, respectively. Other technologies that develop in the future can be added to this framework.

Table 5-1. Overview of LNAPL remedial technologies

LNAPL technology	Description of technology
1. Excavation	LNAPL body is physically removed and properly treated or disposed (LNAPL mass recovery).
2. Physical or hydraulic containment (barrier wall, French drain, slurry wall, wells, trenches)	Subsurface barrier is constructed to prevent or impede LNAPL migration (LNAPL mass control).
3. In situ soil mixing (stabilization)	LNAPL body is physically/chemically bound within a stabilized mass to reduce mobility (LNAPL mass control).
4. Natural source zone depletion (NSZD)	LNAPL constituents are naturally depleted from the LNAPL body over time by volatilization, dissolution, absorption and, degradation (LNAPL phase-change remediation).
5. Air sparging/soil vapor extraction (AS/SVE)	AS injects air into LNAPL body to volatilize LNAPL constituents, and vapors are vacuum extracted. AS or SVE can also be used individually if conditions are appropriate (LNAPL phase-change remediation).
6. LNAPL skimming	LNAPL is hydraulically recovered from the top of the groundwater column within a well (LNAPL mass recovery).
7. Bioslurping/enhanced fluid recovery (EFR)	LNAPL is remediated via a combination of vacuum-enhanced recovery and bioventing processes (LNAPL phase-change remediation).
8. Dual-pump liquid extraction (DPLE)	LNAPL is hydraulically recovered by using two pumps simultaneously to remove LNAPL and groundwater (LNAPL mass recovery).
9. Multiphase extraction (MPE)(dual pump)	LNAPL and groundwater are removed through the use of two dedicated pumps. Vacuum enhancement is typically added to increase LNAPL hydraulic recovery rates (LNAPL mass recovery).
10. Multiphase extraction (MPE) (single pump)	LNAPL is recovered by applying a vacuum to simultaneously remove LNAPL, vapors, and groundwater (LNAPL mass recovery).
11. Water flooding (incl. hot water flooding)	Water is injected to enhance the hydraulic LNAPL gradient toward recovery wells. Hot water may be injected to reduce interfacial tension and viscosity of the LNAPL and further enhance LNAPL removal by hydraulic recovery (LNAPL mass recovery).
12. In situ chemical oxidation (ISCO)	LNAPL is depleted by accelerating LNAPL solubilization by the addition of a chemical oxidant into the LNAPL zone (LNAPL phase-change remediation).
13. Surfactant-enhanced subsurface remediation (SESR)	A surfactant is injected that increases LNAPL solubilization and LNAPL mobility. The dissolved phase and LNAPL are then recovered via hydraulic recovery (LNAPL phase-change remediation and LNAPL mass recovery).
14. Cosolvent flushing	A solvent is injected that increases LNAPL solubilization and LNAPL mobility. The dissolved phase and LNAPL are then recovered via hydraulic recovery (LNAPL phase-change remediation and LNAPL mass recovery).
15. Steam/hot-air injection	LNAPL is removed by forcing steam into the aquifer to vaporize, solubilize, and induce LNAPL flow. Vapors, dissolved phase, and LNAPL are recovered via vapor extraction and hydraulic recovery (LNAPL phase-change remediation, and LNAPL mass recovery).
16. Radio-frequency heating (RFH)	Electromagnetic energy is used to heat soil and groundwater to reduce the viscosity and interfacial tension of LNAPL for enhanced hydraulic recovery. Vapors and dissolved phase may also be recovered via vapor extraction and hydraulic recovery (LNAPL phase-change remediation and LNAPL mass recovery).
17. Three- and six-phase electrical resistance heating	Electrical energy is used to heat soil and groundwater to vaporize volatile LNAPLs constituents and reduce the viscosity and interfacial tension of LNAPL for enhanced hydraulic recovery. Vapors and dissolved phase may also be recovered via vapor extraction and hydraulic recovery (LNAPL phase-change remediation and LNAPL mass recovery).

Table 5-2. Summary information for remediation technologies

LNAPL technology	Advantages	Disadvantages[a]	Applicable geology (fine, coarse)[b]	Applicable to unsaturated zone, saturated zone[c]	Applicable type of LNAPL[d]	LNAPL remedial objective type (saturation, composition)[e]	Potential time frame[f]	Appendix A reference table numbers
Excavation	100% removal, time frame	Accessibility, depth limitations, cost, waste disposal	F, C	U + S	LV, LS, HV, HS	**Sat** + Comp	V. short	A-1.x
Physical or hydraulic containment (barrier wall, French drain, slurry wall)	Source control, mitigation of downgradient risk	Hydraulic control required, site management, cost, depth and geologic limitations	F, C	S	LV, LS, HV, HS	**Sat** + Comp	V. long	A-2.x
In situ soil mixing (stabilization)	Time frame, source control	Accessibility, required homogeneity, depth limitations, cost, long-term residual management	F, C	U + S	LV, LS, HV, HS	**Sat** + Comp	V. short to short	A-3.x
Natural source zone depletion	No disruption, implementable, low carbon footprint	Time frame, containment	F, C	U + S	HV, HS	Sat + **Comp**	V. long	A-4.x
Air sparging/soil vapor extraction	Proven, implementable, vapor control	Does not treat heavy-end LNAPLs/low-permeability soils, off-gas vapor management	C	U + S	HV, HS	Sat + **Comp**	Short to medium	A-5.x
LNAPL skimming	Proven, implementable	Time frame, limited to mobile LNAPL, ROI[g]	F, C	S	LV, LS, HV, HS	**Sat**	Long to v. long	A-6.x
Bioslurping/ enhanced fluid recovery	Proven, implementable, vapor control	Time frame, limited to mobile LNAPL, ROI	F, C	U + S	LV, LS, HV, HS	Sat + **Comp**	Long to v. long	A-7.x
Dual-pump liquid extraction	Proven, implementable, hydraulic control	Time frame, limited to mobile LNAPL, ROI	C	S	LV, LS, HV, HS, > residual	**Sat**	Long to v. long	A-8.x
Multiphase extraction (dual pump)	Proven, implementable, hydraulic control	Generated fluids treatment	C	S	LV, LS, HV, HS, > residual	**Sat** + Comp	Medium	A-9.x

Table 5-2. Summary information for remediation technologies

LNAPL technology	Advantages	Disadvantages[a]	Applicable geology (fine, coarse)[b]	Applicable to unsaturated zone, saturated zone[c]	Applicable type of LNAPL[d]	LNAPL remedial objective type (saturation, composition)[e]	Potential time frame[f]	Appendix A reference table numbers
Multiphase extraction (single pump)	Proven, implementable, hydraulic control, vapor control	Generated fluids treatment	C	U + S	LV, LS, HV, HS, > residual	**Sat** + Comp	Medium	A-10.x
Water flooding (incl. hot water flooding)	Proven, implementable	Capital equipment, hydraulic control required, homogeneity, flood sweep efficiency[h]	C	S	LV, LS, HV, HS, > residual	**Sat**	Short	A-11.x
In situ chemical oxidation	Time frame, source removal	Rate-limited hydraulic control required, by-products, cost, vapor generation, rebound, accessibility/spacing homogeneity, MNO_2 crusting	C	U (ozone oxidant) + S	HV, HS	**Comp**	V. short to short	A-12.x
Surfactant-enhanced subsurface remediation	Time frame, source removal	Hydraulic control required, by-products, cost, dissolved COCs[i] treatment, required homogeneity, water treatment, access	C	S	LV, LS, HV, HS	**Sat + Comp**	V. short to short	A-13.x
Cosolvent flushing	Time frame, source removal	Hydraulic control required, by-products, cost, vapor generation, access, sweep efficiency	C	S	LV, LS, HV, HS	**Sat + Comp**	V. short to short	A-14.x
Steam/hot-air injection	Time frame, source removal, proven, implementable	Hydraulic control required, capital equipment, cost, required homogeneity, vapor generation, access, sweep efficiency	C	U + S	LV, LS, HV, HS	**Sat + Comp**	V. short	A-15.x
Radio-frequency heating	Time frame, source removal, proven, implementable	Hydraulic control required, by-products, cost, vapor generation, access	F	U + S	LV, LS, HV, HS	**Sat** + Comp	V. short	A-16.x

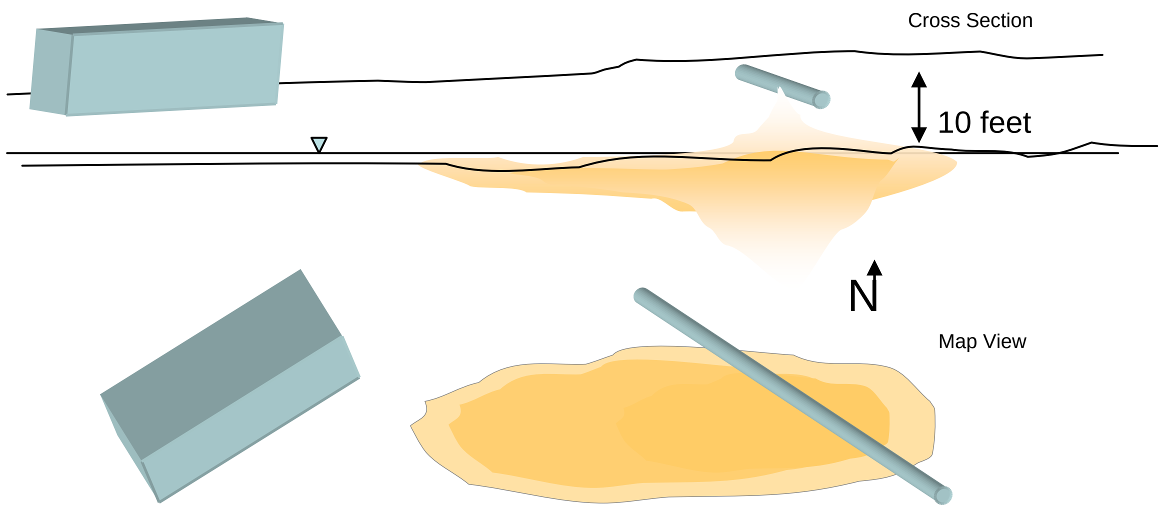
Table 5-2. Summary information for remediation technologies

LNAPL technology	Advantages	Disadvantages[a]	Applicable geology (fine, coarse)[b]	Applicable to unsaturated zone, saturated zone[c]	Applicable type of LNAPL[d]	LNAPL remedial objective type (saturation, composition)[e]	Potential time frame[f]	Appendix A reference table numbers
Three- and six-phase electrical resistance heating	Low-permeability soils, time frame, source removal	Hydraulic control required, by-products, cost, energy required, vapors, spacing, access	F	U + S	LV, LS, HV, HS	**Sat + Comp**	V. short	A-17.x

[a] Any of these technologies may have particular state-specific permitting requirements. Check with your state regulatory agency.
[b] Applicable geology: F = clay to silt, C = sand to gravel.
[c] Applicable zone: U = unsaturated zone, S = saturated zone.
[d] LNAPL type: LV, LS = low volatility, low solubility, medium or heavy LNAPL (e.g., weathered gasoline, diesel, jet fuel, fuel oil, crude oil); HV, HS = high volatility, high solubility, light LNAPL with significant percentage of volatile or soluble constituents (e.g., gasoline, benzene); > residual = only for LNAPL saturation greater than residual.
[e] Primary mechanism is in bold.
[f] V. short = <1 year, Short = 1–3 years, Medium = 2–5 years, Long = 5–10 years, V. long = >10 years.
[g] ROI = radius of influence.
[h] Sweep efficiency is analogous to ROI, but injection technology refers to effectiveness of injectate dispersal (sweep).
[i] COC = constituent of concern.

Using Section 6 (see Figure 5-1), the user can first screen the technologies based on their conceptual potential to achieve LNAPL remedial objectives, given the general site and LNAPL conditions. The second step in Section 6 is to evaluate the technologies based on their geologic factors, referring to the A-series tables in Appendix A. Leaving Section 6, the user will have a list of technologies that have the conceptual potential to achieve the LNAPL remedial objectives, given the geologic conditions at the site. Further screening is performed using Section 7 and the B-series tables (see Figure 5-1), based on other important evaluation factors that carry varying degrees of significance with respect to the site, including remedial time frame, public concern, carbon footprint, and site use. The final evaluation step is to select a technology based on engineering data requirements (see Figure 5-1). The C-series tables will assist the user in recognizing the critical requirements that must be evaluated for selecting the final technology and for establishing LNAPL remediation goals and performance metrics. It is at this step where ability to achieve the LNAPL remedial objective is critically assessed.

The example case introduced below and developed in Sections 6 and 7 illustrates how to use the screening tools provided in those sections. The example case ends at Section 7 with a screened list of potentially viable and acceptable technologies that could then be implemented or further screened in the more technical evaluation process explained in Section 8.



An historical LNAPL release from a gasoline pipeline was discovered during pipeline upgrade work. The cause of the LNAPL release was abated at some time in the past. The LNAPL is potentially mobile, but the LNAPL footprint is not expanding under current site conditions. The LNAPL impacts an unconfined aquifer not designated for domestic use.

Geologic/Hydrogeologic and LNAPL Conditions

- Unsaturated zone: fine-grained siltstone/mudstone (F).
- Saturated zone: silt to fine sand (F).
- Groundwater is unconfined.
- LNAPL at the capillary fringe and within the saturated zone (S).
- LNAPL is light (HS, HV).

LNAPL Concerns

- LNAPL body is mobile and could be induced to migrate.
- LNAPL is a source of dissolved-phase groundwater impact.

6. PRELIMINARY LNAPL REMEDIAL TECHNOLOGY SCREENING

This section defines a preliminary "screening" process to narrow the list of 17 LNAPL remedial technologies introduced in Table 5-1 to potentially applicable technologies given the site LNAPL concerns, remedial objectives, remediation goals, and site and LNAPL conditions. The technologies screened for applicability possess the minimum capabilities anticipated to meet performance requirements. Other technologies may be more than capable of meeting performance requirements and could be considered, but to focus the effort, only the technologies with the minimum capabilities are considered or are screened and identified for further evaluation.

The technology screening process has two-steps (Figure 6-1). Table 6-1 is used for Screening Step 1. The **Geologic factors** portion of the A-series table (Figure 6-1) in Appendix A for each technology screened in Table 6-1 is used for Screening Step 2. Each step is described below. These two screening steps produce a narrowed list of potentially appropriate technologies that can be further evaluated, using the process described in Section 7.

6.1 Technology Screening Step 1

<u>6.1.1 Overview of Screening Tool Table 6-1</u>

The Table 6-1 screening tool matches LNAPL remedial technologies with stated LNAPL remedial objectives and associated remediation goals and site and LNAPL conditions. LNAPL remedial objectives and remediation goals, explained in Section 4, are based on the site-specific LNAPL concerns.

Following adequate and appropriate LNAPL assessment and LCSM development, the potential LNAPL concern(s) at the site, if any, are identified. For each identified concern, the associated LNAPL remedial objective to specifically resolve that LNAPL concern is established. The first column of Table 6-1 lists a range of LNAPL remedial objectives covering the typical spectrum of LNAPL concerns at sites.

An LNAPL remedial objective commonly has more than one LNAPL remediation goal (column 2, Table 6-1), reflecting that typically more than one technology can achieve the LNAPL remedial objective. The LNAPL remediation goal is basically a restatement of the LNAPL remedial objective in the context of the remediation technology. If multiple LNAPL remediation goals exist for an LNAPL remedial objective, then the objective can be achieved in multiple ways. Together, the technology group and performance metrics columns (columns 3 and 4, Table 6-1) explain how the LNAPL is addressed in the context of that goal and how achievement of the goal is demonstrated (metrics). The performance metrics are different for the different LNAPL remediation goals, but all signal achievement of the LNAPL remedial objective. A suite of potentially applicable technologies are associated with each LNAPL remediation goal.[1]

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[1] The potentially applicable technologies listed in Table 6-1 are limited to those most likely to be selected from, in the opinion of the LNAPLs Team. Other technologies than those listed may be conceptually applicable, but in the opinion of the LNAPLs Team, they are considerably less likely to survive screening and so were not listed.

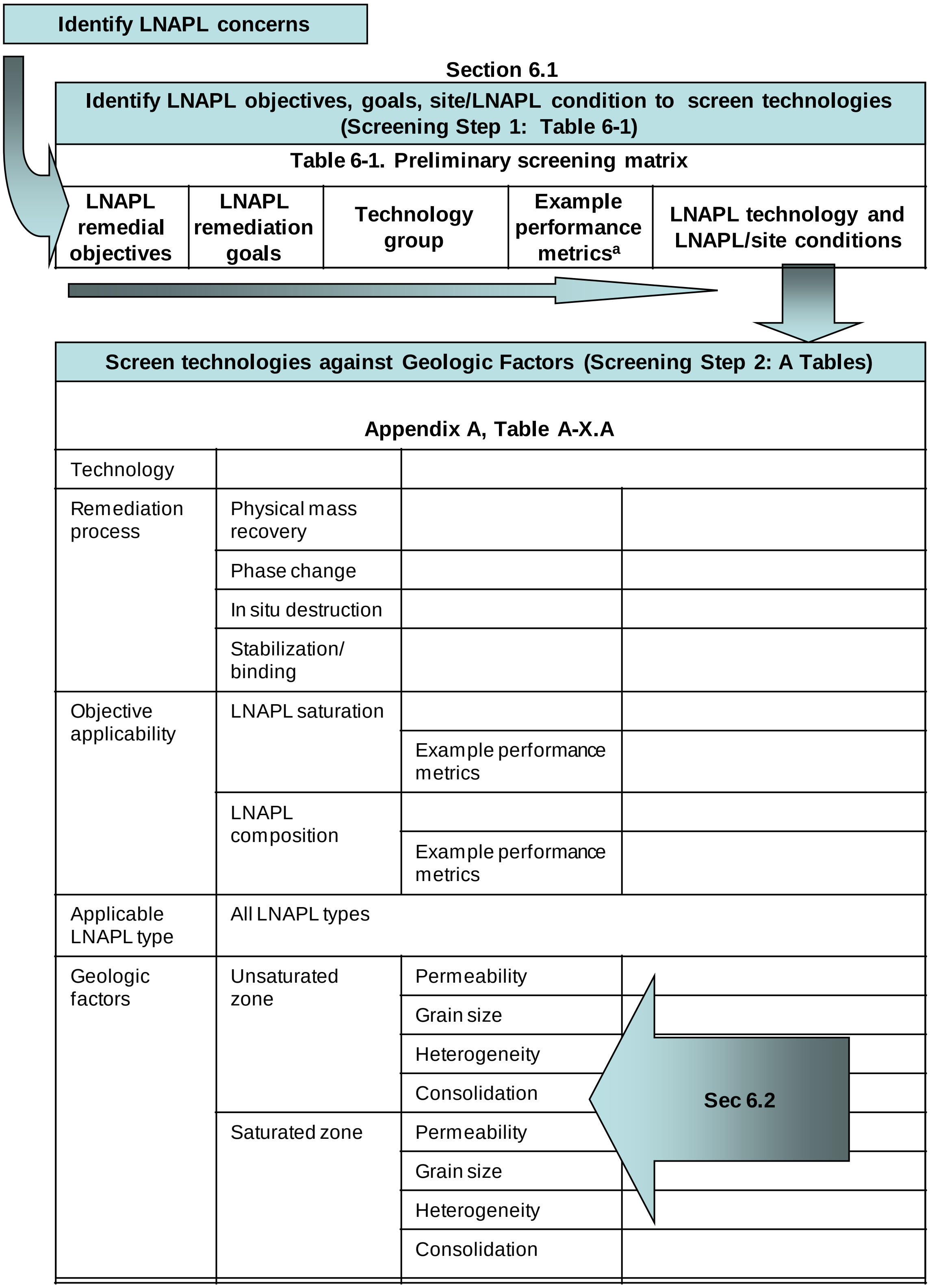

Figure 6-1. Process overview of preliminary Screening Steps 1 and 2.

Table 6-1. Preliminary screening matrix

LNAPL remedial objective	LNAPL remediation goal	Technology group	Example performance metrics[a]	LNAPL technology and LNAPL/ site conditions[b,c]
LNAPL saturation-based remedial objectives				
Reduce LNAPL saturation when LNAPL is above the residual range	Recover LNAPL to maximum extent practicable	LNAPL mass recovery	• LNAPL transmissivity • Limits of technology • Limited/infrequent well thickness • Decline curve analysis • Asymptotic performance of the recovery system • Cost of mass removal • Soil concentration at regulatory standard	• DPLE [C, S, LV, LS, HV, HS] • MPE (dual pump) [C, S, LV, LS, HV, HS] • MPE (single pump) [C, S, LV, LS, HV, HS] • Water flooding [C, S, LV, LS, HV, HS] • LNAPL skimming [F, C, S, LV, LS, HV, HS] • Bioslurping/EFR [F, C, U, S, LV, LS, HV, HS] • Excavation [F, C, U, S, LV, LS, HV, HS]
Reduce LNAPL when LNAPL is within residual saturation range	Further abate LNAPL beyond hydraulic or pneumatic recovery	LNAPL mass recovery	• Limits of technology • Asymptotic mass removal • Cost of mass removal • Soil concentration at regulatory standard	• Cosolvent flushing [C, S, LV, LS, HV, HS] • SESR [C, S, LV, LS, HV, HS] • AS/SVE [C, U, S, HV, HS] • ISCO [C, U**, S, HV, HS] • RFH [F, U, S, LV, LS, HV, HS] • Three- and six-phase heating [F, U, S, LV, LS, HV, HS] • Steam/hot-air injection [C, U, S, LV, LS, HV, HS] • NSZD [F, C, U, S, HV, HS]
Terminate LNAPL body migration and reduce potential for LNAPL migration	Abate LNAPL body migration by sufficient physical removal of mobile LNAPL mass	LNAPL mass recovery	• Total system recovery rate vs. background LNAPL flux • LNAPL saturation profile • LNAPL footprint/center of mass stabilization • Stable dissolved-phase plume concentrations, dissolved-plume shape	• Excavation [F, C, U, S, LV, LS, HV, HS] • DPLE [C, S, LV, LS, HV, HS] • MPE (dual pump) [C, S, LV, LS, HV, HS] • MPE (single pump) [C, S, LV, LS, HV, HS]
	Stop LNAPL migration by physical barrier	LNAPL mass control	• No first LNAPL occurrence downgradient	• Physical containment (barrier wall, French drain, slurry wall) [F, C, S, LV, LS, HV, HS]
	Sufficiently stabilize mobile LNAPL fraction to prevent migration	LNAPL mass control	• Stable dissolved-phase plume, dissolved-plume shape • No first LNAPL occurrence downgradient in LNAPL-unaffected soils	• In situ soil mixing (stabilization) [F, C, V, LV, LS, HV, HS]

LNAPL remedial objective	LNAPL remediation goal	Technology group	Example performance metrics[a]	LNAPL technology and LNAPL/ site conditions[b,c]
LNAPL compositional-based remedial objectives				
Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source[d]	Abate unacceptable vapor accumulations by sufficient depletion of volatile constituents in LNAPL	LNAPL phase change and LNAPL mass recovery	• LNAPL composition change • Soil volatile organic compound (VOC) concentrations to below regulatory standard • Soil vapor plume concentrations to below regulatory standard • Asymptotic performance of the recovery system • Cost of mass removal	• AS/SVE [C, U, S, HV, HS] • RFH [F, U, S, LV, LS, HV, HS] • Three- and six-phase heating [F, U, S, LV, LS, HV, HS] • Steam/hot-air injection [C, U, S, LV, LS, HV, HS]
	Abate unacceptable soil vapor concentrations by physical barrier or containment	LNAPL mass (vapor) control	• Soil VOC concentrations to below regulatory standard	• Physical or hydraulic containment (vapor barrier, barrier wall) [F, C, S, LV, LS, HV, HS] • SVE (vapor management and collection) [C, U, S, HV, HS]
	Control or treat soluble plume to abate unacceptable dissolved-phase concentrations at a specified compliance point	LNAPL mass control (interception of dissolved-phase plume) or LNAPL phase change[e]	• No first constituent occurrence at unacceptable levels downgradient • Dissolved-phase regulatory standard met at compliance point • Reduced dissolved-phase concentrations downgradient of the barrier	• AS/SVE [C, U, S, HV, HS] [e] • Modified AS for enhanced biodegradation (e.g., oxygen injection) [C, U, S, HV, HS, LS, LV] • Physical or hydraulic containment (barrier wall, French drain, slurry wall, wells, trenches) [F, C, S, LV, LS, HV, HS] • DPLE [C, S, LV, LS, HV, HS] • MPE (dual pump) [C, S, LV, LS, HV, HS] • MPE (single pump) [C, S, LV, LS, HV, HS] • NSZD [F, C, U, S, HV, HS]
Reduce constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source	Further reduction of groundwater and vapor concentration beyond acceptable levels	LNAPL phase change		• NSZD [F, C, U, S, HV, HS]

LNAPL remedial objective	LNAPL remediation goal	Technology group	Example performance metrics[a]	LNAPL technology and LNAPL/ site conditions[b,c]
LNAPL aesthetic-based remedial objectives				
Aesthetic LNAPL concern abated (saturation objective)	Geotechnical soil instability abated	LNAPL mass recovery	• Specific soil concentration that results in desired soil stability	• Excavation [F, C, U, S, LV, LS, HV, HS] • NSZD [F, C, U, S, HV, HS]
		LNAPL mass control	• Soil concentrations remain stable or decreasing • Acceptable structural strength	• In situ soil mixing (stabilization) [F, C, U, S, LV, LS, HV, HS] • NSZD [F, C, U, S, HV, HS]
Aesthetic LNAPL concern abated (composition objective)	Offensive odors abated	LNAPL mass (vapor) control	• Vapor concentrations (to below odor threshold) • Specific soil concentration	• Physical containment (barrier wall, French drain, slurry wall) [F, C, S, LV, LS, HV, HS] • SVE (vapor management and collection) [C, U, S, HV, HS] • AS (addition of oxygen)/SVE [C, U, S, HV, HS] • NSZD [F, C, U, S, HV, HS]

[a] Overall, until such time as the risks are mitigated by the LNAPL remedial technology(ies), risks should be managed via engineering or institutional controls.
[b] C = coarse soils, F = fine-grained soils, S = saturated zone, U = unsaturated zone, U** = unsaturated zone with ozone oxidant; LV = low volatility, LS = low solubility, HV = high volatility, HS = high solubility.
[c] If explosive conditions exist, emergency response approach is assumed to mitigate risk (i.e., immediate engineering control and abatement of vapors is assumed to reduce risk).
[d] Considered potentially most effective technology, without significant underutilization of technology capability.
[e] To correct an omission, this table cell was updated in August 2011 to reflect AS/SVE (phase change technology).

Site and LNAPL conditions are presented as footnotes to Table 6-1. Site conditions include the following:

- the predominant grain size, porosity, and permeability of the soil containing the LNAPL
  - coarse (sand to gravel, and fractured media where the LNAPL is primarily in the fractures)
  - fine (silt to clay)
- LNAPL occurrence zone
  - unsaturated zone
  - saturated zone

LNAPL conditions distinguish whether the LNAPL has relatively high volatility or solubility (e.g., gasoline, benzene) and therefore likely to readily partition into the vapor or dissolved phase, or low volatility or solubility (e.g., weathered gasoline, diesel, jet fuel, fuel oil, or crude oil) and therefore less likely to readily weather or degrade.

6.1.2 Table 6-1 Screening Tool Use

- Identify the first applicable LNAPL remedial objective for the site (Figure 6-1).
- Select the preferred LNAPL remediation goal for the LNAPL remedial objective. (Compare between the technology group and performance metrics for the different remediation goals to distinguish how the different goals are achieved and the data type or information needed to demonstrate that the LNAPL remediation goal has been achieved to discern the significance of selecting the different LNAPL remediation goals.) If the preferred or required LNAPL remediation goal is not apparent, proceed to Section 7 and evaluate additional factors as they may clarify the appropriate goal.
- Determine the applicable site and LNAPL condition (e.g., F, C, HV, HS, LV, LS).
- Identify all technologies listed for that LNAPL remedial objective and LNAPL remediation goal matching the footnoted conditions. These pass Screening Step 1.
- Repeat the procedures above for each applicable LNAPL remedial objective.
- Take technologies passing Screening Step 1 into Screening Step 2.

6.2 Technology Screening Step 2

> Note those technologies applicable across multiple LNAPL remedial objectives as they may offer the greatest utility for the site.

Next, screen the technologies carried forward from Screening Step 1 using the **Geologic factors** portion of the A-series technologies tables provided in Appendix A (see Figure 6-1). This screening step eliminates technologies that rely on critical geologic factors that are not present at the site. For some technologies, no particular significant geologic factors must be met for technology suitability. Other technologies, however, depend on certain geologic conditions existing at the site. Technologies carried forward from Screening Step 2 can be selected, or those technologies can be further evaluated as explained in Section 7.

If no remedial technology survives Screening Steps 1 or 2, repeat Screening Step 1, but select an alternative LNAPL remediation goal and repeat the process. If no technology will achieve the required objectives based on screening, consider discussing this outcome with the regulatory authority.

Example Case

<u>From Table 6-1:</u>

Step 1a: Identify LNAPL remedial objectives, remediation goals, performance metrics

1. Reduce LNAPL mass to further reduce potential mobility.
   - Recover LNAPL to maximum extent practicable.
     - LNAPL transmissivity reduced to 0.3 ft^2/day.
2. Reduce chemical flux of dissolved COCs from LNAPL plume.
   - Abate generation of dissolved-phase concentrations by LNAPL phase-change concentrations.
     - Dissolved-phase concentrations below regulatory standard at point of compliance.

Step 1b: Identify potentially applicable technologies

- Excavation – Goals 1, 2
- DPLE – Goal 1
- MPE dual – Goal 1
- MPE single – Goal 1
- Water flooding – Goal 1
- LNAPL skimming – Goal 1
- Bioslurping/EFR – Goal 1
- NSZD – Goals 1, 2
- AS/SVE – Goals 1, 2
- RFH – Goals 1, 2
- Three- and six-phase heating – Goals 1, 2
- Steam/hot-air injection – Goals 1, 2
- Cosolvent flushing – Goals 1, 2
- SESR – Goals 1, 2
- ISCO – Goal 2

Step 2: Review geologic factors in applicable A-series tables for each technology to further screen

- Excavation: no limiting geologic factors
- DPLE: not for fine-grained soils
- MPE dual: can be applicable to fine-grained soils
- MPE single: can be applicable to fine-grained soils
- LNAPL skimming: no applicable limiting geologic factors
- Bioslurping/EFR: no applicable limiting geologic factors
- NSZD: no limiting geologic factors
- Excavation: no applicable limiting geologic factors
- RFE: no applicable limiting geologic factors
- Three- and six-phase heating: no applicable limiting geologic factors
- Steam/hot-air injection: not for fine-grained soils
- Cosolvent flushing: not for fine-grained soils
- SESR: not for fine-grained soils
- ISCO: not for fine-grained soils

Screening Outcome

Goal 1: Screen out DPLE, water flooding.
Goal 2: Screen out AS/SVE, steam/hot-air injection, cosolvent flushing, SESR, ISCO.

7. LNAPL TECHNOLOGY EVALUATION FOR THE SHORT LIST

After the user has identified a list of technologies that are potentially applicable to the site, as outlined in Section 6, these technologies should be further evaluated to identify the ones that can achieve all of the applicable LNAPL remedial objectives. A wide variety of factors may be valuable for remedial technology evaluation, including the “nine criteria” recommended in EPA guidance for remedy selection along with other considerations (EPA 1993). In addition, preferences for specific LNAPL remediation goals may be apparent upon reviewing the list of potentially applicable technologies. As discussed previously, LNAPL remediation goals depend on both the LNAPL remedial objective and the specific technology. Consideration of the LNAPL remediation goals as part of the additional evaluation factors, or subsequently, may further refine the list of technologies.

Alternatively, if the most suitable LNAPL remediation goal is unapparent in Steps 1 and 2 (Section 6), then review of the additional evaluation factors may clarify which LNAPL remediation goal is best suited. Then the user can return to Steps 1 and 2 in Section 6 and complete the initial technology screening process.

7.1 Potential Technology Evaluation Factors

Based on the LCSM and LNAPL remediation goals, the user should identify a short list of factors (typically four to six) that are likely to be more relevant for technology selection. Table 7-1 provides a recommended list of factors from which the key factors for the project can be selected. To ensure acceptance of the technology selection process, this set of factors should be selected in consultation with all of the site stakeholders. Following stakeholder acceptance, this subset of factors should be used for quantitative or semiquantitative evaluation of the technologies retained from Section 6. If an acceptable remediation technology is not determined, it may be necessary to go back to Section 6 and reevaluate LNAPL remediation goals or technologies or to evaluate other factors from Table 7-1.

Table 7-1. Evaluation factors[a]

Remedial time frame	Defined	The time frame by which the LNAPL remedial objective is to be met. The time frame may be a regulatory or nonregulatory evaluation factor. Any one LNAPL remediation project may have different time frames to meet different LNAPL remedial objectives or remediation goals.
	Impact	Holding all other variables the same, the shorter the time frame, the more aggressive the effort required, which often increases costs. For a given technology, the time required to meet an end point increases with size of LNAPL body unless the remediation system scale increases. Increased permitting requirements for one technology over another increases the time that lapses before technology implementation. Increased infrastructure/site barriers commonly slow technology implementation because of the need to avoid infrastructure impacts and compensate for barriers.
Safety	Defined	Safety issues at a particular site that may present particular challenge to a technology, and safety considerations unique or particular to a technology. This guidance presumes that all construction activities will be in compliance with Occupational Safety and Health Administration (OSHA) health and safety requirements and that system operation will be within applicable regulations. In addition, it is presumed that any engineered technology has inherent basic safety issues, but the technology may involve addition of electricity, heat, or chemicals that may pose particular operational risk if applied at large field scale or in close proximity to workers or the public. Published accident rates for the construction or operational activities may suffice for screening.
	Impact	Safety considerations at urban and rural sites may be different or more intensive. At public access, nonrestricted access facilities, it may be more difficult to reliably manage safety issues. Infrastructure issues may be more critical for certain technologies than for others. Some technologies may produce waste streams or site conditions that are particularly difficult to manage at a particular site or that potentially escalate quickly to a critical state.
Waste stream generation and management	Defined	Level of effort required to manage any waste stream from the remediation.
	Impact	Increased permitting generally increases the time before a technology can be deployed. Waste streams may be more toxic or more difficult to control than the parent LNAPL. Larger waste streams present more of a challenge for disposal or treatment and on-site management pending disposal or treatment.
Community concerns	Defined	Concerns expressed by the community, nearby homeowners, civic organization, elected officials, or concerns that are likely to be expressed as the LNAPL remediation progresses.
	Impact	• The technology poses a particular societal risk. • The completion of the remediation causes more harm than good or renders a site less fit for active and productive use or reduces the existing level of ecological use. • The LNAPL remediation is applied to public lands possibly controlling the degree or timing of public participation or requiring additional permits (National Environmental Policy Act). • The remedy is not, or is not perceived to be, consistent with current and future planned land use, reducing property value or use. • LNAPL site is in close proximity to sensitive receptors. • LNAPL technology is particularly vulnerable to environmental justice considerations.
Carbon footprint/ energy requirements	Defined	Source energy usage and carbon emission/greenhouse gas emissions considerations and availability of necessary energy.
	Impact	• The energy usage or carbon emissions are disproportionate to other technologies. • An energy source is not reliably or amply available to power the technology as required. • Natural passive energy sources (solar, wind) can power the technology adequately.
Site restrictions	Defined	Physical, logistical, or legal obstacles to system deployment at the site (e.g., building locations, high-traffic areas, small property size, noise ordinances, site geology [e.g., depth to bedrock, presence of bedrock, depth to groundwater], or nearby sensitive receptors, such as schools, day cares, hospitals, etc.)
	Impact	Site restrictions and limitations impact the implementation of some technologies more than others, due to equipment size, degree of surface disruption, etc. At sites with more potential physical, logistical, or legal site restrictions, the physically larger, more "disruptive" technologies may be less feasible to implement.

LNAPL body size	Defined	The three-dimensional limits (volume distribution) of the LNAPL body.
	Impact	The larger the LNAPL body, the larger the scale of remedial effort required. The feasibility of some technologies may be limited to small-scale application, while others are more feasible for small- and large-scale application. Treatment of larger sites may be complicated by access limitations, physical barriers, cost constraints, technology limitations (see McGuire, McDade, and Newell 2006 and Kingston 2008 for additional discussion).
Other regulations	Defined	Some technologies require specific permitting to deploy (e.g., underground injection control [UIC], air, waste management, remediation, maximum available air control technology [air emissions], or OSHA compliance).
	Impact	The greater degree of the permitting required for technology deployment, the higher the costs and more likely the delays to system deployment.
Cost	Defined	Monetary value of expenditures for supplies, services, labor, products, equipment, and other items purchased for both implementation and operational phases.
	Impact	Each technology has different costs, and those costs vary widely depending on the site conditions, inflation, and time it takes to remediate. Reasonably accurate planning-level cost estimates (+100%/–50%) would be required for each technology based on knowledge of the treatment area, key physical constraints, and unit cost rates. Design level costs (i.e., ±30%) typically are not available at the screening stage. Consider capital costs vs. life-cycle costs, even at the screening level.
Other	Defined	
	Impact	

[a] These factors are used in the B-series tables in Appendix A. Some factors are weighted High, Moderate, or Low. “High” means the technology has high sensitivity or contribution to the factor. “Low” means the technology has low sensitivity or contribution to the factor.

7.2 Sustainable or Green Remediation

Sustainable development is commonly defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). Consideration of sustainability when evaluating environmental remediation technologies is becoming more common and involves consideration of some the aspects described above, as well as other environmental and societal factors in a structured way. In essence, remediation is viewed as more than an environmental activity under a sustainable approach where environmental, social, and economic considerations are all accounted for when evaluating benefits and impacts of a remediation project.

The environmental footprint and overall eco-efficiency of a remediation project may be evaluated through consideration of core elements, including greenhouse gas emissions, air emissions, energy consumption, waste generation, land ecosystems protection, and water resources. Sustainable remediation considers natural resources, ecology, human health and safety, quality of life, and economic issues and has the potential to achieve cost savings because the efforts invested in enhancing the operational efficiency of the project can result in a streamlined process in which, for instance, energy inputs and wastes are minimized. In addition, adopting and communicating a sustainable remediation strategy can be instrumental in managing risks at contaminated sites, as well as engaging with communities and stakeholders in a transparent and proactive way.

Although the terms “green” and “sustainable” are sometimes used interchangeably, green remediation can be considered as having a focus on environmental factors, whereas sustainable environmental remediation is of a more holistic view and considers not only environmental factors but social responsibility (e.g., minimizing risk to surrounding communities) and economic aspects as well. Green and sustainable remediation expands on current environmental practices and employs strategies for cleanups that use natural resources and energy efficiently, reduce negative impacts on the environment, minimize or eliminate pollution at its source, protect and benefit the community at large, and reduce waste to the greatest extent possible, thereby minimizing the environmental "footprint" and maximizing the overall benefit of cleanup actions.

Tools are being developed for evaluation of sustainable or green remediation that enable various criteria to be evaluated (e.g., environmental, economic, societal; see Appendix E). Of importance is the carbon footprint or measure of the impact remediation activities have on the environment in terms of the amount of greenhouse gases produced, measured in units of carbon dioxide. The carbon footprint is a useful concept for evaluating a technology's impact in contributing to global warming. Sustainability concepts and tools may be both used to compare different technologies as part of a technology evaluation process or to evaluate the sustainability and efficiency of an existing technology relative to LNAPL remediation achieved. Depending on the in situ technology under consideration, there may be significant energy requirements (e.g., technologies that use heat or steam), chemicals introduced in the subsurface could potentially result in undesirable secondary impacts (e.g., surfactants), or waste streams (vapor, water) that require treatment prior to discharge. Technologies such as excavation and off-site disposal may have different issues to consider, including energy, disturbance, and safety. For example, there may be concerns associated with transport along public roadways and disposal of waste materials. EPA (2008) provides guidance on calculating the impact of a remediation system and methods for sustainable environmental practices into remediation of contaminated sites.

For More Information on Green Remediation

- California Department of Toxic Substances Control "Green Team"
  www.dtsc.ca.gov/omf/grn_remediation.cfm
- EPA Green Remediation
  www.epa.gov/superfund/greenremediation
- Sustainable Remediation Forum SuRF "White Paper," June 2009
  www.sustainableremediation.org
- Navy Sustainable Environmental Remediation Fact Sheet
  www.ert2.org/ERT2Portal/uploads/SER%20Fact%20Sheet%202009-08%20Final.pdf
- AFCEE Sustainable Remediation Tool
  www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sustainableremediation/srt/index.asp

7.3 Scenarios with No Feasible Remedial Options

At some sites, evaluation using the selected factors and the available LNAPL remediation goals may result in elimination of all of the retained technologies. In these cases, the user either identifies additional technologies for evaluation or modifies the remedial objectives so that one or more technologies are retained through the evaluation process. For example, if no active LNAPL remediation technology can achieve all of the remedial objectives, then risk mitigation will need to be addressed through the use of controls (i.e., administrative, engineering, and/or institutional) in addition to or as an alternative to active remediation. Alternatively, one might consider a combination of technologies that might collectively achieve the objective.

Example Case Study

Principal characteristics of the site	Volatile/soluble LNAPL—gasoline, moderate permeability, unconfined LNAPL conditions, not domestic water use groundwater			
Most pertinent site conditions	Landowner plans to sell property within 5 years. Immediate need to abate body expansion.	Clean Air Act nonattain-ment area	Groundwater restoration concern, vocal stakeholder group	Borders urban area
Factors	1. Time frame concerns	2. Regulatory concerns	3. Community concerns	4. Safety concerns
Short-list technologies				
Excavation (Goals 1, 2)	Low	Moderate	Low to moderate	Moderate
MPE dual pump (Goal 1)	Moderate	Moderate	Moderate	Moderate
MPE single pump (Goal 1)	Moderate	Moderate	Moderate	Moderate
LNAPL skimming (Goal 1)	High	Low	Low	Low
Bioslurping/EFR (Goal 1)	High	Moderate	Moderate	Low
NSZD (Goals 1, 2)	Very high	Low	Low to moderate	Low
RFH (Goal 2)	Very low	Low	Moderate	Moderate
Three- and six-phase heating (Goal 2)	Very low	Moderate	Low to moderate	High

Each of the technologies remaining after the Section 6 screening process is evaluated using the applicable B-series tables from Appendix A. The primary factors considered and the results are presented in the table above.

From the factors evaluation, NSZD, LNAPL skimming, and bioslurping/EFR will not meet the required timeline and are thus screened out. Three-phase heating does not score well on the safety factor. Excavation, MPE dual and single pump, and RFH remain for further evaluation of actual effectiveness (see Section 8), or other factors from Table 7-1 might be considered to further screen.

8. MINIMUM DATA REQUIREMENTS AND CRITICAL CONSIDERATIONS FOR TECHNOLOGY EVALUATION

After one or more technologies have been selected through the processes described in Sections 6 and 7, minimum data requirements need to be defined to support the following:

- final technology selection
- engineering the technology to meet remediation goals
- evaluation of remedial progress toward those goals

This section describes these minimum data requirements. Table 8-1 briefly outlines them for all the technologies, and the C-series tables in Appendix A describe the data requirements for each one in more detail, to the extent information is available. Information provided in this section does not replace the necessary services of qualified professionals in the technology selection, engineering, and evaluation process. The information that is provided in this section is designed to support review of site-specific plans and indicate the types of data that are typically used for the required evaluations. Federal, state, and local requirements should be researched and understood by those individuals implementing the technology selection and design.

Table 8-1. Minimum data requirements and case study examples

LNAPL technology (Appendix A Table with further details)	Minimum data requirements					Modeling tools/ applicable models	Case study examples	Pilot scale or full scale	Case study reference
	Site-specific data for technology evaluation	Bench-scale testing	Pilot testing	Full-scale design	Monitor performance				
Excavation (A-1.C)	Site access	NA	NA	Soil type, DTW	$LNAPL_t$				
Physical or hydraulic containment (barrier wall, French drain, slurry wall, wells, trenches) (A-2.C)	Lithology, site access	Soil column testing, $LNAPL_c$		Soil type, DTW	$LNAPL_t$, DTW, M	MODFLOW			
In situ soil mixing (stabilization) (A-3.C)	Lithology, compatibility	Leach testing		Lithology, homogeneity	$LNAPL_t$				
NSZD (A-4.C)	Qualitative and quantitative site evaluation data (ITRC 2009; Johnson, Lundegard, and Liu 2006)	Leaching and accelerated weathering tests (ITRC 2009; Johnson, Lundegard, and Liu 2006)	Quantitative evaluation data (ITRC 2009; Johnson, Lundegard, and Liu 2006)	Quantitative evaluation data and predictive modeling (ITRC 2009; Johnson, Lundegard, and Liu 2006)	<u>Aqueous concentrations</u> of O_2, NO_3, SO_4, Fe^{2+}, Mn^{2+}, and LNAPL fractions <u>Vapor-phase concentrations</u> of O_2, CH_4, TPH, and BTEX	API-LNAST, BIONAPL3D, PHT3D, RT3D, SourceDK, etc. (Table 4-2, ITRC 2009)	Former Guadalupe Oil Field (Johnson, Lundegard, and Liu 2006; retail service station release site (ITRC 2009)	Full and pilot scale	Example problem (ITRC 2009)
AS/SVE (A-5.C)	K_{soil}, K_{gw}, $LNAPL_c$	NA	Field test	C_{in}, K_{soil}, K_{gw}, ROI	C_{in}, O_2, CO_2, M	SOILVENT			
LNAPL skimming (A-6.C)	K_{gw}, $LNAPL_c$	NA	NA	K_{gw}, ROI	$LNAPL_t$, M	API LDRM			
Bioslurping/EFR (A-7.C)	K_{gw}, $LNAPL_c$	NA	NA	K_{gw}, ROI	$LNAPL_t$, M	API LDRM			
DPLE (A-8.C)	K_{gw}, $LNAPL_c$	NA	NA	K_{gw}, ROC	$LNAPL_t$, M	API LDRM	BP, Sugar Creek, MO		
MPE (dual pump) (A-9.C)	K_{gw}, $LNAPL_c$	NA	NA	K_{gw}, ROC, ROI	C_{in}, O_2, CO_2, $LNAPL_t$, M	API LDRM	BP, Sugar Creek, MO		
MPE (single pump) (A-10.C)	K_{gw}, $LNAPL_c$	NA	NA	K_{gw}, ROC, ROI	C_{in}, O_2, CO_2, $LNAPL_t$, M	API LDRM			
Water flooding (A-11.C)	K_{gw}, $LNAPL_c$	NA	Field test	K_{gw}, ROC	$LNAPL_t$, M	API LDRM	Suncor, Commerce City, CO	Pilot scale	

LNAPL technology (Appendix A Table with further details)	Minimum data requirements					Modeling tools/ applicable models	Case study examples	Pilot scale or full scale	Case study reference
	Site-specific data for technology evaluation	Bench-scale testing	Pilot testing	Full-scale design	Monitor performance				
ISCO (A-12.C)	K_{gw}, $LNAPL_c$, homogeneity	Soil cores for column test, COCs, $LNAPL_c$		ROI, soil oxidant demand, homogeneity	$LNAPL_t$		Union Pacific Railroad, Scottsbluff, NE	Pilot scale	Union Pacific Railroad,, Scottsbluff, NE
SESR (A-13.C)	K_{gw}, $LNAPL_c$, COCs, compatibility	Soil cores for column test, COCs, $LNAPL_c$	COCs, $LNAPL_c$	K_{gw}, ROC, lithology, homogeneity	$LNAPL_t$, M	UTCHEM	EPA 1995b; NAVFAC 2006; Laramie Tie Plant (EPA 1991)	Pilot and full scale	EPA 1995b; NAVFAC 2006; Laramie Tie Plant (EPA 1991)
Cosolvent flushing (A-14.C)	K_{gw}, $LNAPL_c$, bench-scale tests	Soil cores for column test, COCs, $LNAPL_c$	Field test	K_{gw}, ROC	C_{gw}, $LNAPL_t$, M	UTCHEM			
Steam/hot-air injection (A-15.C)	K_{gw}, $LNAPL_c$	Soil cores for column test, COCs, $LNAPL_c$	Field test	K_{gw}, ROC, ROI	C_{gw}, temp, $vapor_c$, $LNAPL_t$, M		Richardson et al. 2002; UNOCAL Guadalupe	Pilot scale	Richardson et al. 2002; UNOCAL Guadalupe
RFH (A-16.C)	EC, K, $LNAPL_c$		Field test	K_{gw}, ROC, ROI	C_{gw}, temp, $vapor_c$, $LNAPL_t$, M				
Three and six-phase heating (A-17.C)	EC, K, $LNAPL_c$		Field test	K_{gw}, ROC, ROI	C_{gw}, temp, $vapor_c$, $LNAPL_t$, M		Chevron Cincinnati; Skokie, IL	Pilot scale	Chevron Cincinnati; Skokie, IL; Montana Department of Environmental Quality, Ronan, MT

Abbreviations:
BTEX = benzene, toluene, ethylbenzene, and xylenes
C_{gw} = groundwater concentration
C_{in} = influent concentration
CH_4 = methane
CO_2 = carbon dioxide
COCs = constituents of concern
DTW = depth to water (groundwater)
EC = electrical conductance
K_{gw} = groundwater conductivity
K_{soil} = soil permeability
$LNAPL_c$ = LNAPL characteristics/LNAPL saturation
$LNAPL_t$ = LNAPL thickness
M = Mass removed
MNA = monitored natural attenuation parameters
O_2 = oxygen
ROC = radius of capture (groundwater)
ROI = radius of influence (unsaturated zone)
temp = temperature
$vapor_c$ = vapor concentrations

8.1 Minimum Data for Final Evaluation of Technology Suitability

The technology or technologies that are selected through the processes in Sections 6 and 7 require final screening and site-specific testing to confirm the suitability of the technology to the site and the remedial objectives. It is important to conduct this screening and testing with several objectives in mind, including collection of data for full-scale engineering and site-specific technology testing. Even though considerable effort may have been exerted to get to the point of conducting a site-specific test, it is important to allow negative test results (if any) to prompt reconsideration of the technology and/or LNAPL remediation goals. That is, if a test result is unfavorable to the selected technology, then it may be necessary to conclude that the selected technology will not work for the particular tested site and/or LNAPL remediation goal.

The data collection and testing recommended should allow for a 90% design cost estimate to be developed, which is an important step in evaluating the feasibility of a selected technology. Accurate costing for application of the selected remedial technology or technologies may provide a final discriminating factor between technologies or as a go/no-go point for a single selected technology.

8.1.1 Site-Specific Data for Technology Evaluation

These basic data are likely to have been collected already as part of the technology selection process. They are reiterated here along with a brief description of their relevance for evaluating specific technologies. For the most part, these are measurements of site-specific hydrogeological or LNAPL characteristics. The representativeness of the measured characteristics is a factor that should be carefully considered. For example, for the results of a pumping test to be relevant to the design of an MPE system, it should have been conducted in the area where the system will be implemented or in an area where the LCSM indicates that hydrogeologic conditions are similar. Otherwise, use of the data may lead to erroneous design calculations.

8.1.2 Bench-Scale Testing

Bench-scale testing of a remedial technology can be an important step toward evaluation of feasibility. It can provide initial estimates of important data and parameters for engineering a remedial technology. In general, bench-scale tests are most useful when applied to investigate the feasibility of technologies where reagent injection is a key element of the selected technology. For example, bench-scale testing of an in situ chemical oxidant provides information about effectiveness in destroying the target LNAPL constituents, allows estimates of the portion of the chemical oxidant required just to overcome the natural oxidant demand of the soil, and produces information regarding potential occurrence of unfavorable by-products. In this example, if the natural soil oxidant demand is very high, then feasibility of ISCO may be called into question because of cost and deliverability factors (while it may be hydraulically feasible to deliver the oxidant, the oxidant demand may be such that the oxidant is depleted before it reaches all the target LNAPL constituents).

8.1.3 Pilot Testing

Pilot testing a remedial technology provides data to evaluate field-scale application and design of a remedial technology. In many cases, a pilot test involves collecting more data (spatially and temporally) than during full-scale remediation. For example, pilot testing of an SVE system includes pressure and soil-vapor concentration observations at varying distances to determine the ROI, which is then used to estimate the SVE well spacing. This expanded data set provides both a final feasibility step and important information for successful engineering, design, and operation of the selected technology.

Pilot testing is recommended for almost all technologies and can often be implemented as a portion of the full-scale design. It is important to gather data that allow evaluation of whether the technology will perform as expected and is capable of achieving the LNAPL remedial objectives. If the technology does not perform as expected, the technology and its selection process should be carefully reevaluated, including updating the LCSM and acknowledging the infeasibility of the technology as warranted. While much effort and capital may have been invested in a selected technology to get it through pilot testing, one of the main reasons for pilot testing is to provide a final confirmation of the remedial approach before investing “full-scale” effort and capital. Ideally, the equipment installed for the pilot test (e.g., monitoring wells, injection wells) can be used as part of the full-scale system.

8.2 Engineering for Full-Scale Design

Full-scale design of the selected technology should consider the data and parameters developed during site investigation and bench- and pilot-scale technology testing. The data and parameters in this section of the C-series tables in Appendix A are crucial to a successful full-scale design. Professional expertise (skill and experience) is particularly critical at this stage.

8.3 Performance Metrics

During full-scale operation of the selected remedial technology, performance monitoring allows for efficient and optimized operation of the remedial system. Careful monitoring of specific data, known as performance metrics, during technology implementation is important for gauging whether the technology continues to perform as expected. These metrics given for each technology are necessary for evaluating remedial progress and demonstrating when a technology has been applied successfully and/or to the extent practicable. These metrics allow interpretation of the extent of progress toward the remedial objective. If progress appears to be too slow, the design and operation of the remedial technology should be reevaluated, either throughout the site or in the portion of the site where performance is inadequate. For example, if for an LNAPL skimming system the performance metric of in-well LNAPL thickness at the downgradient edge of an LNAPL body does not demonstrate sufficient reduction in the LNAPL body’s migration potential in one particular segment of the body front, then additional skimming wells in that segment may be warranted. It is also possible that segment contains a previously unrecognized faster-flow channel and that skimming will not work in that particular location. This example highlights the importance of reevaluating the LCSM throughout the life of the remedial operations, particularly whenever unexpected data are observed (and confirmed). A complete and up-to-date LCSM allows the best possible decisions about application and operation of remedial technology(ies) to be made. See ASTM 2007 for additional performance metrics examples and additional insights in updating the LCSM.

8.4 Applicable Models

In some cases, semianalytical and/or numerical models are a useful tool for technology evaluation. They may be used to assist in a feasibility study for a selected technology, engineering design of a remedial system, remedial progress evaluation, and/or development of metrics of application of a technology to the extent practicable. Models can be very powerful tools and give relevant insights into the application of a technology. They also have uncertainty, however, that is inherent in the simplifications necessary to implementing modeling, such as simplification of the heterogeneity of the actual hydrogeologic system or simplification of LNAPL behavior. Recognition of this uncertainty and appropriate quantification, such as sensitivity studies, allow model results to be used to their fullest extent and, just as importantly, limit their use to what is reasonable. Care should be taken to calibrate the model against known site conditions and site data. Implementation of models, and in particular implementation of numerical models for simulation of multiphase flow and behavior, is another area where relevant professional skills and experience are considered particularly important.

8.5 References, Case Studies, and Further Information

The technologies briefly described in this document have been more fully documented in other sources, some of which are given here. After initial technology selection, it is strongly recommended that these additional sources, as well as others that are available (or become available after this document was published), be consulted. This process will allow the practitioner and regulator to develop a good, working understanding of the technology so that the most appropriate decisions for application of the LNAPL remedial technology can be made.

9. CONCLUSIONS

Following the completion of the more detailed evaluation in Section 8, the potentially applicable technologies should be identified. There may be other factors that need to be resolved or considered before a technology is deployed, if any technology needs to be deployed. Consider also what remedial efforts may be needed for the non-LNAPL soil, groundwater, or vapor impacts; those remedial efforts should complement the LNAPL remedial effort and vice versa. When multiple technologies are necessary to achieve the LNAPL remedial objectives, consider the potential for sequencing and strategically targeting technologies to certain LNAPL areas or conditions. Further discussion of such opportunities is outside the scope of this document.

If no technology survives the evaluation or if the technology identified using this guidance is infeasible based on other considerations, then reevaluate the LNAPL remedial objectives or LNAPL remediation goals and repeat the process (Figure 5-1). Alternatively, additional site data collection may be needed to provide better information (refine the LCSM) to address screening decisions required in Sections 6 and 7 (Figure 5-1).

In any event, adequately assess the LNAPL site, consider the concerns posed by the LNAPL and the objectives that need to be met, and then begin the process of identifying and implementing an LNAPL remediation technology that will meet those objectives. Also, when an LNAPL remedial objective is met, LNAPL may still be present at the site. Frequently, reasonable and appropriate LNAPL remedial objectives will not be synonymous with complete LNAPL removal. The presence of LNAPL after LNAPL remedial objectives are met can be a fully protective outcome when a more rigorous objective is unwarranted. Failed deployment of an LNAPL remedial technology that is inappropriate for the LNAPL site or that was inappropriately deployed because of an insufficient LCSM is not an appropriate basis to terminate LNAPL management. Nor is it appropriate to continue with ineffective remedial efforts without reassessing the LNAPL management strategy and revising the approach.

The framework presented in this guidance provides for systematic evaluation of LNAPL remedial technologies, and when coupled with a good LCSM and sound practices by environmental professionals, its use will improve upon the current state of LNAPL remediation effectiveness and facilitate consistent regulatory oversight.

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Appendix A

Technology Tables
Series A, B, C

TECHNOLOGY TABLES: SERIES A, B, C

NOTE: References begin on p. A-59.

Table A-1.A. Excavation

Technology	Excavation/large-diameter borings	The targeted LNAPL area is removed from the surface or subsurface via excavation or large diameter boring.	
Remediation process	Physical mass recovery	Yes	LNAPL physically removed.
	Phase change	No	Not the intended remedial process, but enhanced volatilization can occur as LNAPL exposed to atmosphere.
	In situ destruction	No	N/A
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	LNAPL physically removed.
		Example performance metrics	Maximum soil concentration reduced to cleanup criteria, reduced LNAPL transmissivity, direct analysis of soil to measure changes in LNAPL saturation profile.
	LNAPL composition	No	N/A
		Example performance metrics	N/A
Applicable LNAPL type	All LNAPL types		
Geologic factors	Unsaturated zone	Permeability	Not typically a factor.
		Grain size	Not typically a factor.
		Heterogeneity	Not typically a factor.
		Consolidation	Unconsolidated easier to excavate; loosely consolidated may collapse; bedrock excavation has limited practicability.
	Saturated zone	Permeability	High permeability can maximize water inflow to excavation or “flowing sand” concerns destabilize side walls.
		Grain size	Not typically a factor.
		Heterogeneity	Not typically a factor.
		Consolidation	Unconsolidated easier to excavate; loosely consolidated may collapse; bedrock excavation has limited practicability.

Table A-1.B. Evaluation factors for excavation

Technology: Excavation		
Remedial time frame	Concern	Low
	Discussion	Very short. The size of the LNAPL source zone and depth of the source have an impact on the time to implement an excavation. Off-site disposal and handling may also factor in the time it takes to conduct an excavation project. Very large excavation projects may be slowed by the rate at which trucks can be moved from the site to disposal facility.
Safety	Concern	Moderate
	Discussion	Some potentially significant safety issues, but construction related and typically routine. Large excavations involve side-stability issues and the potential for collapse. In an area with dense infrastructure, these may significantly impact the safety concern for excavation. Traffic safety could also be an issue. Excavated material could come in contact with workers. Potential for worker exposure to contaminated soil, liquids, and vapors must be managed.
Waste management	Concern	Moderate to high
	Discussion	Significant waste stream may be generated. Excavation projects often involve off-site waste handling, waste characterization, and disposal.
Community concerns	Concern	Low to moderate
	Discussion	Public generally familiar with and accustomed to construction excavations. Concerns may be significant due to volatile emissions, dust, noise, odors, traffic, exhaust, visual/aesthetic, and safety impacts, etc.
Carbon footprint/energy requirements	Concern	High
	Discussion	Equipment emissions and short-term energy requirements large. Energy is used for the excavation machinery and trucks to haul the wastes off site. In addition, for volatile LNAPLs, the excavation generates emissions.
Site restrictions	Concern	High
	Discussion	Disruptive technology, physical space, and logistical demands significant. Often excavation is infeasible due to site improvements, buildings, structures, roads, etc. Due to the use of large, heavy equipment and the need for clearance on either side of the excavation, could be constrained due to buildings, facility requirements, utilities, and natural habitats.
LNAPL body size	Concern	Small to moderate
	Discussion	Very large LNAPL bodies may be infeasible to excavate. The size of the LNAPL body directly affects the cost and extent of the excavation. Smaller LNAPL bodies may be more amenable to excavation. If the LNAPL body is areally extensive, it will take longer to excavate or present more logistical challenges.
Other regulations	Concern	Low to moderate
	Discussion	Waste management characterization, waste manifesting, construction storm water protection plans, construction permits, and transport provisions applicable. Typically routine compliance with local and state regulations. Potential vapor emissions limits.
Cost	Concern	High
	Discussion	May be a high-cost alternative.
Other	Concern	
	Discussion	

Table A-1.C. Technical implementation considerations for excavation

Data requirements	Site-specific data for technology evaluation	Site access and subsurface utility and infrastructure locations	
	Bench-scale testing	N/A	
	Pilot-scale testing	N/A	
	Full-scale design	Soil type	
		Depth to LNAPL zone	
		Depth to water	
	Performance metrics	LNAPL thickness	Reduced LNAPL transmissivity.
		Soil concentration	Maximum soil concentration reduced to cleanup criteria.
		LNAPL saturation	Direct analysis of soil to measure changes in LNAPL saturation profile.
Modeling tools/applicable models			
Further information		USACE. 2003. *Engineering and Design: Safety and Health Aspects of HTRW Remediation Technologies,* Chap. 3, “Excavations.” EM 1110-1-4007. http://140.194.76.129/publications/eng-manuals/em1110-1-4007/c-3.pdf	
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Table A-2.A. Physical or hydraulic containment

Technology	Containment	Containment uses engineered barriers that either control horizontal migration of LNAPL, isolate LNAPL as a vapor or dissolved source, block physical access to LNAPL body, or prevent recharge infiltration through the LNAPL body (vertical barrier).	
Remediation process	Physical mass recovery	Potential	Not primary intent, but hydraulic control measures (interception wells or trenches) implemented as a containment system may remove some LNAPL.
	Phase change	No	N/A
	In situ destruction	No	Physical or hydraulic containment does not typically involve in situ treatment.
	Stabilization/ binding	Yes	Halts LNAPL migration.
Objective applicability	LNAPL saturation	Yes	Halts LNAPL movement.
		Example performance metrics	No first LNAPL occurrence downgradient of LNAPL containment, LNAPL constituent meets standard at point of compliance, reduced vapor concentrations.
	LNAPL composition	Yes	N/A
		Example performance metrics	N/A
Applicable LNAPL type	All LNAPL types		
Geologic factors	Unsaturated zone	Permeability	Soil permeability a factor when determining the amount of amendments (e.g., bentonite or cement) needed to achieve the desired permeability or for determining necessary hydraulic removal rates.
		Grain size	For backfill activities, large gravels or cobbles (>6 inches in diameter) typically not used in barrier wall construction.
		Heterogeneity	Not a factor for trenches; needs to be considered for wells.
		Consolidation	Consolidated material may be easier to trench because of side wall stability; cemented or indurated material may be difficult to excavate.
	Saturated zone	Permeability	Soil permeability a factor when determining the amount of amendments (e.g., bentonite or cement) needed to achieve the desired permeability or for determining necessary hydraulic removal rates.
		Grain size	Not typically a factor, although during backfill activities, large gravels or cobbles (>6 inches in diameter) not typically used in barrier wall construction.
		Heterogeneity	For keyed physical barriers, determine that a continuous aquitard or bedrock exists and determine its elevation along the alignment; barrier must intersect LNAPL vertical interval under all seasonal groundwater elevations.
		Consolidation	Consolidated material may be easier to trench because of side wall stability; cemented or indurated material may be difficult to excavate.

Table A-2.B. Evaluation factors for physical or hydraulic containment

Technology: Physical containment		
Remedial time frame	Concern	Low
	Discussion	Very short to deploy, but potential long-term application. Time to construct containment structure varies with type, length, and depth, and other logistical factors. Time to achieve remedial goals depends on site-specific requirements (e.g., mitigate risk, remove LNAPL, reach regulatory standards in groundwater, etc.).
Safety	Concern	Low to moderate
	Discussion	Some potentially significant safety issues, but construction related and typically routine. The use of large, heavy equipment can be a factor. Potential side wall collapse during excavation and long-term geotechnical stability. In addition, if a slurry wall is the containment structure of choice, the excavated materials may come into contact with workers.
Waste management	Concern	Moderate
	Discussion	Significant liquid waste stream may be generated. Soils visibly saturated with LNAPL cannot be used in the slurry mix and are segregated. Excess slurry and soils not included in the slurry mix are waste materials. Pumping-based hydraulic interception may require treatment of effluent.
Community concerns	Concern	Low to moderate
	Discussion	Typically familiar with and accustomed to excavation/construction work. Concerns may be significant due to volatile emissions, odors, traffic, exhaust, etc. If a sheet pile containment structure or aboveground effluent treatment is used, noise could be a factor. Also, the public may see containment as not equal to cleanup.
Carbon footprint/ energy requirements	Concern	High
	Discussion	Equipment emissions and energy requirements large. Energy is used for the excavation machinery and trucks to haul the wastes off site. In addition, for volatile LNAPLs, the slurry trench generates volatile emissions. Active hydraulic interception requires energy for pumping and treatment.
Site restrictions	Concern	High
	Discussion	Disruptive technology, physical space, and logistical demands significant. Due to the use of large, heavy equipment and the need for approximately 20–30 feet of clearance on either side of the physical containment structure, could be limited due to buildings, utilities, and natural habitats.
LNAPL body size	Concern	Low to moderate
	Discussion	Applicable to only migrating portion of the LNAPL. The extent of the containment infrastructure depends on the LNAPL body needing to be contained.
Other regulations	Concern	Low to moderate
	Discussion	Normal construction, well, storm water, and discharge permitting. Other regulatory agencies may need to be included in decision making for the alignment of the containment infrastructure due to wetlands impacts; floodplain construction; water rights of adjacent land owners; or other federal, state, or local regulations.
Cost	Concern	Moderate to high
	Discussion	Depends on the length and depth of the physical containment structure, the type of physical containment structure chosen, and any possible site restrictions.
Other	Concern	
	Discussion	

Table A-2.C. Technical implementation considerations for physical or hydraulic containment

Data requirements	Site-specific data for technology evaluation	Soil type(s)/lithology	Soil type should be taken into account for physical or hydraulic design to ensure it meets performance metrics.
		Depth to LNAPL	
		Depth to water	Range of seasonal water level change needs to be defined.
		Hydraulic gradient	
		Site access	Including locations of utilities and foundations.
	Bench-scale testing	Soil column testing	
		Treatability testing	To test permeability of barrier wall mixes.
	Pilot-scale testing	N/A	
	Full-scale design	Soil type(s)/lithology	
		Depth to LNAPL	
		Depth to water	
		Hydraulic gradient	
	Performance metrics	LNAPL thickness	Monitoring wells downgradient of barrier to verify no occurrence of LNAPL.
		Depth to water	For hydraulic interception barriers (wells or trenches), maintain reversal of hydraulic gradient.
		Downgradient concentrations	LNAPL constituent meets standard at point of compliance.
Modeling tools/applicable models		MODFLOW	Other groundwater flow models may be applicable.
Further information		USACE. 1994. *Engineering and Design: Design of Sheet Pile Walls*. EM 1110-2-2504. http://140.194.76.129/publications/eng-manuals/em1110-2-2504/entire.pdf	
		EPA. n.d. "Technology Focus: Permeable Reactive Barriers, Permeable Treatment Zones, and Application of Zero-Valent Iron." http://clu-in.org/techfocus/default.focus/sec/Permeable_Reactive_Barriers,_Permeable_Treatment_Zones,_and_Application_of_Zero-Valent_Iron/cat/Overview	
		EPA. 1998. *Permeable Reactive Barrier Technologies for Contaminant Remediation*. EPA/600/R-98/125. http://clu-in.org/download/rtdf/prb/reactbar.pdf	
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Table A-3.A. In situ soil mixing and stabilization

Technology	In situ soil mixing (stabilization)	Uses mechanical mixing of soil or aquifer materials with low-permeability materials such as clay and/or reactive media such as chemical oxidants or electron acceptors and/or stabilizing media such as Portland cement.	
Remediation process	Physical mass recovery	No	Manages mass in place by creating a homogenous zone of soil with a lower mass flux in the dissolved phase.
	Phase change	No	Soil mixing itself does not induce a phase change, but LNAPL is redistributed throughout the mixed interval; some incidental volatilization may occur.
	In situ destruction	Maybe	If reactive media added, some LNAPL constituents can be destroyed.
	Stabilization/ binding	Yes	Stabilization of LNAPLs in place is the primary mechanism of this technology.
Objective applicability	LNAPL saturation	Yes	Homogenizing LNAPL zone reducing LNAPL saturation level to immobile (residual) saturations.
		Example performance metrics	Reduced LNAPL mobility, direct analysis of soil to measure changes in LNAPL saturation profile, maximum soil concentration reduced to cleanup criteria, reduced or stable dissolved-mass flux downgradient.
	LNAPL composition	Maybe	If no reactive media added, no change in chemical composition expected; if reactive media added, destruction of some LNAPL constituents.
		Example performance metrics	Change in LNAPL constituent ratios or mass.
Applicable LNAPL type	All LNAPL types		
Geologic factors	Unsaturated zone	Permeability	Not typically a factor.
		Grain size	Not typically a factor.
		Heterogeneity	Most advantageous in heterogeneous settings where complex LNAPL saturation profiles due to geologic heterogeneities are homogenized due to soil mixing.
		Consolidation	Works well in all unconsolidated geologic settings.
	Saturated zone	Permeability	Not typically a factor.
		Grain size	Grain sizes including cobbles may be difficult to treat with soil mixing.
		Heterogeneity	Most advantageous in heterogeneous settings where complex LNAPL saturation profiles due to geologic heterogeneities are homogenized due to soil mixing.
		Consolidation	Works well in all unconsolidated geologic settings.

Table A-3.B. Evaluation factors for in situ soil mixing and stabilization

Technology: In situ soil mixing and stabilization		
Remedial time frame	Concern	Low
	Discussion	Very short to short. Area and depth of treatment are the major factors on time.
Safety	Concern	High to moderate
	Discussion	Some potentially significant safety issues, but construction related and typically routine. Large equipment on site to mix the soils. If chemical oxidants or other amendments are added, there may be chemical mixing and injecting under pressure. Potential temporary ground surface instability.
Waste management	Concern	Low
	Discussion	No to minimal waste streams; possibly no soils removed from the site.
Community concerns	Concern	Low to moderate
	Discussion	Public generally familiar with and accustomed to construction excavations. Concerns may be significant due to volatile emissions, odors, traffic, exhaust, etc. Also, the public may see stabilization as not equal to cleanup.
Carbon footprint/ energy requirements	Concern	Moderate to high
	Discussion	Equipment emissions and energy requirements large. Fuel is used to power machinery to mix soils, and there may be some reaction if oxidants are injected.
Site restrictions	Concern	High
	Discussion	Disruptive technology, physical space and logistical demands significant. Heavy equipment operating on site. Due to the use of large, heavy equipment and the need for clearance on either side of the target zone, the working area could be limited due to buildings, facility requirements, utilities, and natural habitats.
LNAPL body size	Concern	High
	Discussion	Physical obstructions such as buildings will be a limiting factor. If there is a significant depth requirement, special equipment may be required.
Other regulations	Concern	Low
	Discussion	May be required to monitor air quality.
Cost	Concern	Moderate to high
	Discussion	Costs increase with increasing volume of LNAPL-impacted soil to be mixed and stabilized. Depends on area and depth of treatment and any special restrictions.
Other	Concern	
	Discussion	

Table A-3.C. Technical implementation considerations for in situ soil mixing and stabilization

Data requirements	Site-specific data for technology evaluation	Soil type(s)/lithology	
		Depth to LNAPL zone	
		Site access	Including locations of utilities and foundations.
	Bench-scale testing	Leachability testing	
	Pilot-scale testing	N/A	
	Full-scale design	Soil type(s)/lithology	
		Homogeneity	
		Depth to LNAPL zone	
	Performance metrics	LNAPL thickness	Monitoring wells downgradient of barrier to verify no occurrence of LNAPL.
		Downgradient concentrations	LNAPL constituent meets standard at point of compliance.
		Mass flux	Estimated dissolved mass discharge less than goal.
		LNAPL saturation	Direct analysis of soil to measure changes in LNAPL saturation profile.
Modeling tools/ applicable models			
Further information		FRTR. n.d. "Remedial Technology Screening and Reference Guide, Version 4.0, "Solidification and Stabilization." www.frtr.gov/matrix2/section4/4-8.html	
		Portland Cement Association. Information and resources about the use of solidification/stabilization with cement to treat wastes. www.cement.org/waste	
		USACE. 1999. *Engineering and Design: Solidification/Stabilization*. EM 1110-1-4010. http://140.194.76.129/publications/eng-manuals/em1110-1-4007/c-4.pdf	
		Larsson, S. 2004. *Mixing Processes for Ground Improvement by Deep Mixing*. Swedish Deep Stabilization Research Centre. http://kth.diva-portal.org/smash/record.jsf?pid=diva2:9502	

Table A-4.A. Natural source zone depletion

Technology	Natural source zone depletion	LNAPL mass reduction via naturally occurring volatilization (in the unsaturated zone), aqueous dissolution (in the saturated zone), and biodegradation (in both zones); site-specific LNAPL mass loss rates can be quantified empirically.	
Remediation process	Physical mass recovery	No	N/A
	Phase change	Yes	Volatile LNAPL fractions volatilize naturally to the gas phase in unsaturated soils; soluble LNAPL fractions dissolve to groundwater in the saturated zone.
	In situ destruction	Yes	In situ biodegradation processes destroy dissolved LNAPL in groundwater and volatilized LNAPL in unsaturated zone soil gas.
	Stabilization/binding	No	N/A
Objective applicability	LNAPL saturation	No	N/A
		Example performance metrics	N/A
	LNAPL composition	Yes	Modify LNAPL composition; can increase viscosity because of preferential loss of light fractions and will gradually concentrate in recalcitrant constituents as less recalcitrant constituents are depleted.
		Example performance metrics	Stable or reducing dissolved-phase plume, dissolved-phase plume shape, LNAPL composition change, soil VOC concentrations to below regulatory standard, soil vapor levels to regulatory standard.
Applicable LNAPL type	LNAPLs containing higher proportions of more soluble and more volatile hydrocarbon fractions deplete more efficiently via dissolution, volatilization, and biodegradation. As volatile LNAPL constituents are stripped, LNAPL can become more viscous, and more recalcitrant constituents can become more concentrated.		
Geologic factors	Unsaturated zone	Permeability	Unsaturated zone permeability, grain size, heterogeneity, consolidation, and soil moisture all affect the effective diffusivity rate of volatilized LNAPL soil gas in the subsurface. The effective diffusion rate of volatilized LNAPL soil gas greatly influences the LNAPL mass loss rate.
		Grain size	
		Heterogeneity	
		Soil moisture	
		Consolidation	Not typically a factor.
	Saturated zone	Permeability	Hydraulic properties that lead to higher groundwater velocities may result in higher LNAPL dissolution mass loss rates; lower groundwater velocities may limit the dissolution rate.
		Grain size	
		Heterogeneity	
		Consolidation	

Table A-4.B. Evaluation factors for natural source zone depletion

Technology: Natural source zone depletion		
Remedial time frame	Concern	High to very high
	Discussion	Very long term; natural volatilization and dissolution in unsaturated and saturation zones control the time frame.
Safety	Concern	Low
	Discussion	If there are no surface dangers.
Waste management	Concern	Low
	Discussion	No wastes generated; no waste removal from site.
Community concerns	Concern	Low to moderate
	Discussion	Potential perception of no action. Community may want active remediation and cleanup of site instead of monitoring. Need for more monitoring and reporting of results to educate the community on the improvements if achieved.
Carbon footprint/ energy requirements	Concern	Low
	Discussion	No emissions or energy requirements.
Site restrictions	Concern	Low
	Discussion	No constraints except to access monitoring network.
LNAPL body size	Concern	High
	Discussion	Large LNAPL plume will take significantly longer to remediate than smaller body.
Other regulations	Concern	Low
	Discussion	No additional regulatory or permitting requirements.
Cost	Concern	Low to moderate
	Discussion	Monitoring of the site is typically needed.
Other	Concern	
	Discussion	

Table A-4.C. Technical implementation considerations for natural source zone depletion

<table>
<tr><td rowspan="19">Data requirements</td><td rowspan="9">Site-specific data for NSZD evaluation</td><td>LCSM (saturated zone and unsaturated zone)</td><td>Detailed LCSM appropriate and verification of depletion mechanisms.</td></tr>
<tr><td>Submerged LNAPL source zone distribution</td><td>Site-specific LNAPL distribution at and beneath the capillary fringe.</td></tr>
<tr><td>Exposed LNAPL source zone distribution</td><td>Site-specific LNAPL distribution above the capillary fringe.</td></tr>
<tr><td>LNAPL characteristics</td><td>Estimate volatile fraction of exposed LNAPL in unsaturated zone, estimate effective solubility of submerged LNAPL in saturated zone.</td></tr>
<tr><td>Dissolved LNAPL concentrations</td><td>Dissolved LNAPL constituent fraction concentrations upgradient and downgradient of submerged LNAPL source zone.</td></tr>
<tr><td>Dissolved electron acceptor/ biotransformation products</td><td>Dissolved cation and anion groundwater geochemical constituents used to quantify mass loss via biodegradation processes.</td></tr>
<tr><td>Soil vapor LNAPL concentrations</td><td>Volatilized LNAPL constituent fraction concentrations at various depths in soil vapor originating in LNAPL source zone</td></tr>
<tr><td>Soil gas oxygen/ methane concentrations</td><td>Oxygen and methane concentration profile vs. depth to LNAPL source zone to identify biodegradation zones</td></tr>
<tr><td>Groundwater hydraulics of saturated zone</td><td>Hydraulic conductivity, groundwater-specific discharge.</td></tr>
<tr><td rowspan="3">NSZD design parameters</td><td>Control volume determination</td><td>Establish three-dimensional boundaries for LNAPL source zone control volume.</td></tr>
<tr><td>Saturated zone LNAPL mass loss rate</td><td>Calculate net mass flux in saturated zone by LNAPL dissolution and biodegradation leaving control volume based on dissolved-phase constituents.</td></tr>
<tr><td>Unsaturated zone LNAPL mass loss rate</td><td>Calculate net mass flux in unsaturated zone by LNAPL volatilization and biodegradation leaving control volume based on volatilized LNAPL and oxygen/methane soil gas constituents.</td></tr>
<tr><td rowspan="2">Bench-scale tests for NAPL longevity</td><td>Long-term soluble source mass loss</td><td>Serial batch equilibrium dissolution experimental measurements, scale lab-time LNAPL mass loss rates up to LNAPL field-time mass loss rates.</td></tr>
<tr><td>Long-term volatile source mass</td><td>Serial batch equilibrium volatilization and diffusivity experimental measurements, scale lab-time LNAPL mass loss rates up to LNAPL field-time mass loss rates.</td></tr>
<tr><td rowspan="3">Performance metrics</td><td>Saturated zone dissolution/ biodegradation mass loss rate</td><td>Current LNAPL source zone mass loss rate associated with LNAPL dissolution and subsequent biodegradation groundwater.</td></tr>
<tr><td>Unsaturated zone volatilization/ biodegradation mass loss rate</td><td>Current LNAPL source zone mass loss rate associated with LNAPL volatilization and subsequent biodegradation in soil column.</td></tr>
<tr><td>Long-term mass loss estimates</td><td>Extrapolation of short-term laboratory experiments (bench tests) to long-term LNAPL source zone mass loss.</td></tr>
<tr><td colspan="2">Modeling tools/ applicable models</td><td>See ITRC 2009, etc.</td><td>Numerous computer simulation models exist that are capable of estimating the results of NSZD process parameters using equilibrium relationships; many models cannot account for site-specific kinetics.</td></tr>
<tr><td colspan="2" rowspan="3">Further information</td><td colspan="2">ITRC. 2009. Evaluating Natural Source Zone Depletion at Sites with LNAPL. LNAPL-1. www.itrcweb.org/Documents/LNAPL-1.pdf</td></tr>
<tr><td colspan="2">Johnson, P. C., P. Lundegard, and Z. Liu. 2006. “Source Zone Natural Attenuation at Petroleum Hydrocarbon Spill Sites: I. Site-Specific Assessment Approach,” Ground Water Monitoring and Remediation 26(4): 82–92.</td></tr>
<tr><td colspan="2">Lundegard, P. D., and P. C. Johnson. 2006. “Source Zone Natural Attenuation at Petroleum Hydrocarbon Spill Sites: II. Application to a Former Oil Field,” Ground Water Monitoring and Remediation 26(4): 93–106.</td></tr>
</table>

Table A-5.A. Air sparging/soil vapor extraction

Technology	Air sparging/ soil vapor extraction	AS injects ambient air or other gases (e.g., oxygen) down well bores or trenches below the groundwater table, aerating groundwater and volatilizing LNAPL. SVE induces a vacuum that volatilizes LNAPL if present above the water table and removes LNAPL vapors from the subsurface. AS and SVE may be used individually if conditions allow.	
Remediation process	Physical mass recovery	Yes	AS volatilizes LNAPL from saturated zone and capillary fringe; SVE extracts LNAPL vapors from unsaturated zone.
	Phase change	Yes	AS and SVE induce volatilization of the LNAPL.
	In situ destruction	Yes	Ambient air or oxygen sparging below the water table and vacuum induced circulation of atmospheric air into the unsaturated zone enhance in situ aerobic biodegradation.
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	Can potentially reduce LNAPL saturations to below residual saturation.
		Example performance metrics	Mass removal to an asymptotic recovery of a well-operated and -maintained system (usually quantified in pounds of LNAPL constituent per day).
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change, soil VOC concentrations to below regulatory standard, soil vapor plume concentrations to below regulatory standard.
Applicable LNAPL type	All LNAPL types although better-suited to more volatile LNAPLs (e.g., gasoline, kerosene). SVE-induced vacuum extracts volatile LNAPL from the pores and increases oxygen content of unsaturated zone which, enhances aerobic respiration of heavier-phase LNAPLs. AS helps volatilize LNAPL from the capillary fringe and saturated zone as well as enhancing aerobic degradation of heavier-phase LNAPLs. As volatile LNAPL constituents are stripped, LNAPL can become more viscous, and more recalcitrant constituents can become more concentrated.		
Geologic factors	Unsaturated zone	Permeability	SVE is more effective in higher permeability materials and where treatment zone capped with a confining layer or impermeable surface to increase the ROI.
		Grain size	Small to very small proportion of fine-grained soil.
		Heterogeneity	AS/SVE is more efficient in homogeneous soils; in heterogeneous soils, air flow will follow preferential pathways, possibly short-circuiting remediation coverage, but LNAPL may also be distributed along preferential pathways.
		Consolidation	Not typically a factor.
	Saturated zone	Permeability	AS may be most effective in moderate-permeability materials, which are less prone to severe air channeling but do not severely restrict air flow.
		Grain size	As above, medium grain size balances AS air flow rate with distribution (ROI); small grain size may require entry pressures that exceed confining pressure and result in soil heaving for shallow treatment zones.
		Heterogeneity	Fractured bedrock and more permeable zones will induce preferential flow.
		Consolidation	Not typically a factor.

Table A-5.B. Evaluation factors for air sparging/soil vapor extraction

Technology: Air sparging/soil vapor extraction		
Remedial time frame	Concern	Low to moderate
	Discussion	Short to medium—typically 1–5 years. Depends on soil type and LNAPL type. Low-permeability soils and heavier LNAPL require more time to remediate.
Safety	Concern	Low to moderate
	Discussion	Vapor releases and potential of volatilization due to sparging and vapor migration in the subsurface (if AS used without SVE). Pressurized piping systems. Low safety concern for SVE alone.
Waste management	Concern	Low to moderate
	Discussion	Vapors generated by SVE systems may require treatment. Recovered LNAPL should be recycled.
Community concerns	Concern	Low to moderate
	Discussion	Noise of treatment equipment may be an issue. AS-induced vapor migration in the subsurface can be controlled using SVE. Concern with technology unfamiliar to general public.
Carbon footprint/ energy requirement	Concern	Moderate to high
	Discussion	Carbon footprint depends on the energy required for treatment (e.g., thermal oxidation make-up fuel or energy for activated carbon regenerations) and energy used to power blowers/compressors, which can be significant.
Site restrictions	Concern	Low to moderate
	Discussion	Vertical AS/SVE wells can usually be spaced and located around site restrictions or accessed through the use of directional drilling equipment.
LNAPL body size	Concern	Moderate
	Discussion	The size and depth of the LNAPL body directly affect the cost and extent of the remediation system, although there is an economy of scale with the need for one blower and compressor to operate on multiple wells and sparge points.
Other regulations	Concern	Low to moderate
	Discussion	Air emissions permitting may be required.
Cost	Concern	Low to moderate
	Discussion	In general, AS/SVE is more cost-effective than other active LNAPL technologies and has been proven at many sites for over 20 years.
Other	Concern	
	Discussion	

Table A-5.C. Technical implementation considerations for air sparging/soil vapor extraction

Data requirements	Site-specific data for technology evaluation	Soil permeability (to air, e.g., in unsaturated zone) (k_{soil})	Permeability to air in the unsaturated zone directly affects the radius of treatment that can be developed around each SVE well for a given vapor extraction rate; lower-permeability soils require more SVE wells per unit area.
		Groundwater conductivity (K_{gw})	Hydraulic conductivity is an indicator of the potential effectiveness of AS. Lower hydraulic conductivity soils ($<10^{-4}$ cm/sec) are likely to restrict air flow and limit the mass removal rate of volatile LNAPL fraction. Very high hydraulic conductivity soils (10^{-1} cm/sec) are likely to require deeper AS wells and high air-flow rates to be effective.
		LNAPL characteristics ($LNAPL_c$)	AS/SVE is effective on only the volatile fraction of the LNAPL. AS/SVE performed on an LNAPL with a small volatile fraction (e.g., jet fuel or a strongly weathered gasoline) does not result in significant volatile mass removal, but may contribute to aerobic biodegradation.
	Bench-scale testing	N/A	
	Pilot-scale testing	AS air entry pressure	To evaluate safe injection pressures.
		AS pressure vs. flow	Safety and feasibility
		AS ROI (vs. flow)	Feasibility can be measured by observing transient groundwater mounding, monitoring a tracer gas added to sparge air, or monitoring vapor concentration changes or dissolved oxygen coincident with sparge operation.
		SVE vacuum vs. flow	Feasibility
		SVE ROI (vs. flow)	Feasibility
		SVE influent concentration	Treatment system type and sizing
	Full-scale design	AS pressure and flow	Compressor sizing
		AS ROI	AS well spacing
		SVE vacuum and flow	Blower sizing
		SVE ROI	SVE well spacing
		SVE influent concentration	Treatment system type and sizing
	Performance metrics	SVE well head and blower vacuum	Basic system performance—large differences can be an indicator of system problems, e.g., water in conveyance piping.
		AS well head and compressor pressure	Basic system performance
		SVE influent concentration	Tracking mass removal rate
		O_2 influent concentration	Indicator of aerobic biodegradation
		CO_2 influent concentration	Indicator of aerobic biodegradation
		Cumulative mass removed or mass removal rate	Treatment effectiveness
		AS dissolved oxygen	System performance
Modeling tools/ applicable models		SOILVENT	
Further information		NAVFAC. 2001. *Air Sparging Guidance Document*. NFESC TR-2193-ENV. www.clu-in.org/download/contaminantfocus/dnapl/Treatment_Technologies/Air_Sparg_TR-2193.pdf	
		Johnson, P. C., C. C. Stanley, M. W. Kemblowski, D. L. Byers, and J. D. Colthart. 1990. "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems," *Ground Water Monitoring Review* **10**(2): 159–78.	
		Johnson, P. C., M. W. Kemblowski, and J. D. Colthart. 1990. "Quantitative Analysis for the Cleanup of Hydrocarbon-Contaminated Soils by In Situ Soil Venting," *Ground Water Journal* **3**(28): 413–29.	
		Battelle. 2002. *Air Sparging Design Paradigm*. www.estcp.org/documents/techdocs/Air_Sparging.pdf	
		EPA. 1995. "Air Sparging." www.epa.gov/swerust1/cat/airsparg.htm	
		EPA. n.d. "Technology Focus: Soil Vapor Extraction." www.clu-in.org/techfocus/default.focus/sec/Soil_Vapor_Extraction/cat/Overview	

Table A-5.C. continued

Further information (continued)	AFCEE. n.d. "Soil Vapor Extraction." www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sourcezonetreatment/background/soilvaporextract/index.asp
	EPA. 1997. *Analysis of Selected Enhancements for Soil Vapor Extraction*. EPA-542-R-97-007. www.clu-in.org/download/remed/sveenhmt.pdf
	Ground Water Remediation Technologies Analysis Center. 1996. *Air Sparging Technology Overview Report*. http://clu-in.org/download/toolkit/sparge_o.pdf
	USACE. 2002. *Engineering and Design: Soil Vapor Extraction and Bioventing*. EM 1110-1-4001. http://140.194.76.129/publications/eng-manuals/em1110-1-4001/toc.htm
	USACE. 2008. *Engineering and Design: In Situ Air Sparging*. EM 1110-1-4005. http://140.194.76.129/publications/eng-manuals/em1110-1-4005/toc.htm
	EPA. 1994. *How To Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites, A Guide for Corrective Action Plan Reviewers*. EPA 510-B-94-003. www.epa.gov/oust/pubs/tums.htm

Table A-6.A. Skimming

Technology	Active LNAPL skimming	Uses a single pump or hydrophobic belt (e.g., bladder pump, pneumatic pump, or belt skimmer) to extract LNAPL from a well at air/LNAPL interface under natural gradients. The available drawdown is limited based on the LNAPL thickness, the density difference between LNAPL and water, and the heterogeneity of the adjacent soil. LNAPL skimming typically induces a limited ROI of <25 feet in unconfined conditions. LNAPL skimming is effective for confined, unconfined, and perched LNAPL.	
Remediation process	Physical mass recovery	Yes	Removes LNAPL at the groundwater surface; does not affect residual LNAPL mass.
	Phase change	No	LNAPL remains in liquid phase.
	In situ destruction	No	N/A
	Stabilization/binding	No	N/A
Objective applicability	LNAPL saturation	Yes	Active skimming drives LNAPL saturation towards residual saturation, decreasing LNAPL transmissivity and mobile LNAPL extent.
		Example performance metrics	Direct analysis of soil to indicate changes in formation LNAPL saturations; LNAPL transmissivity reduction/ LNAPL conductivity reduction, LNAPL/water ratio, asymptotic recovery of LNAPL from a well.
	LNAPL composition	No	N/A—Skimming recovers LNAPL as a fluid and does not exploit volatilization or dissolution, so it does not lead to a compositional change.
		Example performance metrics	N/A
Applicable LNAPL type	All LNAPL types; however, lower-viscosity LNAPL (0.5–1.5 cP) is much more recoverable than high-viscosity LNAPL (>6 cP).		
Geologic factors	Unsaturated zone	Permeability	Technology not applicable to LNAPL in the unsaturated zone.
		Grain size	
		Heterogeneity	
		Consolidation	
	Saturated zone	Permeability	Soil permeability is proportional to recovery rate—higher LNAPL recovery and saturation reduction in higher permeabilities. Permeability has significant effect on ROI of a skimming well. LNAPL permeability greater at lower water table levels when saturations are higher (smear zone opened).
		Grain size	Skimming can be effective in all grain size distributions; can achieve lower residual saturation in coarser materials where capillary pressures are less.
		Heterogeneity	Moderately sensitive to heterogeneity, affecting ROI; well screen location and pump depth can help overcome heterogeneities.
		Consolidation	Not typically a factor.
Cost	Per well, the capital costs of skimming wells are low compared to other technologies; however, to achieve a remedial time frame similar to that of dual pump or total fluids extraction, a denser well spacing is required due to the small ROC and lower per-well rate of LNAPL removal. Skimming wells typically need to be operated longer than DPLE because they can have lower recovery rates achieved compared to other mass recovery technologies.		

Table A-6.B. Evaluation factors for skimming

Technology: LNAPL skimming		
Remedial time frame	Concern	High
	Discussion	Long to very long. Depends on soil type, LNAPL type, release size, footprint, and end point (e.g., LNAPL thickness, sheen, or oil transmissivity goal). Low-permeability soils and heavier LNAPL require more time to remediate.
Safety concerns	Concern	Low
	Discussion	Potential release from primary containment into secondary containment. Overall skimmers represent a low safety risk.
Waste management	Concern	Low to moderate
	Discussion	Recovered LNAPL requires treatment, disposal, and/or recycling.
Community concerns	Concern	Low
	Discussion	Concern with noise, aesthetic, and access issues and length of operation vs. other methods.
Carbon footprint/ energy requirements	Concern	Low to moderate
	Discussion	Carbon footprint depends on time frame, duration, frequency of events, and the amount of volatiles generated.
Site restrictions	Concern	Low
	Discussion	LNAPL skimming can usually be implemented in wells located around site restrictions.
LNAPL body size	Concern	Moderate to high
	Discussion	The size of the LNAPL body directly affects the cost and extent of the well network required to implement LNAPL skimming. Skimming ROI affects the number of wells required to address the LNAPL body.
Other regulations	Concern	Low
	Discussion	No additional regulations.
Cost	Concern	Low to moderate
	Discussion	Low for capital costs and low to medium for operation and maintenance, depending on life span of the project.
Other	Concern	
	Discussion	

Table A-6.C. Technical implementation considerations for skimming

Data requirements	Site-specific data for technology evaluation	LNAPL conductivity (K_{LNAPL}), LNAPL transmissivity (T_{LNAPL})	LNAPL transmissivity data indicate the LNAPL extraction rate. Transmissivity data may be obtained from LNAPL baildown tests or predictive modeling.
		LNAPL characteristics ($LNAPL_c$)	Low-viscosity LNAPLs are more amenable to pumping than higher-viscosity LNAPLs. Hence, lighter-end, low-viscosity LNAPL such as gasoline, kerosene, jet fuel, diesel and No. 2 fuel oil are more amenable to dual-phase extraction than a No. 6 fuel oil or Bunker C.
		Soil type/grain size	Coarser-grained materials, homogeneous soils allow larger ROI to develop; finer-grained soils interbeds impede or lessen capture.
		Safety precautions	Explosivity of LNAPL—potential need for bonding and grounding of metal equipment/containers and other associated safety requirements.
		Available power/utilities	The power source must be determined. Drop-line power may be readily available. Alternatively, on-site sources such as generators or solar power may be needed. Power supply must be compatible with skimmer pump demand.
	Bench-scale testing	N/A	
	Pilot-scale testing	LNAPL ROI/ROC	Establish LNAPL ROI and capture zone based on LNAPL drawdown.
		LNAPL recovery rate, volume, chemical characteristics	Determine LNAPL recovery rate, volume, and chemical characteristics to assist with design of LNAPL storage, handling, and treatment/discharge options.
	Full-scale design	Number of extraction wells	Determine number of extraction wells necessary to achieve adequate zone of LNAPL recovery consistent with LNAPL site objective(s).
		Conveyance piping	Determine locations, lengths, materials for horizontal conveyance piping to/from wells to/from recovery/treatment system. Assess pipe insulation and heat tracing needs for winter conditions, if applicable.
		LNAPL ROI/ROC	Establish LNAPL ROI and capture zone based on LNAPL drawdown.
	Performance and optimization metrics	LNAPL recovery rates and volumes	Basic system performance monitoring.
		System uptime vs. downtime	
		LNAPL recovery vs. groundwater recovery	Quantity of LNAPL recovered as a percentage of incidental recovered groundwater.
		Total LNAPL equivalent recovery cost metric	Cost per gallon of LNAPL recovered.
Modeling tools/ applicable models		Projected future LNAPL recovery	Use of decline curve analysis, semi-log plots, etc. to predict future LNAPL recoveries and help determine when LNAPL recovery is approaching asymptotic.
Further information		EPA. 1996. *How to Effectively Recover Free Product at Leaking Underground Storage Tank Sites: A Guide for State Regulators.* Office of Underground Storage Tanks. EPA 510-R-96-001. www.epa.gov/oust/pubs/fprg.htm	
		EPA. 1994. *How To Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers*. EPA 510-B-94-003. www.epa.gov/oust/pubs/tums.htm	

Table A-7.A. Bioslurping/enhanced fluid recovery

Technology	Bioslurping/ enhanced fluid recovery	Bioslurping/EFR reduces LNAPL saturations in subsurface through applied vacuum in conjunction with up to two pumps (e.g., a vacuum with a downhole stinger tube or vacuum applied in conjunction with a positive-displacement pump). LNAPL is primarily removed as a liquid, but bioslurping/EFR also removes LNAPL through volatilization and aerobic biodegradation with an applied vacuum.	
Remediation process	Physical mass recovery	Yes (primary)	1. Bioslurping/EFR removes liquid LNAPL from saturated zone and perched LNAPL zones. 2. Induced vacuum extracts LNAPL vapors from unsaturated zone and capillary fringe.
	Phase change	Yes (secondary)	The EFR-induced vacuum volatilizes and evaporates the LNAPL.
	In situ destruction	Yes (secondary)	Infiltration of oxygenated air from the surface enhances in situ aerobic biodegradation of the LNAPL.
	Stabilization/ binding	No	
Objective applicability	LNAPL saturation	Yes	Bioslurping/EFR reduces LNAPL saturations.
		Example performance metrics	Direct analysis of soil to measure changes in LNAPL saturation; direct measurement of LNAPL thickness reduction in wells, reduced LNAPL transmissivity/LNAPL conductivity, LNAPL-to-water ratio for a given vacuum induced, asymptotic recovery of a well operated and maintained system, dissolved-phase stability, and LNAPL plume monitoring.
	LNAPL composition	Yes	Bioslurping/EFR reduces the volatile constituent fraction of the LNAPL. Volatilization loss and likely also the soluble fraction of the LNAPL. Aerobic degradation reduces LNAPL concentrations of degradable compounds in dissolved phase and drives preferential dissolution of those compounds from LNAPL. More volatilization occurs closer to the well(s) than at greater distance.
		Example performance metrics	Removal of VOC concentrations in extracted vapor to a concentration end point (e.g., 1 ppm-v), reduced dissolved-phase concentrations to regulatory standard at compliance point.
Applicable LNAPL type	All LNAPL types, although better suited to less viscous LNAPLs (e.g., gasoline, kerosene).		
Geologic factors	Unsaturated zone	Permeability	More effective in higher-permeability materials where gas-phase flow is easier but can also be applied in lower-permeability materials through the use of stronger vacuum.
		Grain size	More applicable to sands and gravels but can also be applied in silts and clays.
		Heterogeneity	In heterogeneous soils, vacuum extracts LNAPL from preferential pathways, possibly short-circuiting remediation coverage, but LNAPL is often also in preferential pathways.
		Consolidation	Not typically a factor.
	Saturated zone	Permeability	Can achieve faster LNAPL removal and lower LNAPL saturations in higher-permeability materials.
		Grain size	More applicable to sands and gravels but can also be applied in silts and clays.
		Heterogeneity	Fractured bedrock and more permeable zones will induce preferential flow. More applicable to perched LNAPL and unconfined LNAPL due to unsaturated zone exhibiting impacts and equivalent or higher permeability than saturated zone. Less applicable to confined conditions because the benefits of the applied vacuum are limited, although vapor treatment may still be necessary. The ratio of vacuum induced drawdown to water production–induced drawdown can be optimized for the given hydrogeologic scenario (e.g., perched LNAPL would require little to no water production, focusing the vacuum enhancement on the LNAPL recovery).
		Consolidation	Not typically a factor.

Table A-7.B. Evaluation factors for bioslurping/enhanced fluid recovery

Technology: Bioslurping/enhanced fluid recovery		
Remedial time frame	Concern	High to very high
	Discussion	Long to very long. Depends on soil type, LNAPL type, release size, footprint, and end point (e.g., LNAPL thickness, sheen, or transmissivity goal) and aggressiveness of pumping. Low-permeability soils and heavier LNAPL will require more time to remediate.
Safety	Concern	Low
	Discussion	Vapor releases and potential of volatilization due to vacuum operations.
Waste management	Concern	Moderate
	Discussion	Recovered fluids require treatment and LNAPL should be recycled. Can have an LNAPL/water/air emulsion that is difficult to break.
Community concerns	Concern	Low to medium
	Discussion	Concern with noise of treatment equipment and vapor releases from vacuum truck.
Carbon footprint/energy requirements	Concern	Low to moderate
	Discussion	Carbon footprint depends on time frame, duration, frequency of events, and the amount of volatiles generated. Energy source needed for vacuum.
Site restrictions	Concern	Low to moderate
	Discussion	Bioslurping/EFR can usually be implemented in wells located around site restrictions or in wells under obstructions through the use of directional drilling equipment.
LNAPL body size	Concern	Moderate to high
	Discussion	The size of the LNAPL body directly affects the cost and extent of the well network required to implemented bioslurping/EFR. ROI affects the number of wells required to address the LNAPL Body. Lower-permeability soils require closer well spacing. Intermittent operation may enhance overall recovery after initial saturation asymptote is reached.
Other regulations	Concern	Low
	Discussion	
Cost	Concern	Low to moderate
	Discussion	Overall, low for capital costs and low to medium for operation and maintenance, depending on life span of the project. In general, bioslurping/EFR are more cost-effective than other active LNAPL technologies and have been proven at many sites for over 20 years. Longer time frames may, however, not be cost-effective compared to other technologies.
Other	Concern	
	Discussion	

Table A-7.C. Technical implementation considerations for bioslurping/EFR

Data requirements	Site-specific data for technology evaluation	Hydraulic conductivity (K_w), transmissivity (T_w)	Hydraulic conductivity and transmissivity determine the appropriate groundwater extraction rate that may be sustained by the groundwater pump. Formations with low conductivities/ transmissivities may require the use of low-flow pneumatic pumps, as opposed to higher-flow submersible pumps.
		LNAPL conductivity (K_{LNAPL}), LNAPL transmissivity (T_{LNAPL})	LNAPL conductivity and transmissivity determine the LNAPL extraction rate that may be sustained by the LNAPL pump. These data may be obtained from LNAPL baildown tests or from predictive modeling.
		LNAPL characteristics ($LNAPL_c$)	Low-viscosity LNAPLs are more amenable to pumping than higher-viscosity LNAPLs.
		Soil type/grain size	Granular soils (sands and gravels) experience higher airflows with lower operating vacuums. Fine-grained soils (silts and clays) experience lower airflows with higher operating vacuums.
		Safety precautions	
		Available power/utilities	
	Bench-scale testing	N/A	
	Pilot-scale testing	Groundwater ROI/ROC	Establish groundwater ROI/capture for different groundwater pumping rates and determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		LNAPL ROI/ROC	Establish LNAPL ROI/capture for different LNAPL pumping rates.
		Groundwater recovery rate, volume, and influent concentrations	Determine groundwater recovery rate, volume, and influent concentrations to assist with design of water handling, treatment, and discharge options.
		LNAPL recovery rate, volume, chemical characteristics	Determine LNAPL recovery rate, volume, and chemical characteristics to assist with design of LNAPL storage, handling, and treatment/discharge options.
		Airflow and vacuum	Determine system airflow and vacuum and individual extraction wellhead airflows and vacuums.
		Induced vacuum ROI	Determine vacuum ROI by measuring induced vacuums on adjacent monitoring wells.
		Influent vapor concentrations	Assess influent vapor concentrations and system airflow rates to determine potential off-gas treatment requirements/permitting issues and to calculate vapor-phase LNAPL recovery.
	Full-scale design	Number of extraction wells	Determine number of extraction wells required to achieve adequate zone of LNAPL recovery consistent with LNAPL site objective(s).
		Conveyance piping	Determine locations, lengths, and materials for all horizontal conveyance piping to/from recovery/treatment system. Assess pipe insulation and heat tracing needs for winter conditions, if applicable.
		Groundwater ROI/ROC	
		LNAPL ROI/ROC	
		Vacuum losses	Calculate potential vacuum losses due to conveyance pipe diameters, lengths, materials. Try to minimize losses between system and wellheads.
		Air permitting/off-gas treatment issues	Assess and design for air permitting and/or off-gas treatment requirements.
	Performance metrics	Groundwater/LNAPL recovery rates and volumes	Basic system performance monitoring.
		System uptime vs. downtime	
		Cumulative groundwater/ LNAPL recovery	
		LNAPL recovery vs. groundwater recovery	Quantity of LNAPL recovered as a percentage of recovered groundwater.
		Vapor-phase LNAPL recovery	
		Total LNAPL equivalent recovery cost metric	Cost per gallon of LNAPL recovered.

Table A-7.C. continued

Modeling tools/ applicable models	Projected future LNAPL recovery	Use of decline curve analysis, semi-log plots, etc. to predict future LNAPL recoveries and help determine when LNAPL recovery is approaching asymptotic.
Further information	Ground-Water Remediation Technologies Analysis Center. 1996. *Bioslurping Technology Overview Report*. TO-96-05. http://clu-in.org/download/toolkit/slurp_o.pdf	
	Naval Facilities Engineering Service Center. 1996. *Best Practice Manual for Bioslurping*. https://portal.navfac.navy.mil/portal/page/portal/navfac/navfac_ww_pp/navfac_nfesc_pp/environmental/erb/bioslurp-old/bestprac.pdf	
	AFCEE. "Bioslurping." www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/bioslurping/index.asp	
	NAVFAC. 1998. *Application Guide for Bioslurping. Volume 1: Summary of the Principles and Practices of Bioslurping*. NFESC TM-2300-ENV. https://portal.navfac.navy.mil/portal/page/portal/navfac/navfac_ww_pp/navfac_nfesc_pp/environmental/erb/resourceerb/tm-2300.pdf	
	NAVFAC. 1998. *Application Guide for Bioslurping. Volume II: Principles and Practices of Bioslurping*. NFSEC TM-2301-ENV https://portal.navfac.navy.mil/portal/page/portal/navfac/navfac_ww_pp/navfac_nfesc_pp/environmental/erb/resourceerb/tm-2301.pdf	
	EPA. 1996. *How to Effectively Recover Free Product at Leaking Underground Storage Tank Sites: A Guide for State Regulators.* EPA 510-R-96-001. www.epa.gov/oust/pubs/fprg.htm	

Table A-8.A. Dual-pump liquid extraction

Technology	Dual-pump liquid extraction	LNAPL recovered using two pumps (one dedicated to removing LNAPL and one dedicated to remove groundwater). The groundwater pump creates a cone of depression that induces LNAPL flow into the well through an increased hydraulic gradient. The LNAPL pump then recovers the LNAPL as it accumulates in the well. The LNAPL pump can be a bladder pump, pneumatic pump, or belt skimmer that extracts LNAPL only via a floating inlet at the air/LNAPL interface, while the groundwater pump is typically a submersible positive displacement pump. Each phase (LNAPL, groundwater) is typically treated separately.	
Remediation process	Physical mass recovery	Yes	Removes mobile LNAPL with a capture zone dictated by the cone of groundwater depression; does not affect residual LNAPL mass.
	Phase change	No	N/A. LNAPL remains in original liquid phase.
	In situ destruction	No	N/A
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	LNAPL recovery reduces LNAPL saturation toward residual saturation; does not typically improve dissolved-phase concentrations due to residual LNAPL mass left behind.
		Example performance metrics	Direct analysis of soil to indicate changes in formation LNAPL saturations; LNAPL transmissivity/LNAPL conductivity, LNAPL/water ratio, asymptotic recovery of a well-operated and -maintained system.
	LNAPL composition	No	N/A. Skimming recovers LNAPL as a fluid and does exploit volatilization or dissolution, so it does not lead to a compositional change.
		Example performance metrics	N/A
Applicable LNAPL type	All LNAPL types; however, lower-viscosity LNAPL (0.5–1.5 cP) is much more recoverable than high-viscosity LNAPL (>6 cP).		
Geologic factors	Unsaturated zone	Permeability	Technology is not applicable to LNAPL in the unsaturated zone.
		Grain size	
		Heterogeneity	
		Consolidation	
	Saturated zone	Permeability	Soil permeability is proportional to LNAPL recovery rate—higher LNAPL recovery and saturation reduction in higher-permeability soils; permeability affects the ROI of a recovery well. A second key factor is the ratio between LNAPL transmissivity to aquifer transmissivity; low-conductivity materials (K_w <10^{-6} cm/sec) may experience poor total fluid recovery.
		Grain size	LNAPL within fine-grained soils may not be feasible to remove by DPLE.

Table A-8.B. Evaluation factors for dual-pump liquid extraction

Technology: Dual-pump liquid extraction		
Remedial time frame	Concern	Moderate
	Discussion	Medium. Depends on soil type, LNAPL type, release size, footprint, and end point (e.g., LNAPL thickness, sheen, or oil transmissivity goal). Low-permeability soils and heavier LNAPL require more time to remediate.
Safety	Concern	Moderate
	Discussion	There may electrical concerns with a submersible pump in a well with LNAPL and confined-space entry issues with access to well vaults.
Waste management	Concern	Moderate
	Discussion	Recovered LNAPL and groundwater water need to be properly disposed. LNAPL should be recycled. Need construction of wastewater treatment.
Community concerns	Concern	Low to moderate
	Discussion	Concern with noise, potential odors, and volatile emissions.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	Remediation runs continuously or cycles.
Site restrictions	Concern	Moderate
	Discussion	Typically all equipment is in a compound and piping is below ground. Equipment typically can be deployed to accommodate many site restrictions.
LNAPL body size	Concern	Low
	Discussion	Capable of remediating large and small LNAPL plumes. Lithology and permeability determine the spacing between recovery wells.
Other regulations	Concern	High
	Discussion	May need permits for discharge of water.
Cost	Concern	Moderate
	Discussion	Capital costs are higher than skimmer pumps, and operation and maintenance are much higher to maintain the system potentially for a shorter time frame.
Other	Concern	
	Discussion	

Table A-8.C. Technical implementation considerations for dual-pump liquid extraction

Data requirements	Site-specific data for technology evaluation	Hydraulic conductivity (K_w), transmissivity (T_w)	Hydraulic conductivity and transmissivity data help determine the appropriate groundwater extraction rate that may be sustained by the groundwater pump. These data may be obtained from slug tests or groundwater pumping tests or from predictive modeling. Relatively tight formations with low-conductivity/transmissivity soils may require the use of low-flow pneumatic pumps, as opposed to higher-flow submersible pumps.
		LNAPL conductivity (K_{LNAPL}), LNAPL transmissivity (T_{LNAPL})	LNAPL transmissivity data indicate the LNAPL extraction rate. Transmissivity data may be obtained from LNAPL baildown tests or predictive modeling.
		LNAPL characteristics ($LNAPL_c$)	Low-viscosity LNAPLs are more amenable to pumping than higher-viscosity LNAPLs. Hence, lighter-end, low-viscosity LNAPL such as gasoline, kerosene, jet fuel, diesel and No. 2 fuel oil are more amenable to DPLE than a No. 6 fuel oil or Bunker C.
		Soil type/grain size	Coarser-grained, more-homogeneous soils allow larger ROI to develop. Finer-grained soil interbeds impede or lessen capture.
		Safety precautions	Explosivity of LNAPL—potential need for bonding and grounding of metal equipment/containers and other associated safety requirements.
		Available power/utilities	The power source must be determined. Drop-line power may be readily available. Alternatively, on-site sources such as generators or solar power may be needed. Power supply must be compatible with skimmer pump demand.
	Bench-scale testing	N/A	
	Pilot-scale testing	Groundwater ROI/ROC	Establish groundwater ROI/ROC for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained for design groundwater drawdown.
		LNAPL ROI/ROC	Establish LNAPL capture for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		Groundwater recovery rate, volume, and influent concentrations	Determine groundwater recovery rate, volume, and influent concentrations to assist with design of water handling, treatment, and discharge options.
		LNAPL recovery rate, volume and chemical characteristics	Determine LNAPL recovery rate, volume and chemical characteristics to assist with design of LNAPL storage, handling, treatment, and discharge options.
	Full-scale design	Number of extraction wells	Determine number of required DPLE wells necessary to achieve adequate zone of LNAPL recovery consistent with LNAPL site objective(s).
		Conveyance piping	Determine locations, lengths, materials for all horizontal conveyance piping to/from DPLE wells to/from recovery/treatment system. Assess pipe insulation and heat tracing needs for winter conditions, if applicable.
		Groundwater ROC	Establish groundwater capture for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		LNAPL ROC	Establish LNAPL capture for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.

Table A-8.C. continued

Data requirements (cont.)	Performance metrics	Groundwater/LNAPL recovery rates and volume	Basic system performance monitoring
		System uptime vs. downtime	
		Cumulative groundwater/LNAPL recovery	
		LNAPL recovery vs. groundwater recovery	LNAPL/water ratio
		LNAPL recovery cost metric	Cost per gallon of LNAPL recovered
		LNAPL thickness	
		Mass removed	
Modeling tools/ applicable models		API LDRM	
Further information		EPA. 2005. *Cost and Performance Report for LNAPL Recovery: Multi-Phase Extraction and Dual-Pump Recovery of LNAPL at the BP Former Amoco Refinery, Sugar Creek, MO*. EPA-542-R-05-016.	
		API. 1999. *Free-Product Recovery of Petroleum Hydrocarbon Liquids*. API PUBL 4682.	
		EPA. 1996. *How to Effectively Recover Free Product at Leaking Underground Storage Tank Sites: A Guide for State Regulators.* EPA 510-R-96-001. www.epa.gov/oust/pubs/fprg.htm	

Table A-9.A. Multiphase extraction (dual pump)

Technology	Multi-phase extraction (dual pump)	MPE technology employs vacuum-enhancement as well as two dedicated pumps to extract liquids (LNAPL through a bladder pump, pneumatic pump, or belt skimmer and groundwater typically through a positive-displacement submersible pump) from an extraction well simultaneously. It can also be known as total fluids excavation or vacuum-enhanced, dual-phase extraction. One dedicated pump targets LNAPL located at the groundwater surface; the second pump enhances LNAPL recovery with groundwater extraction, as well as vacuum enhancement at the wellhead. The groundwater extraction induces additional drawdown into the well over and beyond what skimming alone can induce. Because each fluid is recovered by an exclusive pump, emulsification of LNAPL is limited to that which may occur in the formation as a result of LNAPL weathering and dissolved-phase impacts within groundwater. MPE using dual pumps and vacuum enhancement is more applicable to cases where LNAPL is recovered at a rate sufficient to require the continuous operation of a dedicated LNAPL pump or where minimization of emulsification is desired and cycling of the LNAPL recovery pump is feasible. The cycling of the LNAPL pump allows LNAPL exhibiting lower recovery rates to build up substantial LNAPL thickness in the well, which can then be pumped off during a pump cycle.	
Remediation process	Physical mass recovery	Yes	Removes mobile LNAPL at the groundwater surface.
	Phase change	No	Vacuum induces volatilization, which changes the LNAPL constituent composition.
	In situ destruction	No	N/A
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	LNAPL recovery reduces LNAPL saturation toward residual saturation; does not typically improve dissolved-phase concentrations due to residual LNAPL mass left behind.
		Example performance metrics	Direct analysis of soil to indicate changes in formation LNAPL saturations, LNAPL transmissivity/LNAPL conductivity, LNAPL/water ratio, asymptotic recovery of a well-operated and -maintained system.
	LNAPL composition	Yes	Yes
		Example performance metrics	Removal of VOC concentrations in extracted vapor to a concentration end point (e.g., 1 ppm-v); vapor-phase or dissolved-phase concentrations meet regulatory standard at compliance point; reduced volatile or soluble LNAPL constituent mass fraction.
Applicable LNAPL type	All LNAPL types; however, lower-viscosity LNAPL (0.5–1.5 cP) is much more recoverable than high-viscosity LNAPL (>6 cP).		
Geologic factors	Unsaturated zone	Technology is not applicable to LNAPL in the unsaturated zone.	
	Saturated zone	Permeability	Soil permeability is proportional to LNAPL recovery rate; higher LNAPL recovery and saturation reduction in higher-permeability soils. Permeability affects the ROI of a recovery well. A low-permeability setting maximizes drawdown, exposing the LNAPL smear zone for LNAPL recovery via vapor extraction, and reduced groundwater recovery minimizes groundwater treatment costs. The higher the permeability (or conductivity), the greater the water production will be to dewater the smear zone.
		Grain size	LNAPL in fine-grained soils may not be feasible to remove by MPE.
		Heterogeneity	Moderately sensitive to heterogeneity; affects the ROI of a recovery well. Focuses on LNAPL at the groundwater surface and LNAPL that can drain with a depressed groundwater surface. MPE is not applicable to thin, perched LNAPL layers, from which drawdown is limited; moderately applicable to unconfined LNAPL conditions; however, in low-permeability settings, smearing could occur due to excessive drawdowns. Excellent applicability for confined LNAPL since little to no additional smearing will occur. Well screen location and submersible pump depth can help overcome heterogeneities.
		Consolidation	Not typically a factor.

Table A-9.A. continued

Cost	Per well, the capital costs of MPE dual-pump wells are higher than skimming but lower than DPLE wells and bioslurping/EFR. Fewer wells are required to achieve the same goal within the same time frame as skimming.

Table A-9.B. Evaluation factors for multiphase extraction (dual pump)

Technology: Multiphase extraction (dual pump)		
Remedial time frame	Concern	Moderate
	Discussion	Medium. Depends on soil type, LNAPL type, release size, footprint, and end point (e.g., LNAPL thickness, sheen, or oil transmissivity goal). Low-permeability soils and heavier LNAPL require more time to remediate.
Safety	Concern	Moderate
	Discussion	The remediation equipment is either placed in a compound or trailer mounted. There are moving parts, piping under pressure and vacuum, and potential for vapor accumulation in remediation trailers.
Waste management	Concern	Moderate
	Discussion	Recovered LNAPL and water need to be properly recycled or disposed. Recovered vapors have to be managed or destroyed.
Community concerns	Concern	Moderate
	Discussion	Although equipment is usually out of sight, there is a potential for concerns with noise, potential odors, volatile emissions, aesthetic, and access issues.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	Remediation runs continuously or cycles. Little recovered vapors that need treatment.
Site restrictions	Concern	Moderate
	Discussion	Typically all equipment is in a compound and piping is below ground. Equipment can typically be deployed in manner to accommodate many site restrictions. Power needs to be supplied to the system, and produced water needs treatment.
LNAPL body size	Concern	High
	Discussion	The size of the LNAPL body directly affects the cost and extent of the well network required to implement MPE. MPE ROI affects the number of wells required to address the LNAPL body.
Other regulations	Concern	Moderate
	Discussion	May need permits to discharge water and vapors.
Cost	Concern	Moderate
	Discussion	Capital costs are higher than skimmer pumps, and operation and maintenance are much higher to maintain the system potentially for a shorter time frame.
Other	Concern	
	Discussion	

Table A-9.C. Technical implementation considerations for multiphase extraction (dual pump)

Data requirements	Site-specific data for technology evaluation	Hydraulic conductivity (K_w), transmissivity (T_w)	Hydraulic conductivity and transmissivity data help determine the appropriate groundwater extraction rate that may be sustained by the groundwater pump. These data may be obtained from slug tests, groundwater pumping tests, or predictive modeling. Relatively tight formations with low-conductivity/transmissivity soils may require the use of low-flow pneumatic pumps, as opposed to higher-flow submersible pumps.
		LNAPL conductivity (K_{LNAPL}), LNAPL transmissivity (T_{LNAPL})	LNAPL conductivity and transmissivity data help determine the appropriate LNAPL extraction rate that may be sustained by the LNAPL pump. These data may be obtained from LNAPL baildown tests, pumping tests, or predictive modeling. Relatively tight formations or sites with low LNAPL transmissivity/LNAPL conductivity may require the use of low-flow pneumatic pumps, as opposed to higher-flow submersible pumps.
		LNAPL characteristics ($LNAPL_c$)	Low-viscosity LNAPLs are more amenable to pumping than higher viscosity LNAPLs. Hence, lighter-end, low-viscosity LNAPL such as gasoline, kerosene, jet fuel, diesel and No. 2 fuel oil are more amenable to MPE than a No. 6 fuel oil or Bunker C.
		Soil permeability (to air, e.g., in unsaturated zone) (k_{soil})	Permeability to air in the unsaturated zone directly affects the radius of treatment that can be developed around each SVE well for a given vapor extraction rate. Lower-permeability soils require more SVE wells per unit area.
		Safety precautions	Explosivity of LNAPL—potential need for bonding and grounding of metal equipment/containers and other associated safety requirements.
		Available power/utilities	System needs three-phase power.
	Bench-scale testing	N/A	
	Pilot-scale testing	Groundwater ROC	Establish groundwater ROI/ROC for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained for design groundwater drawdown.
		LNAPL ROC	Establish LNAPL ROI/ROC for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		Groundwater recovery rate, volume, and influent concentrations	Determine groundwater recovery rate, volume, and influent concentrations to assist with design of water handling, treatment, and discharge options.
		LNAPL recovery rate, volume, and chemical characteristics	Determine LNAPL recovery rate, volume, and chemical characteristics to assist with design of LNAPL storage, handling, treatment, and discharge options.
		Vacuum and flow	Blower sizing
		Vacuum ROI	Well spacing
		Vacuum influent concentration	Treatment system type and sizing
	Full-scale design	Number of extraction wells	Determine number of required MPE wells necessary to achieve adequate zone of LNAPL recovery consistent with LNAPL site objective(s).
		Conveyance piping	Determine locations, lengths, materials for all horizontal conveyance piping to/from MPE wells to/from recovery/treatment system. Assess pipe insulation and heat tracing needs for winter conditions, if applicable.
		Groundwater ROC	Establish groundwater ROI/ROC for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		LNAPL ROC	Establish LNAPL ROI/ROC for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.

Table A-9.C. continued

Data requirements (cont.)	Performance metrics	Groundwater/LNAPL recovery rates and volumes	Basic system performance monitoring
		System uptime vs. downtime	
		Cumulative groundwater/LNAPL recovery	
		LNAPL recovery vs. groundwater recovery	LNAPL/water ratio
		LNAPL recovery cost metric	Cost per gallon of LNAPL recovered
Modeling tools/ applicable models		Projected future LNAPL recovery	Use of decline curve analysis, semi-log plots, etc. to predict future LNAPL recoveries and help determine when LNAPL recovery is approaching asymptotic.
Further information		FRTR. n.d. "Remedial Technology Screening and Reference Guide, Version 4.0, Dual Phase Extraction." www.frtr.gov/matrix2/section4/4-37.html	
		EPA. 1996. *How to Effectively Recover Free Product at Leaking Underground Storage Tank Sites: A Guide for State Regulators.* EPA 510-R-96-001. www.epa.gov/oust/pubs/fprg.htm	
		EPA. 1995. *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers,* Chap. 11, "Dual-Phase Extraction." EPA 510-R-04-002. www.epa.gov/swerust1/pubs/tum_ch11.pdf	
		API. 1999. *Free-Product Recovery of Petroleum Hydrocarbon Liquids*. API PUBL 4682.	
		EPA. 1997. *Presumptive Remedy: Supplemental Bulletin Multi-Phase Extraction (MPE) Technology for VOCs in Soil and Groundwater*. EPA-540-F-97-004. www.epa.gov/superfund/health/conmedia/gwdocs/voc/index.htm	
		USACE. 1999. *Engineering and Design: Multi-Phase Extraction*. EM 1110-1-4010. http://140.194.76.129/publications/eng-manuals/em1110-1-4010/toc.htm	
		EPA. 1999. *Multi-Phase Extraction. State of the Practice*. EPA 542-R-99-004. http://clu-in.org/download/remed/mpe2.pdf	
		EPA. n.d. "Technology Focus: Multi-Phase Extraction Overview." http://clu-in.org/techfocus/default.focus/sec/Multi%2DPhase%5FExtraction/cat/Overview	

Table A-10.A. Multiphase extraction (single pump)

Technology	Multiphase extraction (single pump)	MPE single-pump technology employs a single pump to extract fluids (e.g., a downhole pneumatic pump that removes groundwater and LNAPL, or a high-vacuum stinger tube to remove groundwater, LNAPL, and vapor) from an extraction well. MPE induces additional drawdown into the well over and beyond what skimming alone can induce. This additional drawdown in turn results in increased LNAPL recovery. MPE may emulsify LNAPL and requires LNAPL/water separation. MPE usually involves lower capital than DPLE. MPE becomes more favorable than DPLE when aboveground LNAPL/water treatment is feasible, LNAPL thicknesses are low, and LNAPL-to-water production ratios are low (e.g., <1:500).	
Remediation process	Physical mass recovery	Yes	Removes LNAPL at the groundwater surface; does not generally affect residual LNAPL mass.
	Phase change	No	Vacuum induces volatilization, which changes the LNAPL constituent composition.
	In situ destruction	No	N/A
	Stabilization/binding	No	N/A
Objective applicability	LNAPL saturation	Yes	LNAPL recovery reduces LNAPL saturation toward residual saturation; does not typically improve dissolved-phase concentrations due to residual LNAPL mass left behind.
		Example performance metrics	Direct analysis of soil to indicate changes in formation LNAPL saturations, LNAPL transmissivity, LNAPL transmissivity/LNAPL conductivity, LNAPL-to-water ratio, asymptotic recovery of a well-operated and -maintained system.
	LNAPL composition	Yes	
		Example performance metrics	Removal of VOC concentrations in extracted vapor to a concentration end point (e.g., 1 ppm-v); vapor-phase or dissolved-phase concentrations meet regulatory standard at compliance point; reduced volatile or soluble LNAPL constituent mass fraction.
Applicable LNAPL type	All LNAPL types; however, lower-viscosity LNAPL (0.5–1.5 cP) is much more recoverable than high-viscosity LNAPL (>6 cP).		
Geologic factors	Unsaturated zone	Technology is not applicable to LNAPL in the unsaturated zone.	
	Saturated zone	Permeability	A low-permeability setting maximizes drawdown, exposing the LNAPL smear zone for LNAPL recovery via vapor extraction, and reduced groundwater recovery minimizes groundwater treatment costs. The higher the permeability (or conductivity), the greater the water production is to dewater the smear zone.
		Grain size	LNAPL within fine-grained soils may not be feasible to remove by MPE.
		Heterogeneity	Moderately sensitive to heterogeneity; affects the ROI of a recovery well. Focuses on LNAPL at the groundwater surface and LNAPL that can drain with a depressed groundwater surface. MPE is not applicable to thin, perched LNAPL layers, from which drawdown is limited; moderately applicable to unconfined LNAPL conditions; however, additional LNAPL smearing could occur due to excessive drawdowns. Excellent applicability for confined LNAPL conditions since little to no additional smearing occurs. Well screen location and submersible pump depth can help overcome heterogeneities.
		Consolidation	Not typically a factor
Cost	Per well, the capital costs of MPE wells are higher than those of active skimming but lower than those of DPLE and bioslurping/EFR. Fewer wells are required to achieve the same goal within the same time frame as skimming. The costs of aboveground oil/water separation should be considered over and above the dual-pump aboveground fluid treatment.		

Table A-10.B. Evaluation factors for multiphase extraction

Technology: Multiphase extraction (single pump)		
Remedial time frame	Concern	Moderate
	Discussion	Medium. Depends on soil type, LNAPL type, release size, footprint, and end point (e.g., LNAPL thickness, sheen, or oil transmissivity goal). Low-permeability soils and heavier LNAPL require more time to remediate.
Safety	Concern	Moderate
	Discussion	The remediation equipment is either placed in a compound or trailer mounted. There are moving parts, piping under pressure and vacuum, and potential for vapor accumulation in remediation trailers.
Waste management	Concern	Moderate to high
	Discussion	Recovered LNAPL and water need to be properly disposed. Recovered vapors have to be managed or destroyed. LNAPL/water/air emulsion may be difficult to break and manage.
Community concerns	Concern	Moderate
	Discussion	Although, equipment is usually out of sight, there is a potential for concerns with noise, potential odors, volatile emissions, aesthetic, and access issues.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	Remediation runs continuously or cycles. Little off-gas needs treatment.
Site restrictions	Concern	Moderate
	Discussion	Typically, all equipment is in a compound, and piping is below ground. Equipment can typically be deployed in manner to accommodate many site restrictions. Power needs to be supplied to the system, and produced water needs treatment.
LNAPL body size	Concern	High
	Discussion	The size of the LNAPL body directly affects the cost and extent of the well network required to implement MPE. MPE ROI affects the number of wells required to address the LNAPL body.
Other regulations	Concern	Moderate
	Discussion	May need a permit to discharge water and vapor.
Cost	Concern	Moderate
	Discussion	Capital costs are higher than skimmer pumps, and operation and maintenance are much higher to maintain the system.
Other	Concern	
	Discussion	

Table A-10.C. Technical implementation considerations for multiphase extraction (single pump)

Data requirements	Site-specific data for technology evaluation	Hydraulic conductivity (K_w), transmissivity (T_w)	Hydraulic conductivity and transmissivity data help determine the appropriate groundwater extraction rate that may be sustained by the single pump. These data may be obtained from slug tests, groundwater pumping tests, or predictive modeling. Relatively tight formations with low-conductivity/transmissivity soils may require the use of low-flow pneumatic pumps, as opposed to higher-flow submersible pumps.
		LNAPL conductivity (K_{LNAPL}), LNAPL transmissivity (T_{LNAPL})	LNAPL conductivity and transmissivity data help determine the appropriate LNAPL extraction rate that may be sustained by the single pump. These data may be obtained from LNAPL baildown tests, pumping tests, or predictive modeling. Relatively tight formations or sites with low LNAPL conductivity/transmissivity may require the use of low-flow pneumatic pumps, as opposed to higher-flow submersible pumps.
		LNAPL characteristics ($LNAPL_c$)	Low-viscosity LNAPLs are more amenable to pumping than higher-viscosity LNAPLs. Hence, lighter-end, low-viscosity LNAPL such as gasoline, kerosene, jet fuel, diesel and No. 2 fuel oil are more amenable to MPE than a No. 6 fuel oil or Bunker C.
		Soil permeability (to air, e.g., in unsaturated zone) (k_{soil})	Permeability to air in the unsaturated zone directly affects the radius of treatment that can be developed around each SVE well for a given vapor extraction rate. Lower-permeability soils require more SVE wells per unit area.
		Safety precautions	Explosivity of LNAPL—potential need for bonding and grounding of metal equipment/containers and other associated safety requirements.
		Available power/utilities	
	Bench-scale testing	N/A	
	Pilot-scale testing	Groundwater ROI/ROC	Establish groundwater ROI/ROC for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		LNAPL ROI/ROC	Establish LNAPL ROI/ROC for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		Groundwater recovery rate, volume, and influent concentrations	Determine groundwater recovery rate, volume, and influent concentrations to assist with design of water handling, treatment, and discharge options.
		LNAPL recovery rate, volume, and chemical characteristics	Determine LNAPL recovery rate, volume, and chemical characteristics to assist with design of LNAPL storage, handling, treatment, and discharge options.
		LNAPL emulsification issues	Determine level of emulsification occurring, feasibility of LNAPL/water separation, required residence time for LNAPL/water separation.
		Vacuum and flow	Blower sizing
		Vacuum ROI	Well spacing
		Vacuum influent concentration	Treatment system type and sizing
	Full-scale design	Number of extraction wells	Determine number of MPE wells required to achieve adequate zone of LNAPL recovery consistent with LNAPL site objective(s).
		Conveyance piping	Determine locations, lengths, materials for all horizontal conveyance piping to/from MPE wells to/from recovery/treatment system. Assess pipe insulation and heat tracing needs for winter conditions, if applicable.
		Groundwater ROI/ROC	Establish groundwater ROI/ROC for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained for design groundwater drawdown.
		LNAPL ROI/ROC	Establish LNAPL ROI/capture for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		LNAPL emulsification issues	Determine level of emulsification occurring, feasibility of LNAPL/water separation, required residence time for LNAPL/water separation.

Table A-10.C. continued

Data requirements (cont.)	Performance metrics	Groundwater/LNAPL recovery rates and volumes	Basic system performance monitoring
		System uptime vs. downtime	
		Cumulative groundwater/LNAPL recovery	
		LNAPL recovery vs. groundwater recovery	Quantity of LNAPL recovered as a percentage of recovered groundwater
		LNAPL recovery cost metric	Cost per gallon of LNAPL recovered
Modeling tools/ applicable models		Projected future LNAPL recovery	Use of decline curve analysis, semi-log plots, etc. to predict future LNAPL recoveries and help determine when LNAPL recovery is approaching asymptotic.
Further information		FRTR. n.d. “Remedial Technology Screening and Reference Guide, Version 4.0, Dual Phase Extraction.” www.frtr.gov/matrix2/section4/4-37.html	
		EPA. 1996. *How to Effectively Recover Free Product at Leaking Underground Storage Tank Sites: A Guide for State Regulators.* EPA 510-R-96-001. www.epa.gov/oust/pubs/fprg.htm	
		EPA. 1995. *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites A Guide for Corrective Action Plan Reviewers*. “Chapter 11. Dual-Phase Extraction.” EPA 510-R-04-002. www.epa.gov/swerust1/pubs/tum_ch11.pdf	
		API. 1999. *Free-Product Recovery of Petroleum Hydrocarbon Liquids*. API PUBL 4682.	
		USACE. 1999. *Engineering and Design: Multi-Phase Extraction*. EM 1110-1-4010. http://140.194.76.129/publications/eng-manuals/em1110-1-4010/toc.htm	
		EPA. 1999. *Multi-Phase Extraction. State of the Practice*. EPA 542-R-99-004. http://clu-in.org/download/remed/mpe2.pdf	
		EPA. n.d. “Technology Focus: Multi-Phase Extraction Overview.” http://clu-in.org/techfocus/default.focus/sec/Multi%2DPhase%5FExtraction/cat/Overview	

Table A-11.A. Water flooding (including hot-water flooding)

Technology	Water flooding (including hot-water flooding)	Water flooding involves groundwater recirculation in a combined injection/ extraction well configuration, where groundwater flow is directed through the LNAPL zone to increase the hydraulic gradient and enhance LNAPL flow, displacement, and removal. The mobilized LNAPL is recovered via hydraulic recovery. Water flooding causes a faster rate of LNAPL flow toward recovery wells. The important process factor in water flooding is the enhanced hydraulic gradient. The recirculated water can be heated prior to injection to decrease the viscosity and interfacial tension of the LNAPL, thereby further facilitating its recovery. Injection and extraction wells can be installed in lines on either side of the LNAPL zone (line-drive approach) or interspersed in a multispot grid pattern.	
Remediation process	Physical mass recovery	Yes	Water flooding enhances LNAPL extraction by increasing the hydraulic gradient toward extraction wells; heating the injected water can further increase the LNAPL extraction rate.
	Phase change	No	Hot-water flooding may slightly increase the solubility of LNAPL components.
	In situ destruction	No	N/A
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	Enhances LNAPL fluid flow and recovery and can reduce LNAPL to residual saturation. Hot-water injection can reduce the LNAPL saturation more quickly and may reach a lower residual saturation level than DPLE or skimming.
		Example performance metrics	Reduced LNAPL thickness in wells and extent of wells containing LNAPL; reduced LNAPL saturation in soil samples.
	LNAPL composition	No	N/A
		Example performance metrics	N/A
Applicable LNAPL type	Water flooding applies to all LNAPL types. Hot-water flooding is most beneficial for viscous LNAPLs but can accelerate recovery of any LNAPL.		
Geologic factors	Unsaturated zone	Technology is typically not applicable to LNAPL in the unsaturated zone unless saturated conditions can be achieved by first raising the water table.	
	Saturated zone	Permeability	Higher-permeability materials may allow lower residual saturations to be achieved but require higher injection/extraction flow rates to significantly increase the hydraulic gradient. Moderate-permeability materials may facilitate an increase in the hydraulic gradient at a manageable flow rate. Low-permeability materials may exhibit limited enhancement in LNAPL flow using water flooding.
		Grain size	Can achieve lower residual saturation in coarser-grain materials where displacement pressures are lower; see related discussion on permeability, above.
		Heterogeneity	Moderately sensitive to heterogeneity.
		Consolidation	Consolidated media may affect water flooding effectiveness, primarily by heterogeneity that is introduced and the reduction in pore size.

Table A-11.B. Evaluation factors for water flooding (including hot water flooding)

Technology: Water flood		
Remedial time frame	Concern	Moderate
	Discussion	Short to medium. Use of hot water reduces the required time for remediation.
Safety	Concern	Moderate to high
	Discussion	Water-handling equipment to inject, extract, and treat; water-heating equipment, if used, has additional risks.
Waste management	Concern	Moderate
	Discussion	Need to recycle or dispose of LNAPL and potentially treat water source prior to injection.
Community concerns	Concern	Low to moderate
	Discussion	Concerns with noise, potential odors, aesthetics, and volatile emissions. Potentially significant equipment requirements on site.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	Equipment to inject and extract groundwater. Water-heating equipment, if used, increases energy use.
Site restrictions	Concern	Moderate to high
	Discussion	Potentially significant equipment requirements on site.
LNAPL body size	Concern	Moderate
	Discussion	Applicable to any size of LNAPL zone; size can be scaled.
Other regulations	Concern	Moderate
	Discussion	May need a permit to reinject groundwater.
Cost	Concern	High
	Discussion	Continuous injection and circulation of water, high operation and maintenance costs, heating the water prior to reinjection further increase cost over a relatively short time period.
Other	Concern	
	Discussion	

Table A-11.C. Technical implementation considerations for water flooding (including hot-water flooding)

Data requirements	Site-specific data for technology evaluation	Transmissivity of hydrogeologic unit containing LNAPL	Transmissivity data helps determine compatibility of formation for injection, potential injection rates, and sweep efficiency. Injected water flows preferentially through higher-permeability layers. Ideally, a confining unit is present above and below the LNAPL zone to better control the injected water.
		LNAPL fluid characteristics	Includes temperature-sensitive changes if hot-water flooding is applied.
	Bench-scale testing	LNAPL changes with temperature	If hot-water flooding is applied.
	Pilot-scale testing	Groundwater/LNAPL ROC	Aquifer tests to determine the ROC so can target water injection within the ROC to enable control of the injected water to maximize the efficiency of the sweep through the LNAPL body.
		Groundwater recovery rate, volume, and influent concentrations	Determine groundwater recovery rate, volume, and influent concentrations to assist with design of water handling, treatment, and discharge options.
		LNAPL recovery rate and volume	Determine LNAPL recovery rate and volume to assist with design of LNAPL storage, handling, treatment, and discharge options.
		Field test	Hot-water flooding may require closer well spacing due to heat loss to the formation after injection. Also, hot-water buoyancy effects should be considered in the design process.
	Full-scale design	Number of injection/ extraction wells	Determine number of required injection/extraction (e.g., DPLE) wells necessary to achieve adequate zone of LNAPL recovery consistent with LNAPL site objective(s).
		Conveyance piping	Determine locations, lengths, materials for all horizontal conveyance piping to/from extraction (e.g., DPLE) wells to/from recovery/treatment system. Assess pipe insulation and heat tracing needs for winter conditions, if applicable.
		Groundwater ROC	Establish groundwater capture for different groundwater pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
		LNAPL ROC	Establish LNAPL capture for different LNAPL pumping rates. For continuous pumping systems, determine acceptable pumping rate that may be sustained without creating unacceptable drawdown.
	Performance metrics	LNAPL thickness	
		Mass removed	
Further information		Ground-Water Remediation Technologies Analysis Center. 1997. *In Situ Soil Flushing Technology Overview Report*. TO-97-02. http://clu-in.org/download/remed/flush_o.pdf	
		EPA. n.d. "Technology Focus: In Situ Soil Flushing." www.clu-in.net/techfocus/default.focus/sec/In_Situ_Flushing/cat/Overview	
		EPA. 1992. *Chemical Enhancements to Pump and Treat Remediation*. EPA/540/S-92/001. www.epa.gov/tio/tsp/download/chemen.pdf	
		INDOT. 2007. *INDOT Guidance Document for In Situ Soil Flushing*. http://rebar.ecn.purdue.edu/JTRP_Completed_Project_Documents/SPR_2335/FinalReport/SPR_2335_Final/SPR_0628_2.pdf	

Table A-12.A. In situ chemical oxidation

Technology	In situ chemical oxidation	ISCO involves injecting an oxidant to react with and destroy organic compounds. Treatment of LNAPL sites using ISCO may focus on treatment of the dissolved plume, soils, or LNAPL; however, oxidation reactions occur in the dissolved phase. The oxidant must be matched to the site conditions and the project objectives. Effective oxidant delivery and contact with the target treatment media, as well as delivery of an adequately aggressive and stoichiometrically correct oxidant dose, are requisites for effective ISCO application.	
Remediation process	Physical mass recovery	No	N/A
	Phase change	Yes	Mass destruction in the dissolved-phase drives mass transfer from the LNAPL phase.
	In situ destruction	Yes	Under appropriate conditions, ISCO acts to break the hydrocarbon molecular bonds, producing CO_2 and water as by-products.
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	No	N/A
		Example performance metrics	N/A
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change; soil VOC concentrations to below regulatory standard; soil vapor plume concentrations to below regulatory standard.
Applicable LNAPL type	Applicability depends on the chemical oxidation susceptibility of the chemicals in the LNAPL or of the LNAPL constituents in either soil or groundwater.		
Geologic factors	Unsaturated zone	Geologic factors for ISCO application in the unsaturated zone are dominated by oxidant transport and delivery requirements. It is very difficult to deliver aqueous-phase oxidants to the unsaturated zone due to the limitations of unsaturated flow. Ozone, a gaseous oxidant, is amenable to delivery in the unsaturated zone, although its high rate of reaction is a transport limitation which often dictates relatively close injection-well spacing. More homogeneity and higher permeability result in more effective treatment.	
	Saturated zone	Low permeability and heterogeneity are challenging for amendment delivery and reduce efficiency and effectiveness. Delivery of gaseous oxidants to the saturated zone involves gas sparging, which is strongly affected by geologic heterogeneity and grain size and permeability distributions. High natural oxidant demand exerted by the native aquifer matrix, including both reduced minerals and soil organics, reduces ISCO efficiency.	

Table A-12.B. Evaluation factors for in situ chemical oxidation

Technology: In situ chemical oxidation		
Remedial time frame	Concern	Very low to low
	Discussion	Very short to short—typically less than one year. Best used on residual LNAPL. Not unusual for two or three injection applications for dissolved phase only; many more may be needed depending on LNAPL volume and desired end point.
Safety	Concern	High
	Discussion	Oxidants reactions can be very rapid and exothermic. Oxidant handling requires personal protective equipment (PPE). Infrastructure materials (e.g., piping and valves for injection) must be compatible with the oxidant.
Waste management	Concern	Low
	Discussion	All reactions are in situ. Recirculation type delivery requires waste management.
Community concerns	Concern	Low to moderate
	Discussion	Concerns with noise, potential odors, aesthetics, and volatile emissions. Personnel in protective clothing may give public some concern.
Carbon footprint/energy requirements	Concern	Low
	Discussion	Low external energy requirements. Recirculation type delivery requires more energy.
Site restrictions	Concern	Moderate
	Discussion	Injected down well bores, so generally not hampered by site restrictions, but may have to restrict public access during application of the oxidants.
LNAPL body size	Concern	Moderate to high
	Discussion	Higher success rate on small areas with minor LNAPL in-well thickness of a few inches or less. Free-product remediation is safe and accessible to solid peroxygens.
Other regulations	Concern	Moderate
	Discussion	May need an injection permit. Fracturing of the formation is a potential concern, which could impede UIC authorization for injection.
Cost	Concern	Moderate to high
	Discussion	May be cost-effective where LNAPL body is small or impact localized.
Other	Concern	
	Discussion	

Table A-12.C. Technical implementation considerations for in situ chemical oxidation

Data requirements	Site-specific data for technology evaluation	Site size and soil characteristics	Soil permeability, plasticity (classification), bulk density, total organic carbon and other natural oxidant sinks, site boundary.
		Groundwater characteristics	Hydraulic, gradient, geochemistry (buffering capacity).
		LNAPL characteristics (LNAPL_c)	LNAPL volume, chemical properties, concentrations, co-contaminants. LNAPL type affects oxidant selection.
		LNAPL depth	Affects delivery method(s).
		LNAPL location	Open area or under building, near utilities, source area identified and removed?
		Permit consideration	Permit may be needed for oxidant injection.
	Bench-scale testing	Soil characteristics	Permeability, natural oxidant demand, classification, bulk density, acid demand.
		Destruction efficiency	Determine efficiency of oxidant selected for destruction of contaminant(s) at site, by-products, oxidant dose.
		Delivery mechanism	Use of soil properties to determine best delivery/oxidant.
	Pilot-scale testing	Injection pressure	If injecting under pressure.
		Placement/number of monitoring wells	Highly recommended ROI be determined.
		Groundwater characteristics	Reducing conditions, oxidation reduction potential (ORP), pH, alkalinity, chloride, etc.
		Number of injection points	Delivery volume, oxidant destruction rate.
		Site conditions	Ability of site to accept oxidant, ROI, heterogeneities. Aquifer metals reactions (mobilization) to high-oxidized conditions.
	Full-scale design	Injection pressure	If injecting under pressure requires care.
		Placement/number of monitoring wells	
		Groundwater characteristics	Reducing conditions, ORP, pH, alkalinity, chloride, dissolved oxygen, etc.
		Number of injection points	Delivery volume, oxidant destruction rate
		Site conditions	Ability of site to accept oxidant, ROI, heterogeneities
	Performance metrics	Post monitoring	Reducing conditions, ORP, pH, alkalinity, chloride, injected oxidant, contaminant, daughter products, and groundwater elevations.
		Delivered amount	
		Daylighting observed	
		Oxidant distribution	
		Contaminant reduction	Long-term monitoring
		Contingency plan	Rebound effects
Modeling tools/ applicable models		Models being developed for predictive capabilities, stoichiometries, etc.	
Further information		EPA. 2006. *Engineering Issue: Chemical Oxidation*. EPA/600/R-06/072. www.epa.gov/ahaazvuc/download/issue/600R06072.pdf	
		Brown, R. A. 2003. "In Situ Chemical Oxidation: Performance, Practice, and Pitfalls." AFCEE Technology Transfer Workshop, Feb. 24–27, San Antonio. www.afcee.af.mil/shared/media/document/AFD-071031-150.pdf	
		Carus Chemical Company. 2004. "Material Safety Data Sheet for CAIROX® Potassium Permanganate." www.caruschem.com/pdf/new_files/CAIROX_MSDS.pdf	
		FMC. 2005. "Bulletin 1. General Efficacy Chart." FMC Environmental Resource Center, Environmental Solutions. http://envsolutions.fmc.com/Portals/fao/Content/Docs/klozurTechBulletin1%20-%20Activation%20chemistries%20Selection%20Guide%20(updated%201-08).pdf	
		FMC. 2006. "Persulfates Technical Information." www.fmcchemicals.com/LinkClick.aspx?fileticket=y%2f0DZcxPM4w%3d&tabid=1468&mid=2563	
		ITRC. 2005. *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater*, 2nd ed. ISCO-2. www.itrcweb.org/Documents/ISCO-2.pdf	
		EPA. 1994. *How To Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers.* EPA 510-B-94-003. www.epa.gov/oust/pubs/tums.htm	
		Ground-Water Remediation Technologies Analysis Center. 1999. *In Situ Chemical Treatment Technology Evaluation Report.* TE-99-01. http://clu-in.org/download/toolkit/inchem.pdf	

Table A-12.C. continued

Further information (continued)	ITRC. 2001. *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater*. ISCO-1. www.itrcweb.org/Documents/ISCO-1.pdf
	ESTP. 2006. *In Situ Chemical Oxidation for Groundwater Remediation—Technology Practices Manual*. ESTCP ER-06. www.serdp-estcp.org/ISCO.cfm

Table A-13.A. Surfactant-enhanced subsurface remediation

Technology	Surfactant-enhanced subsurface remediation	Injection wells deliver surfactant solution to LNAPL zone while extraction wells capture mobilized/solubilized LNAPL.	
Remediation process	Physical mass recovery	Yes	Surfactant enhances LNAPL mobility and recovery by significantly reducing LNAPL/water interfacial tension.
	Phase change	No	LNAPL is solubilized above its typical aqueous solubility.
	In situ destruction	No	Surfactants are cometabolites and may enhance aerobic and anaerobic microbial hydrocarbon digestion.
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	SESR reduces LNAPL saturation and even mobilizes otherwise residual LNAPL from pores. Properly designed surfactant systems enhance removal efficiency of residual LNAPL potentially by several orders of magnitude compared to extraction remediation approach alone, which rely on standard dissolution to remove residual LNAPL.
		Example performance metrics	Reduced LNAPL transmissivity; reduction or elimination of measurable LNAPL in wells.
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change; soil VOC concentrations to below regulatory standard; soil vapor plume concentrations to below regulatory standard.
Applicable LNAPL type	All LNAPL types, though mobility enhancement for those with higher oil-water interfacial tension are less efficient.		
Geologic factors	Unsaturated zone	When unsaturated zone LNAPL is near water table, water table can be raised (via mounding effect) to flood the zone with surfactant. When unsaturated zone LNAPL is far above water table, infiltration techniques may be used to flush the zone with surfactant but are not as effective as saturated zone treatment. More homogeneity and moderate permeability result in more effective treatment through even distribution of surfactant. See saturated zone geologic factors.	
	Saturated zone	Permeability	Surfactant delivery and LNAPL recovery are more rapid and more effective in higher-permeability soil.
		Grain size	LNAPL recovery is more rapid and effective in larger-grained soils (sands) than in smaller-grained soils (e.g., silt and clay).
		Heterogeneity	High levels of heterogeneity can reduce surfactant solution delivery efficiency, which increase the required number of pore volumes.
		Consolidation	High consolidation may reduce pore sizes, permeability, and injection feasibility; unconsolidated/loosely consolidated may allow larger spacing within well network (i.e., tend to be more favorable for recovery).

Table A-13.B. Evaluation factors for surfactant-enhanced subsurface remediation

Technology: Surfactant-enhanced subsurface remediation		
Remedial time frame	Concern	Very low to low
	Discussion	Very short to short. Bench-testing can be used to determine the number of pore volumes needed to remove the LNAPL. Typically, with finer-grained material, additional pore volumes are needed. Generally faster than DPLE and AS/SVE.
Safety	Concern	Low to moderate
	Discussion	Surfactants are not dangerous, but there may be safety issues due to the equipment used to inject the surfactant and treat the extracted mixture. LNAPL may be extracted and handled.
Waste management	Concern	Moderate
	Discussion	The recovered surfactant and LNAPL need to be disposed of as nonhazardous waste. Depending on what is recovered, may be able to dispose into sanitary sewer or transport to a disposal facility. Surfactants cause the aqueous waste stream to contain very high dissolved concentrations of LNAPL constituents and can pose challenges for aqueous-phase treatment systems.
Community concerns	Concern	Low to moderate
	Discussion	Concern with use of chemical treatment, volatile emissions, odors, noise. Trucks and equipment may be on site for some time.
Carbon footprint/ energy requirement	Concern	Low to moderate
	Discussion	Depends on whether the surfactant is gravity fed or injected. Mixing as well as extraction and treatment of waste require energy source.
Site restrictions	Concern	Moderate
	Discussion	No major construction activity or subsurface disruption but may need to restrict application area access while injecting and recovering fluids. Field team on site during application of technology.
LNAPL body size	Concern	Moderate to high
	Discussion	The success rate is higher for very small areas. As the treatment area increases in size, the chance for success decreases. May consider the technology as a follow-up to a traditional technology such as DPLE or MPE to remediate areas missed.
Other regulations	Concern	Moderate
	Discussion	May need a permit to inject and discharge permit.
Cost	Concern	Moderate to high
	Discussion	
Other	Concern	
	Discussion	

Table A-13.C. Technical implementation considerations for surfactant-enhanced subsurface remediation

Data requirements	Site-specific data for technology evaluation	Groundwater hydraulic conductivity	
		LNAPL characteristics	
		Contaminants of concern	
		Groundwater quality/geochemistry	
	Bench-scale testing	Soil cores for column tests	
		Contaminants of concern	
		LNAPL characteristics	
		Surfactant selection	
	Pilot-scale testing	Contaminants of concern	
		LNAPL characteristics	
		Delivery of surfactant solutions(wells)	
		Treatment of extracted mixture	
	Full-scale design	Groundwater hydraulic conductivity	
		Sweep volume	
		Soil type(s)/lithology	
		Homogeneity	
		Treatment system	
	Performance metrics	LNAPL thickness	
		Mass recovered	
		Achieve remedial objective	
Modeling tools/applicable models		UTCHEM	
Further information		EPA. 1995. *Surfactant Injection for Ground Water Remediation: State Regulators' Perspectives and Experiences*. EPA 542-R-95-011. www.epa.gov/tio/download/remed/surfact.pdf	
		Ground-Water Remediation Technologies Analysis Center. 1997*. In Situ Flushing Technology Overview Report*. TO-97-02. http://clu-in.org/download/remed/flush_o.pdf	
		NAVFAC. 2006. *Surfactant-Enhanced Aquifer Remediation (SEAR) Design Manual*. TR-2206-ENV. http://74.125.93.132/search?q=cache:CcfUkrCwimAJ:www.clu-in.org/download/contaminantfocus/dnapl/Treatment_Technologies/SEAR_Design.pdf+Surfactant-Enhanced+Aquifer+Remediation+(SEAR)+Design+Manual&cd=1&hl=en&ct=clnk&gl=us	
		NAVFAC. 2003. *Surfactant-Enhanced Aquifer Remediation (SEAR) Implementation Manual*. NFESC TR-2219-ENV. www.clu-in.org/download/techdrct/td-tr-2219-sear.pdf	
		AFCEE. n.d. "Cosolvent or Surfactant-Enhanced Remediation." www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sourcezonetreatment/background/cosolvent-surfac/index.asp	
		EPA. 1991. *In Situ Soil Flushing*. EPA 540-2-91-021.	

Table A-14.A. Cosolvent flushing

Technology	Cosolvent flushing	Cosolvent flushing involves the injection and subsequent extraction of a cosolvent (e.g., an alcohol) to solubilize and/or mobilize LNAPL.	
Remediation process	Physical mass recovery	Yes	Cosolvents enhance LNAPL mobility and removal by reducing the LNAPL/water interfacial tension.
	Phase change	No	Cosolvents allow LNAPL to be solubilized above its typical aqueous solubility limit, thereby enhancing removal.
	In situ destruction	No	N/A
	Stabilization/binding	No	N/A
Objective applicability	LNAPL saturation	Yes	LNAPL saturation decreases due to direct recovery and enhanced solubilization.
		Example performance metrics	Reduced LNAPL transmissivity, reduction, or elimination of measurable LNAPL in wells.
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change; soil VOC concentrations to below regulatory standard; soil vapor plume concentrations to below regulatory standard.
Applicable LNAPL type	Assuming the primary mechanism is solubilization, cosolvents are most effective with lighter-molecular-weight LNAPLs (ITRC 2003) and become less effective as the molecular weight of the LNAPL increases.		
Geologic factors	Unsaturated zone	When unsaturated zone LNAPL is near the water table, the water table can be raised (via mounding effect) to flood the zone with cosolvent. When unsaturated zone LNAPL is far above water table, infiltration techniques may be used to flush the zone with cosolvent but are not as effective as saturated zone treatment. More homogeneity and moderate permeability results in more effective treatment through even distribution of cosolvent. See saturated zone geologic factors.	
	Saturated zone	Permeability	The overall cosolvent delivery and LNAPL recovery are more rapid in higher-permeability soils, but cosolvent can be delivered to lower-permeability soils; however, the time to complete the flushing process is longer with lower permeability.
		Grain size	The overall LNAPL mass recovery is effective in coarser-grain soils (sands) and finer-grain soils (e.g. silt and clay); however, the time to complete the flushing process is longer in the finer-grain soils.
		Heterogeneity	In highly heterogeneous soils, separate flow network may be required (e.g., one to treat the more permeable zone and another to treat the less permeable zone) if LNAPL is distributed in both zones. In some cases, short-circuiting of flushing is unavoidable. Higher heterogeneity can also reduce cosolvent delivery efficiency, which increases the required number of pore volumes.
		Consolidation	High consolidation may reduce pore sizes, permeability, and injection feasibility. Unconsolidated/loosely consolidated soil may allow larger grids on flow network (i.e., tend to be more favorable for recovery).

Table A-14.B. Evaluation factors for cosolvent flushing

Technology: Cosolvent flushing		
Remedial time frame	Concern	Very low to low
	Discussion	Very short to short. Cosolvent flushing is ideal to address the removal of residual LNAPLs that have become trapped in the pore spaces of a water-bearing unit. Need to be able to sweep the LNAPL by infiltrating or injecting the cosolvent and extracting simultaneously downgradient to maintain hydraulic control.
Safety	Concern	Moderate
	Discussion	A number of chemicals on site along with mechanical equipment; flammability awareness on some alcohols.
Waste management	Concern	Moderate
	Discussion	Wastewater, cosolvent, and LNAPL need to be properly disposed.
Community concerns	Concern	Moderate
	Discussion	There is a series of injection and extraction wells, mixing tanks, fluid separation, and wastewater-handling equipment. Personnel in PPE. Concern with use of chemical treatment, volatile emissions, odors, noise.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	Depends on whether the cosolvent is gravity fed or injected. Extraction and treatment of waste require energy source.
Site restrictions	Concern	Moderate to high
	Discussion	No significant construction activity or subsurface disruption but may need to limit access to application area while injecting and recovering fluids (possibly more safeguards than for SESR). Field team on site during application of technology.
LNAPL body size	Concern	Moderate
	Discussion	The success rate is higher for very small areas. As the treatment area increases in size, the chance for success decreases. May consider the technology as a follow-up to a traditional technology such as DPLE or MPE to remediate areas missed.
Other regulations	Concern	Moderate to high
	Discussion	May need variance or permits for discharge of wastewater and injection permit.
Cost	Concern	High
	Discussion	The ability to remove COCs from recovered fluid for recycling and injecting back into the subsurface is a major factor in controlling the cost of cosolvent flushing.
Other	Concern	
	Discussion	

Table A-14.C. Technical implementation considerations for cosolvent flushing

Data requirements	Site-specific data for technology evaluation	Groundwater hydraulic conductivity	
		LNAPL characteristics	
		Bench-scale testing	
	Bench-scale testing	Soil cores for column testing	
		Contaminants of concern	
		LNAPL characteristics	
		Cosolvent selection	
	Pilot-scale testing	Field test	
		Cosolvent delivery and recovery	
		Waste treatment/recycle of solvent solution	
	Full-scale design	Groundwater hydraulic conductivity	
		Sweep volume	
	Performance metrics	Groundwater concentration	
		LNAPL thickness	
		Mass recovered	
Modeling tools/applicable models		UTCHEM	
Further information		ITRC. 2003. *Technical and Regulatory Guidance for Surfactant/Cosolvent Flushing of DNAPL Source Zones*. DNAPL-3. www.itrcweb.org/Documents/DNAPLs-3.pdf	
		Ground-Water Remediation Technologies Analysis Center. 1997*. In Situ Flushing Technology Overview Report*. TO-97-02. http://clu-in.org/download/remed/flush_o.pdf	
		AFCEE. n.d. "Cosolvent or Surfactant-Enhanced Remediation." www.afcee.af.mil/resources/technologytransfer/programsandinitiatives/sourcezonetreatment/background/cosolvent-surfac/index.asp	

Table A-15.A. Steam/hot-air injection

Technology	Steam/hot-air injection	Steam and/or hot air is injected into wells to heat the formation and LNAPL. Steam injection induces a pressure gradient that pushes ahead of it, in sequence, a cold water (ambient temperature) front, a hot water front, and a steam front through the LNAPL zone. In the unsaturated zone, a steam and condensation front develops. The mobilized LNAPL is recovered from extraction wells, and volatilized LNAPL is collected via vapor extraction wells.	
Remediation process	Physical mass recovery	Yes	1. Cold water front flushes some of the remaining mobile LNAPL from pores. 2. Hot water and steam fronts or hot air reduce viscosity of LNAPL increasing mobility and recoverability.
	Phase change	Yes	The steam/hot air front volatilizes the LNAPL.
	In situ destruction	Yes	Steam/hot air front potentially causes the LNAPL to undergo thermal destruction or hydrous pyrolysis.
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	Enhances LNAPL fluid flow by reducing interfacial tension and LNAPL viscosity, potentially reducing LNAPL saturations to below residual saturation achieved by standard hydraulic methods. Mass loss also occurs by volatilization and in situ destruction.
		Example performance metrics	Reduced LNAPL transmissivity; reduction or elimination of measurable LNAPL in wells.
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change; soil VOC concentrations to below regulatory standard; soil vapor plume concentrations to below regulatory standard
Applicable LNAPL type	All LNAPL types, though higher-viscosity and/or lower-volatility LNAPL takes longer to treat and/or achieves less remedial effectiveness.		
Geologic factors	Unsaturated zone	Permeability	Steam injection is effective only in relatively permeable materials, where there is less resistance to flow; also, more effective in stratified LNAPL settings, where a low-permeability layer can help to control steam distribution.
		Grain size	Steam injection can achieve more effective saturation reduction in coarser-grain materials.
		Heterogeneity	Steam injection is more efficient in permeable pathways, but LNAPL is also distributed mainly in these pathways.
		Consolidation	High consolidation may reduce pore sizes, permeability, and injection feasibility.
	Saturated zone	Permeability	Steam injection is effective only in relatively permeable materials where there is less resistance to flow; also, more effective in confined LNAPL settings where a low-permeability layer can help to control steam distribution.
		Grain size	Steam injection can achieve more effective saturation reduction in coarser-grain materials.
		Heterogeneity	Steam injection is more efficient in permeable pathways, but LNAPL is also distributed mainly in these pathways.
		Consolidation	High consolidation may reduce pore sizes, permeability, and injection feasibility.

Table A-15.B. Evaluation factors for steam/hot-air injection

Technology: Steam/hot-air injection		
Remedial time frame	Concern	Very low
	Discussion	Very short. A steam front is developed and mobilizes the LNAPL to extraction wells or volatilizes the LNAPL, which is then collected by vapor extraction.
Safety	Concern	High
	Discussion	Steam under pressure and hot water and LNAPL extracted. Possible steam eruption from wells.
Waste management	Concern	Moderate
	Discussion	Collect LNAPL and groundwater with high dissolved concentrations from recovery wells and treat the off-gas.
Community concerns	Concern	Low to moderate
	Discussion	Process equipment, high temperature warnings, and personnel in PPE may be cause for concern. Also, noise, odor, and potential public exposure if steam is not effectively captured and treated.
Carbon footprint/energy requirement	Concern	Moderate
	Discussion	Equipment needed to generate steam requires large supply of energy. VOC emissions, but for a short duration. Extraction and treatment of waste. Footprint lessened by short duration.
Site restrictions	Concern	High
	Discussion	Large amount of equipment, piping, and control of vapor emissions. Field team on site during technology application. Application area restrictions during technology application.
LNAPL body size	Concern	Moderate
	Discussion	The heterogeneity and permeability of the soils greatly determine whether the steam front is successful and may limit the size that can be remediated.
Other regulations	Concern	Moderate
	Discussion	May need an injection permit. For treated groundwater may need a permit to discharge and VOC emissions.
Cost	Concern	Moderate to high
	Discussion	High costs to generate and maintain steam and high operation and maintenance costs. Short duration can make present value cost-competitive.
Other	Concern	
	Discussion	

Table A-15.C. Technical implementation considerations for steam/hot-air injection

Data requirements	Site-specific data for technology evaluation	Site size and soil characteristics	Permeability—venting of vapors to atmosphere (technology works in conjunction with AS/SVE).
		Groundwater characteristics	Hydraulic gradient, geochemistry (buffering capacity—scaling/fouling).
		LNAPL characteristics ($LNAPL_c$)	Chemical properties (composition vapor pressure, boiling point, octanol-water partitioning coefficient, viscosity, etc.).
		LNAPL depth	Lateral extent and vertical depth needed to estimate total soil volume to be heated, steam-generation needs, etc.
		LNAPL location	Open area or under building, near utilities, any other obstructions to injection well placement need special consideration.
		Off-gas treatment	Concentrations and types of contaminants affect loading and off-gas technology selection.
	Bench-scale testing	Similar to AS/SVE	See Table A-5.C.
		Soil characteristics	Permeability, moisture, classification.
		LNAPL characteristics	LNAPL viscosity reduction as a function of temperature.
		Groundwater geochemistry	pH, buffering capacity, O2, etc.
	Pilot-scale testing	Similar to AS/SVE	See Table A-5.C.
		Injection locations	Determine placement of injection and extraction wells.
		Injection rates	Determine required injection pressure rate to ensure overall coverage and minimize short-circuiting to the surface.
		Injection pressures	Increased injection pressure requirements limit mass flux to vapor phase and could result in soil instability.
		Off-gas treatment	Selection of off-gas treatment depends on concentration, contaminants, regulations, etc.
		LNAPL mass recovery	Volume recovered and rate.
		Piping concerns	High temperatures and pressures.
		Boiler capacity	Steam-generation issues.
	Full-scale design	Similar to AS/SVE	See Table A-5.C.
		Injection rates	Determine feasible injection rates on site to ensure overall coverage and minimize short circuiting to the surface.
		Injection pressures	Increased injection pressure requirements limits mass flux to vapor phase and could result in soil instability.
		Off-gas treatment	Selection of off-gas treatment depend on concentration, contaminants, regulations, etc.
		Piping concerns	High temperatures and pressures.
		Steam quality	Higher quality, better transfer of heat into treatment area (quality is measure of liquid in vapor; 100% = 0 liquid), condensation considerations.
		Boiler size, maintenance	Ability to generate and keep generation continuing for duration of injection.
	Performance metrics	Similar to AS/SVE	See Table A-5.C.
		Effluent measurements	
Modeling tools/applicable models			
Further information		EPA. 1998. *Steam Injection for Soil and Aquifer Remediation*. EPA/540/S-97/505. www.epa.gov/tio/tsp/download/steaminj.pdf	
		FRTR. n.d. “Remedial Technology Screening and Reference Guide, Version 4.0, In Situ Thermal Treatment.” www.frtr.gov/matrix2/section4/4-9.html	
		EPA. n.d. “Technology Focus: In Situ Thermal Heating.” www.clu-in.org/techfocus/default.focus/sec/Thermal_Treatment:_In_Situ/cat/Overview	
		EPA. 1995. *In Situ Remediation Technology Status Report: Thermal Enhancements*. EPA/542-K-94-009. www.clu-in.org/download/remed/thermal.pdf	
		USACE. 2009. *Engineering and Design: In Situ Thermal Remediation*. EM-1110-1-4015. http://140.194.76.129/publications/eng-manuals/em1110-1-4015/entire.pdf	

Table A-16.A. Radio-frequency heating

Technology	Radio-frequency heating	RFH energy is introduced into the subsurface via heating antennae. The subsurface is maintained at temperatures low enough to mainly influence the viscosity of the LNAPL, but temperature can be raised to increase volatilization or to result in hydrous pyrolysis. The mobilized LNAPL is recovered hydraulically.	
Remediation process	Physical mass recovery	Yes	Increased subsurface temperatures reduce LNAPL viscosity and increase mobility and recoverability.
	Phase change	Yes	Higher-temperature applications can volatilize LNAPL, which can then be recovered via SVE.
	In situ destruction	Yes	At high temperatures, LNAPL may undergo thermal destruction or hydrous pyrolysis.
	Stabilization/binding	No	N/A
Objective applicability	LNAPL saturation	Yes	Enhances LNAPL recovery, which reduces LNAPL saturations; mass loss by volatilization and in situ destruction may also reduce LNAPL saturation.
		Example performance metrics	Reduced LNAPL transmissivity; reduction or elimination of measurable LNAPL in wells.
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change; soil VOC concentrations to below regulatory standard; soil vapor plume concentrations to below regulatory standard.
Applicable LNAPL type	All LNAPL types, though higher-viscosity and/or-lower volatility LNAPL take longer to treat and/or achieve less remedial effectiveness.		
Geologic factors	Unsaturated zone	Permeability	Most effective in locations with high permeability.
		Grain size	Can achieve more effective saturation reduction in coarser-grain materials.
		Heterogeneity	Heat flow can occur through heterogeneous areas, but LNAPL flow is most enhanced in permeable pathways.
		Consolidation	Not typically a factor.
	Saturated zone	Permeability	Most effective in locations with sand lenses that provide a layer through which fluid flow can occur.
		Grain size	Most effective in locations with sand lenses that provide a layer through which fluid flow can occur.
		Heterogeneity	Heat flow can occur through heterogeneous areas, but LNAPL flow is most enhanced in homogenous settings.
		Consolidation	Not typically a factor.

Table A-16.B. Evaluation factors for radio-frequency heating

Technology: Radio-frequency heating		
Remedial time frame	Concern	Very low
	Discussion	Very short. Temperature is increased for LNAPL removal by extraction wells.
Safety	Concern	Moderate
	Discussion	In moderate-temperature applications, electrical equipment on site and LNAPL recovery containers. In high-temperature applications, potential steam eruptions from wells.
Waste management	Concern	Moderate
	Discussion	Recovered LNAPL and water need to be properly disposed. May need to treat vapors recovered.
Community concerns	Concern	Moderate
	Discussion	Concern with technology that is unfamiliar to general public. The name “radio-frequency heating” may alarm some people. Will need to educate the community on the process and safety.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	AC current used in the radio-frequency generator. Trying to keep volatilization to a minimum.
Site restrictions	Concern	High
	Discussion	Damage to utilities. Could be hampered by need to prohibit site access during application. Access restrictions to application area may be needed.
LNAPL body size	Concern	High
	Discussion	Not known whether it will work on large sites.
Other regulations	Concern	Low
	Discussion	
Cost	Concern	High
	Discussion	Potentially high operation and maintenance costs to keep the system going because it is not a fully proven technology.
Other	Concern	
	Discussion	Radio frequency is not as thoroughly tested and proven as other thermal methods.

Table A-16.C. Technical implementation considerations for radio-frequency heating

Data requirements	Site-specific data for technology evaluation	Site size and soil characteristics	Soil-permeability (venting of vapors to atmosphere—technology works in conjunction with AS/SVE, MPE), plasticity (classification), bulk density, heat capacity.
		Groundwater characteristics	Gradient, aquifer permeability, geochemistry (buffering capacity), depth to water table.
		LNAPL characteristics ($LNAPL_c$)	Chemical properties (vapor pressure, boiling point, solubility, octanol-water partitioning coefficient, viscosity, etc.), concentrations of LNAPL constituents.
		LNAPL depth	Shallow contaminants may require use of surface cover/cap.
		LNAPL location	Accessibility and depth.
		Off-gas treatment	Concentrations of target and nontarget contaminants that may affect loading and off-gas technology selection.
	Bench-scale testing	Similar to AS/SVE	See Table A-5.C.
		Soil characteristics	Permeability, moisture, classification, bulk density, humic portion, heat capacity.
		GW geochemistry/ location	pH, buffering capacity, O_2, etc. Location of the water table.
	Pilot-scale testing	Similar to AS/SVE	See Table A-5.C.
		placement of heating probes	Optimize heating at specific levels and areas of largest contamination.
		Define possible groundwater recharge issues	Minimizing water recharge into thermal zone important. Use of hydraulic barriers, if needed.
		Off-gas treatment	Selection of off-gas treatment dependent upon concentration, contaminants, regulations, etc.
		Power consumption vs. active bed temperature	Basis to justify destruction/removal per unit energy used.
	Full-scale design	Similar to AS/SVE	See Table A-5.C.
		Placement of heating probes	Optimize heating at specific levels and areas of greatest LNAPL core area.
		Define possible groundwater recharge issues	Minimizing water recharge into thermal zone important. Use of hydraulic barriers, if needed.
		Off-gas treatment	Selection of off-gas treatment depends on concentration, contaminants, regulations, etc.
		End-point concentration	Negotiated concentration level.
	Performance metrics	Similar to AS/SVE	See Table A-5.C.
		Power consumption vs. active bed temperature	Active bed temperature is the temperature of the stratigraphic unit(s) targeted by the RFH. Compare to pilot study assessment.
Modeling tools/applicable models			
Further information		U.S. Department of Energy. 1994. *Final Report: In Situ Radio Frequency Heating Demonstration (U)*. www.osti.gov/bridge/servlets/purl/10133397-hP84ua/native/10133397.pdf	
		FRTR. n.d. "Remedial Technology Screening and Reference Guide, Version 4.0, In Situ Thermal Treatment." www.frtr.gov/matrix2/section4/4-9.html	
		EPA. n.d. "Technology Focus: In Situ Thermal Heating." www.clu-in.org/techfocus/default.focus/sec/Thermal_Treatment:_In_Situ/cat/Overview	
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Table A-17.A. Three- and six-phase electric resistance heating

Technology	Three- and six-phase electric resistance heating	Electric resistance heating is a polyphase electrical technique used to resistively heat soil and mobilize and volatilize LNAPL. Electrodes are typically installed using standard drilling techniques to carry the electrical power to the subsurface. Electrical current flows from each electrode to the other electrodes out of phase with it. The soil matrix is heated due to the resistance to electric flow. The mobilized LNAPL is recovered from extraction wells, and volatilized LNAPL is collected via vapor extraction wells.	
Remediation process	Physical mass recovery	Yes	Heating reduces viscosity of LNAPL and increases mobility and recoverability.
	Phase change	Yes	The heating volatilizes the LNAPL.
	In situ destruction	Yes	LNAPL may undergo thermal degradation or hydrous pyrolysis.
	Stabilization/ binding	No	N/A
Objective applicability	LNAPL saturation	Yes	Enhances LNAPL fluid flow, reducing LNAPL saturations to residual saturation; mass loss also by volatilization and in situ destruction.
		Example performance metrics	Reduced LNAPL transmissivity; reduction or elimination of measurable LNAPL in wells.
	LNAPL composition	Yes	Abate accumulation of unacceptable constituent concentrations in soil vapor and/or dissolved phase from an LNAPL source.
		Example performance metrics	LNAPL composition change; soil VOC concentrations to below regulatory standard; soil vapor plume concentrations to below regulatory standard.
Applicable LNAPL type	All LNAPL types, though higher-viscosity and/or lower-volatility LNAPL will take longer to treat and/or achieve less remedial effectiveness.		
Geologic factors	Unsaturated zone	Permeability	Can be effective even in lower-permeability materials where heat loss to groundwater flux is low but electrical conductivity is high.
		Grain size	Fine-grained soils (silts and clays) are typically more electrically conductive than coarse-grained soils and can be more efficiently heated.
		Heterogeneity	Can be employed at sites with widely varying heterogeneity. Moisture content of the individual layers is the key determining factor for soil heating efficiency. LNAPL mobilization along preferential pathways is most likely.
		Consolidation	Not typically a factor.
	Saturated zone	Permeability	Most effective in lower-permeability materials, where fluid flow is reduced.
		Grain size	Fine-grained soils (silts and clays) are typically more electrically conductive than coarse-grained soils and can be more efficiently heated.
		Heterogeneity	Can be employed at sites with widely varying heterogeneity. Increased moisture content of the individual coarse layers and the electrical conductivity of fine-grained soils layers result in heating and increasing mobility over a wide range of soil conditions.
		Consolidation	Not typically a factor.

Table A-17.B. Evaluation factors for three- and six-phase heating

Technology: Three- and six-phase heating		
Remedial time frame	Concern	Very low
	Discussion	Very short. The soil matrix is heated to mobilize the LNAPL from the pores and collected by extraction wells and the volatilized LNAPL are removed by vapor extraction wells.
Safety	Concern	High
	Discussion	Electric equipment and cables on the ground. Possible steam eruption from wells.
Waste management	Concern	Moderate
	Discussion	Collect LNAPL from recovery wells and treat the vapors.
Community concerns	Concern	Low to moderate
	Discussion	Concern with technology that is unfamiliar to general public. Electrical and process equipment, high-voltage and high-temperature warnings, piping, and electrical cables are likely to cause concern. Potential concerns over odors and volatile emissions.
Carbon footprint/energy requirements	Concern	Moderate
	Discussion	Electric generation and vapor treatment offset by short duration of remediation.
Site restrictions	Concern	High
	Discussion	Electric cables on the ground; subsurface utility concerns, and need to restrict access during application.
LNAPL body size	Concern	Moderate
	Discussion	Capable of remediating large LNAPL plumes. Lithology and permeability determine the spacing between electrodes and placement of recovery wells and vapor extraction wells.
Other regulations	Concern	Moderate
	Discussion	Permit to inject water, vapor emissions.
Cost	Concern	Moderate to high
	Discussion	High electric costs and high operation and maintenance costs. Short duration can make present value cost-competitive.
Other	Concern	Low
	Discussion	Need to keep electrodes moist to maintain current. Some water injection is required.

Table A-17.C. Technical implementation considerations for three- and six-phase electrical resistance heating

Data requirements	Site-specific data for technology evaluation	Site size and soil characteristics	Soil resistivity, buried debris, and subsurface utilities. Soil permeability (venting of vapors to atmosphere—technology works in conjunction with AS/SVE, MPE), soil conductivity, plasticity (classification), bulk density, heat capacity, total organic carbon, site boundary—problems of scale.
		Groundwater characteristics	Conductivity, gradient, aquifer permeability, geochemistry (buffering capacity).
		LNAPL characteristics ($LNAPL_c$)	Chemical properties (vapor pressure, boiling point, octanol-water partitioning coefficient, viscosity, etc.), concentrations.
		LNAPL depth	Shallow contaminants may need to implement surface cover/cap.
		LNAPL location	Open area or under building, near utilities.
		Off-gas treatment	Concentrations of nontarget contaminants that may affect loading and vapor technology selection.
	Bench-scale testing	Similar to AS/SVE	See Table A-5.C.
		Soil characteristics	Permeability, moisture, classification.
		Heating effectiveness/ mass recovery	Relationship between heating time and mass recovery.
		Groundwater geochemistry	pH, buffering capacity, O_2, etc.
	Pilot-scale testing	Similar to AS/SVE	See Table A-5.C.
		Define boundary of treatment zone	Six/three-phase heating generally imparts uniform heating to the treatment zone.
		Steam generation	Determine amount of in situ steam generated by subsurface heating.
		Off-gas treatment	Selection of vapor treatment depends on concentration, contaminants, regulations, etc.
		Heating rate	Time needed to reach optimal/maximum temperature in treatment zone.
		Water injection	Possibility of water addition into the treatment zone to maintain conductivity of soil.
		Safety concerns	High voltage, electrical connections, buried metal objects, vapor/ lower explosive limit, others similar to AS/SVE, community concerns.
	Full-scale design	Similar to AS/SVE	See Table A-5.C.
		Power application/ consumption	
		Steam generation	Record amount of in situ steam generated by subsurface heating.
		Off-gas treatment	Selection of off-gas treatment dependent upon concentration, contaminants, regulations, etc.
		Heating rate	Time needed to reach optimal/maximum temperature in treatment zone.
		Water injection	Possibility of water addition into the treatment zone to maintain conductivity of soil.
		Safety concerns	High voltage, electrical connections, buried metal objects, vapor/ lower explosive limit, others similar to AS/SVE, community concerns.
	Performance metrics	Similar to AS/SVE	See Table A-5.C.
		Temperature in treatment zone	How quickly maximum/optimum temperature was reached and held constant.
		Temperature outside of treatment zone	Determine extent of heating at edge of treatment zone.
		Steam generation	Record amount of in situ steam generated by subsurface heating; measure of effective drying and volatilization occurring in treatment zone.
		Water addition	Record amount of water needed to be applied in the treatment zone.
		Mass removal rates	
		Off-gas concentrations	

Table A-17.C. continued

Modeling tools/applicable models	
Further information	Thermal Remediation Services, Inc. n.d. "LNAPL Remediation Using Electrical Resistance Heating." www.thermalrs.com/technology/whitePapers/ERH%20NAPL%20OH%20113009%20acf.pdf
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Appendix B

California State Water Resources Control Board Resolution No. 92-49

CALIFORNIA STATE WATER RESOURCES CONTROL BOARD
RESOLUTION NO. 92-49

In California, tank owners and operators who are eligible for reimbursement from the State Water Resources Control Board (SWRCB), Underground Storage Tank (UST) Cleanup Fund can petition the UST Cleanup Fund Manager for a review of their leaking underground storage tank (LUST) case if they feel the corrective action plan for their site has been satisfactorily implemented but closure has not been granted by the local implementing agency or Regional Water Quality Control Board. The SWRCB has reviewed 16 petitions for closure since 1998, and 14 of these cases were closed with contamination left in place. These petitions can be reviewed on the following website:

www.swrcb.ca.gov/water_issues/programs/ust/publications/closure_orders.shtml.

The regulation that allows the SWRCB to close LUST cases with petroleum hydrocarbon contamination left in place is SWRCB Resolution No. 92-49, "Policies and Procedures for Investigation and Cleanup and Abatement of Discharges Under Water Code Section 13304." Resolution No. 92-49 states that groundwater contaminated by a release from a LUST must attain either background water quality or, if background water quality cannot be restored, the best water quality that is reasonable. Any alternative level of water quality less stringent than background must be consistent with the maximum benefit to the people of the state, not unreasonably affect current and anticipated beneficial use of water, and not result in water quality less than that prescribed in the water quality control plan for the basin within which the site is located.

However, Resolution No. 92-49 does not require that the requisite level of water quality be met at the time of case closure. A case may be closed if the level will be attained within a reasonable period of time.

The determination as to what constitutes a reasonable period of time to attain water quality objectives and the level of petroleum hydrocarbon constituents allowed to remain in the groundwater are based on the evaluation of all relevant factors, including but not limited to the extent and gravity of any threat to public health and the environment during the time period required to meet water quality objectives.

The following rationale for closure was stated by the SWRCB in one of the petitions:

> Although the time required to attain Water Quality Objectives with respect to the 5 ppb odor threshold for TPHg may be more lengthy (e.g., decades to hundreds of years) than that for BTEX and MTBE, it is a reasonable period of time considering that there are no known drinking water wells within one half mile of the site and that it is highly unlikely that remaining petroleum constituents detected in localized areas in the immediate area of the pre-1985 release will migrate substantially beyond the current limited spatial extent. It is also highly unlikely that this particular very limited volume of shallow groundwater in this area of very low yield and in close proximity to numerous surface street runoff collection basins, storm drains, and sanitary sewer mains, will be used as a source of drinking water in the foreseeable future.

The SWRCB also evaluates the technical and economical feasibility of additional corrective action. At one of the petition LUST sites, soil excavation could be used to remove about 550 cubic yards of petroleum hydrocarbon contaminated soil at a cost of about $80,000–$100,000. However, the SWRCB stated that the corresponding reduction in contaminant concentrations in groundwater would not be significant because residual petroleum hydrocarbons would remain in soil in the some areas of the site. Because of the minimal benefit of attaining further reductions in concentrations of TPH-g and TPH-d in groundwater at this site and the fact that the use of the groundwater is not affected or threatened, excavating a portion of the soil to reduce the time period in which water quality objectives would be met in this small volume of groundwater is not economically feasible.

The SWRCB recognizes that residual petroleum hydrocarbon constituents in soil and groundwater are subject to natural attenuation via microbial metabolism. In one case, the SWRCB stated that natural attenuation would be a feasible remedial alternative for the site and that residual gasoline present in the clayey soil would degrade to carbon dioxide and water and, over time, would cease to affect shallow groundwater with constituent concentrations that exceed Basin Plan water quality objectives. The time required to achieve this condition would likely be a few decades. In light of the fact that current or anticipated beneficial uses of groundwater are not threatened, a level of water quality will be attained that is consistent with the maximum benefit to the people of the state.

The SWRCB also evaluates the potential of the shallow groundwater contamination to impact drinking water wells over a "reasonable period of time." At one site, the board stated that, in the unlikely event that a drinking water well was installed nearby, standard well construction practices would prevent the shallow contaminated groundwater from having any adverse effect on deeper aquifers. Given the low permeability and shallowness of the affected water-bearing soils at the site and minimum well construction standards that require 50-foot sanitary seals in municipal supply wells, the residual highly weathered petroleum hydrocarbons would not pose a threat to human health and safety or the environment and would not adversely affect current or probable future beneficial uses of water.

Further, the SWRCB concluded that it was highly unlikely that TPH-g, TPH-d, or benzene detected in site groundwater would migrate substantially beyond its current limited spatial extent. Though the longer chain hydrocarbons composing TPH-g and TPH-d biodegrade more slowly than certain petroleum constituents, such as benzene, they are more recalcitrant and much less mobile (i.e., less volatile, less soluble, and highly sorbed). Thus, the significant period of time that it will take for water quality in this limited area to meet municipal use water quality objectives would be considered "reasonable."

Appendix C

Example LCSM Components

EXAMPLE LCSM COMPONENTS

Table C-1. LCSM components

LCSM Type	What	Why	How
Tier 1: Relatively standard field and lab data	**Field data:** May include geology/ hydrogeology; soil and groundwater analytical results; depth to LNAPL/ water measurements; in-well LNAPL thicknesses	To understand the type of LNAPL present, the general spatial distribution of LNAPL across the site, the response of in-well thicknesses to changes in water table elevation, and potential risk issues associated with the LNAPL body and associated dissolved and vapor phases.	Typical field methods
	Lab data: May include LNAPL fingerprinting/characterization; density; viscosity		Common laboratory methods
	Modeling data: Not typically completed		
Tier 2: May require the collection of numerous soil samples along the vertical profile or the collection of LNAPL-saturated soil cores for laboratory testing and/ or modeling purposes; may include pilot testing to evaluate LNAPL recoverability	**Field Data:** In addition to Tier 1 data, may include: - LNAPL baildown testing - more sophisticated LNAPL delineation techniques such as laser-induced fluorescence (LIF) - the collection of multiple soil samples (per location) for vertical TPH profiling purposes - the collection of LNAPL-saturated soil cores for subsequent lab mobility testing - pilot studies to evaluate LNAPL recoverability	To achieve a much more defined spatial distribution of LNAPL in the subsurface (both above and below the water table). This information may be used to (1) assess the potential volume of LNAPL present, (2) determine strategic locations for the collection of LNAPL-saturated soil cores for subsequent mobility testing, and/or (3) determine strategic locations for the placement of potential recovery wells/screens. Pilot studies may be completed to obtain technology-specific LNAPL recoverability information.	Specialty vendors providing LIF services
	Lab Data: In addition to Tier 1 data, may include:		
	- TPH analysis of multiple soil samples along the vertical profile	To convert TPH soil concentrations into LNAPL saturations and create a laboratory-generated LNAPL saturation profile based on actual TPH sample results.	Typical field sampling methods
	- core photography in both white light and ultraviolet light	White-light photo used to evaluate soil texture and pore structure and to identify changes in stratigraphy. Ultraviolet (UV) light photo used to identify the presence of LNAPL at specific locations in the soil core. This information is used to select subsamples of the soil core to undergo LNAPL mobility testing.	ASTM D5079/API RP40

LCSM Type	What	Why	How
	- LNAPL saturation and residual saturation testing	To determine the potential for LNAPL mobility at specific test locations. The greater the LNAPL saturation above LNAPL residual saturation for a given test location, the greater the potential inherent LNAPL mobility at that location. LNAPL saturation and residual saturation measurements may also be used in subsequent modeling efforts to generate LNAPL saturation profiles and calculate LNAPL relative permeability, conductivity, mobility, and velocity values.	Pore fluid (LNAPL and water) saturations by Dean-Stark, API distillation extraction method using toluene (API RP40); residual saturations by capillary pressure test (LNAPL-water drainage-imbibition, ASTM D6836/API RP40) or Water drive (Proprietary/ API RP40)
	- Air/water capillary pressure testing	To generate a residual water saturation (also referred to as the irreducible water saturation) value and van Genuchten curve fitting parameters to be used in subsequent modeling efforts to generate LNAPL saturation profiles and calculate LNAPL relative permeability, conductivity, mobility and velocity values.	ASTM D6836/API RP40; van Genuchten parameters may be determined using RETC computer program (http://ars.usda.gov/Services/docs.htm?docid=8952)
	- LNAPL density and viscosity	To be used in subsequent modeling efforts to generate LNAPL saturation profiles and calculate LNAPL relative permeability, conductivity, mobility and velocity values.	LNAPL Density: ASTM D1481 LNAPL Viscosity: ASTM D445
	- Interfacial tensions (LNAPL/water, air/water, LNAPL/air)	To be used in subsequent modeling efforts to generate LNAPL saturation profiles and calculate LNAPL relative permeability, conductivity, mobility, and velocity values.	ASTM D971

LCSM Type	What	Why	How
	Modeling Data: May include:		
	- Use of commercially available software to analyze LNAPL baildown test data/observations - Use of API or other analytical models	To calculate LNAPL transmissivity and conductivity values (which may be used to evaluate LNAPL recovery, calculate LNAPL velocity, etc.). To generate LNAPL saturation profiles, calculate LNAPL specific and recoverable volumes, calculate LNAPL relative permeability profiles (as a function of LNAPL saturation), and calculate LNAPL conductivity, mobility and velocity values. To predict LNAPL recovery rates for various technologies, or to use existing pilot study data or actual recovery information to predict future technology-specific recoveries.	Commercially available software API Interactive LNAPL Guide software; API LNAPL Distribution and Recovery Model, others
Tier 3: May require extensive "data density" and the use of sophisticated numerical models	**Field Data:** More detailed site and LNAPL data than Tier 2	To generate an extremely detailed understanding of the current LNAPL characteristics, spatial distribution, and setting and to enable detailed predictions about potential future LNAPL migration and behavior. May be required in situations where sensitive receptors are located in close proximity to the site and/or when proposed future changes in land use may present additional risk issues. This type of LCSM is expected to be needed only in rare circumstances.	
	Lab Data: More comprehensive lab data than Tier 2		
	Modeling Data: Likely requires the use of numerical (either finite difference or finite element) models		Commercially available numerical models

Notes:

1. This table is meant to show example components of a Tier 1, Tier 2, and Tier 3 LCSM. It does not identify all components that make up the LCSM. LCSM components are highly site-specific and need to be tailored to the overall LNAPL site management objective(s).
2. See ASTM 2007 for more information and detailed discussion of developing and updating LCSMs for a site.

Appendix D

In-Well LNAPL Thickness Dilemma

IN-WELL LNAPL THICKNESS DILEMMA

Many states place a significant regulatory emphasis on the presence of LNAPL in a well or the in-well LNAPL thicknesses observed at a given site. When used properly, in-well LNAPL thicknesses provide valuable information relating to the spatial distribution of LNAPL in the subsurface. However, the relevance of in-well LNAPL thicknesses is often misunderstood. Both regulators and the regulated environmental community in general have often used in-well LNAPL thicknesses for far more than they "scientifically" represent. For example, the tendency is to use solely in-well LNAPL thicknesses to determine the following:

- whether LNAPL exists in an area
- if there has been a new or subsequent LNAPL release(s)
- whether the LNAPL is mobile
- whether the LNAPL is recoverable (and the extent to which it can be recovered)
- how an LNAPL recovery program is progressing
- when the LNAPL remediation is completed

Unfortunately, these uses are not necessarily based on the scientific principles governing LNAPL behavior in the subsurface and often lead to poor decision-making. Here are <u>some</u> common examples (with follow-up explanations) where in-well LNAPL thicknesses are inappropriately used or misunderstood:

- The absence of LNAPL in a monitoring well means that LNAPL is not present at that location.

  Not necessarily true: The presence of LNAPL in a well in an LNAPL-affected area is highly dependent on the water table elevation, in relation to the LNAPL impacts, as well as many other factors relating to the characteristics of the LNAPL and soil. In an unconfined setting, in-well LNAPL thicknesses often vary inversely with water table elevation. Hence, an increase in water table elevation typically results in a decrease in in-well LNAPL thickness. Sometimes, during high water tables, the LNAPL becomes entirely submerged, and no LNAPL remains in the well. However, as the water table elevation decreases over time, the LNAPL reappears in the well. In a confined setting, in-well LNAPL thickness varies directly with potentiometric surface elevation. Hence, as the potentiometric surface elevation increases, in-well LNAPL thicknesses also tend to increase.

- LNAPL showing up in a well(s) where it hasn't been detected in an extended period of time (months or years) suggests that the plume is migrating or that a new release has occurred.

  Not necessarily true: Water table elevations/fluctuations may prevent LNAPL from appearing in a given well for months or years. The LNAPL has not necessarily moved away; it may simply be submerged and does not have the ability to displace water and flow into the well screen.

- In-well LNAPL thicknesses are a good indicator of remedial progress. Decreasing in-well LNAPL thicknesses over time (during active LNAPL recovery) indicate that the remedial system is working.

  Not necessarily true: A decrease in in-well LNAPL thickness may or may not be attributed to the LNAPL recovery system. As indicated above, in-well LNAPL thicknesses are highly influenced by water table elevation. High water tables may prevent LNAPL from showing up in wells for extended periods of time, making it appear as though the LNAPL has been recovered.

- The greater the in-well LNAPL thickness, the more LNAPL you should be able to recover from the well.

  Not necessarily true: The potential to recover LNAPL from a given well is a function of LNAPL transmissivity (which in turn is a function of the soil/LNAPL properties) rather than of in-well thickness. Often, the greatest in-well LNAPL thicknesses are found in fine-textured soils (silts and clays) with sand seams, fractures, fissures, etc. that contain LNAPL under pressure. If the monitoring well (which is essentially a large macropore) intercepts the seam/fracture, the LNAPL fills the well to the extent that the pressures equilibrate. Hence, a large in-well thickness could result from a relatively small LNAPL saturated seam/fracture. LNAPL recovery in this situation may be very poor. Conversely, small in-well LNAPL thicknesses in transmissive formations may yield much greater LNAPL recoveries.

- If LNAPL exists in a well, the LNAPL must be mobile and migrating.

  Not necessarily true: LNAPL mobility and migration are functions of LNAPL saturation, relative permeability, and other soil and LNAPL properties. The mere presence of LNAPL in a well does not necessarily mean that the LNAPL has the potential to migrate.

The proper use of in-well LNAPL thickness information requires an examination of LNAPL thickness changes over time in response to fluctuating water table elevations and other potential contributing factors (including whether or not active LNAPL recovery is being conducted in the area). In an unconfined setting, the greatest in-well LNAPL thicknesses (and the best indication of the spatial distribution of the LNAPL) tend to occur during the lowest water table conditions. When used properly, in-well thicknesses measured over time can provide a good general depiction of LNAPL spatial distribution. However, when used inappropriately or misunderstood, decisions based on in-well thickness may not have a sound scientific basis.

Some regulatory requirements/guidance associated with LNAPL indicates that project/site closure may be obtained if no LNAPL, or less than some minimum threshold thickness of LNAPL, is identified in monitoring wells over a stipulated period of time. Numerous projects/ sites have been closed by regulators on the basis that the stipulated in-well LNAPL thickness requirements have been met. However, in some of these situations, the LNAPL has not diminished in presence or been recovered but rather has been submerged by a high water table, thereby preventing its occurrence in monitoring wells. In these situations, the LNAPL will likely reappear in the well when the water table elevation drops. Hence, the stipulated regulatory requirement for project/site closure does not reflect and is not based on the LNAPL "science" and can result in the closure of projects/sites where the true risks associated with the LNAPL may not be understood. This dilemma, in part, has caused some regulatory agencies to move away from the "perception" of LNAPL risks based on in-well thicknesses and toward the LNAPL "science" and the development of a technically sound LCSM.

Appendix E

Sustainable or Green Remediation Tools

SUSTAINABLE OR GREEN REMEDIATION TOOLS

Sitewise™, a sustainable environmental remediation tool developed jointly by Battelle, USACE and the U.S. Navy, is designed to calculate the environmental footprint of remedial alternatives generally used by industry. The tool is a series of Excel spreadsheets providing a detailed baseline assessment of several quantifiable sustainability metrics, including greenhouse gases, energy usage, criteria air pollutants that include sulphur oxides (SO_x), oxides of nitrogen (NO_x), particulate matter, water usage, and accidental risk. The tool uses a "building block" approach to conduct sustainability assessments. SiteWise currently breaks each technology into modules: well installation; soil/groundwater monitoring; system monitoring; system start-up, operations and maintenance; and decommissioning. Each of these modules has activities undertaken (such as transportation, material production, equipment use, and residual management) that have impacts on the environment. SiteWise outputs include both a comparison of the remedial alternatives and a detailed breakdown of the environmental footprint for each alternative. These outputs allow the activities with the greatest footprint to be identified and targeted for footprint reduction during the subsequent remedy design phase. With this structure, the tool is very flexible and can be used to support an evaluation of the environmental footprint of any technology. SiteWise can be applied at remedy selection, design, or implementation stage. The building block approach of the tool makes it flexible enough to be used at the remedy optimization stages as well. The tool will be released to the public domain for use in spring 2010.

The AFCEE Sustainable Remediation Tool (SRT™) is designed to evaluate particular remediation technologies on the basis of sustainability metrics. This easy-to-use tool, using Microsoft Office Excel®, facilitates sustainability planning and evaluation and is intended to aid environmental professionals in decision making. The SRT allows users to estimate sustainability metrics for specific technologies for soil and groundwater remediation. The current technology modules included in the SRT are excavation, soil vapor extraction, pump and treat, enhanced bioremediation, permeable reactive barriers (including biowalls), ISCO, thermal, and long-term monitoring/MNA. AFCEE partnered with members of SuRF for development of the SRT and worked with representatives from the Navy, Army, industry, state regulators, and EPA regulators in the testing, evaluation, and updating of the SRT. Development activities are continuing into 2010, when the SRT will be interfaced with the Remedial Action Cost Engineering and Requirements (RACER™) cost modeling tool to provide environmental professionals with an estimate for sustainability alongside of their budgetary cost estimate.

Appendix F

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Appendix G

Acronyms

ACRONYMS

AFCEE	Air Force Center for Engineering and the Environment
AS/SVE	air sparging/soil vapor extraction
ASTM	ASTM International (formerly American Society for Testing and Materials)
BTEX	benzene, toluene, ethylbenzene, and xylenes
CFR	Code of Federal Regulations
COC	constituent of concern
DPLE	dual-pump liquid extraction
DTW	depth to water
EPA	Environmental Protection Agency
EFR	enhanced fluid recovery
IBT	Internet-based training
ISCO	in situ chemical oxidation
ITRC	Interstate Technology & Regulatory Council
LCSM	LNAPL conceptual site model
LIF	laser-induced fluorescence
LNAPL	light, nonaqueous-phase liquid
LUST	leaking underground storage tank
MTBE	methyl *tert*-butyl ether
MEP	maximum extent practicable
MPE	multiphase extraction
NAPL	nonaqueous-phase liquid
NFA	no further action
NSZD	natural source zone depletion
OSHA	Occupational Safety and Health Administration
ORP	oxidation reduction potential
PPE	personal protective equipment
RBCA	risk-based corrective action
RFH	radio-frequency heating
ROC	radius of capture
ROI	radius of influence
RTDF	Remediation Technologies Development Forum
SESR	surfactant-enhanced subsurface remediation
SVE	soil vapor extraction
SWRCB	(California) State Water Resource Control Board
Tn	LNAPL transmissivity
TPH	total petroleum hydrocarbons
UIC	underground injection control
USACE	U.S. Army Corps of Engineers
UST	underground storage tank
VOC	volatile organic compound