Light non-aqueous phase liquid management strategy

Petroleum Remediation Program

A light non-aqueous phase liquid (LNAPL) is defined as a liquid petroleum product existing in the pores of subsurface sediments and rocks that is immiscible with water and less dense than water. Visible or measurable LNAPL other than a sheen found in an excavation, borehole, or well must be recovered to the maximum extent practicable. This guidance document explains how the maximum extent practicable requirement and a risk-based site management decision is implemented under an LNAPL management strategy. Basic LNAPL concepts are presented to assist with implementing the LNAPL management strategy, and developing a conceptual site model (CSM) upon which the site management decision is based. See Petroleum Remediation Program general policy for more information regarding CSM development and site management decision considerations. This document does not cover dense non-aqueous phase liquids (DNAPL). DNAPL will be managed on a site specific basis.

I. Discovery of LNAPL

The discovery of visible or measurable LNAPL may constitute an emergency and indicates the need for immediate action. If you discover LNAPL, you must take the following actions:

1. **Report the LNAPL discovery.** Call the Minnesota duty officer at 651-649-5451 or 800-422-0798.
2. **Determine the source of the LNAPL, such as a storage tank, pipeline, or spill.** Determine if the source of LNAPL is from an ongoing or historical release. Take immediate action to stop an ongoing release. Aggressive recovery or other actions must be pursued in the event of a recent release in order to prevent the spread of contamination. See Petroleum Remediation Program general policy.
3. **Identify receptors and risks.** Quickly determine whether vapor receptors are present that are or may be affected by the presence of LNAPL. Pay particular attention to possible conduits and preferential migration pathways for LNAPL and vapor migration and accumulation in buildings, basements, crawl spaces, utility trenches, and utility lines. If vapors are detected in any utilities or buildings, contact the local fire department (911) and the Minnesota duty officer immediately. Also, determine whether drinking water supplies or other sensitive receptors such as surface water are present that may be affected by the LNAPL. See Risk evaluation and site management decision at petroleum release sites.
4. **Begin LNAPL recovery.** Keep accurate records of each LNAPL recovery event at each location where it is attempted. Record date, location, method, procedures, and recovered volumes of LNAPL and water, if applicable. Evaluate the need for continued or more aggressive LNAPL recovery, or other interim corrective action, based on risks and cost effectiveness. You must maintain contact with the Minnesota Pollution Control Agency (MPCA) during and after completion of initial LNAPL recovery activities. If risks appear high, aggressive recovery actions must be completed as soon as possible but must be discussed with the MPCA prior to implementation. If risks appear low, the MPCA will typically require initial recovery using manual methods, such as bailing. In the event of a current spill or emergency situation, recovery and/or emergency actions should be implemented immediately in conjunction with notifying the Minnesota duty officer and the local fire department, if necessary.

5. **Submit** [Light non-aqueous phase liquid recovery report] **to the MPCA within 45 days of confirming the presence of LNAPL.** Ideally, the report should be submitted as soon as possible after the initial LNAPL recovery event. The MPCA may require submittal of updated LNAPL recovery reports to document recovery efforts that continue beyond those presented in the initial report.
6. **Submit** [Investigation report] **to the MPCA within 90 days of confirming the presence of LNAPL.** A site where visible or measurable LNAPL is observed is considered high priority.

II. LNAPL concepts

The migration of LNAPL requires displacement of air and water from the pores. It takes less force for LNAPL to displace air than water, therefore, LNAPL preferentially enters air-filled pores. As LNAPL migrates, it will preferentially enter larger pores in both the saturated and unsaturated zones. Geologic heterogeneity, pore geometry, and the presence of groundwater in the pores strongly affect LNAPL migration as do perched, hydraulically confined, and fractured conditions. LNAPL can migrate to depths below the water table and within the saturated zone. It can also occur in hydraulically confined stratigraphic units, in the presence of complex geology. The following discussion assumes relatively homogenous geology and an unconfined, minimally fluctuating water table, but the basic physical concepts can be applied to all geologic conditions.

After a petroleum release, LNAPL infiltrates into the pores and is driven downward by gravitational forces through the unsaturated zone, referred to as the vadose zone. As LNAPL migrates through the vadose zone, some will be left behind, become immobile, and trapped in the pores. This LNAPL in the vadose zone is part of the LNAPL body. If a sufficient volume of petroleum is released in a short period of time, LNAPL will reach the water table, and despite its lower density, may be driven into the saturated zone by the vertical LNAPL head. As LNAPL migrates within the saturated zone, it displaces some of the water in the pore spaces. LNAPL will continue to migrate downward into pores below the water table until vertical equilibrium is reached. Vertical equilibrium usually occurs before horizontal equilibrium, and the LNAPL will continue to spread laterally until horizontal equilibrium is reached. The vertical and horizontal spread of LNAPL is limited by buoyancy and capillary forces, respectively, that counteract the hydraulic force of the LNAPL gradient. Since petroleum is immiscible in water, it will persist in a separate phase in the pores within the saturated zone after the LNAPL body is spatially stable. All of the LNAPL within the saturated zone is part of the LNAPL body.

LNAPL body behavior can be characterized based partly on the LNAPL saturation. LNAPL saturation is defined as the percentage of total pore volume occupied by LNAPL. In the vadose zone, air and water present as soil moisture occupy the balance of the pore volume. In the saturated zone, the remaining pore volume is occupied by water. Under vertical equilibrium in the saturated zone, the relative amount of LNAPL in the pores varies with depth, and higher LNAPL saturations are usually observed near the top of the LNAPL body due to capillary pressure forces. Over time and as the water table fluctuates, some of the LNAPL may be vertically and locally redistributed. Some of the LNAPL will eventually become hydraulically disconnected leaving independent globules of LNAPL in some pores.

Residual LNAPL saturation is defined as the LNAPL saturation under which the LNAPL is immobile under the applied gradient. LNAPL below residual saturation is neither mobile nor hydraulically recoverable. LNAPL exceeding residual saturation is mobile, potentially migrating, and potentially recoverable.

The presence of mobile LNAPL in a given well does not necessarily mean that the LNAPL body is migrating. In order for migration to occur at the edges of the LNAPL body, the forces that drive lateral LNAPL migration, such as the LNAPL gradient that itself attenuates as the LNAPL spreads, must overcome non-attenuating counteracting forces, such as capillary forces, which inhibit LNAPL displacement of water from pores. At some point at the leading edges of the LNAPL body, counteracting forces prohibit further LNAPL migration in the absence of a stronger LNAPL gradient. Therefore, LNAPL bodies will eventually become spatially stable under prevailing conditions even though LNAPL exceeding residual saturation may remain in the core of the LNAPL body.

The detection of visible or measurable LNAPL in a well indicates that some of the LNAPL in the immediate vicinity of the well exceeds residual saturation. The lack of visible or measurable LNAPL in a well does not necessarily mean that there is no LNAPL in the vicinity of the well. It may be below residual saturation. Moreover, LNAPL exceeding residual saturation may be entrapped within the saturated zone due to the stronger force needed to displace water from the pores. That is why LNAPL may appear or accumulate in greater volumes in a well after the water table falls. Thus, water table fluctuations must be accounted for when evaluating LNAPL saturations and the potential for LNAPL migration. Water table fluctuations also affect LNAPL recharge rates and recovery trends.

In the absence of an ongoing release or a migrating LNAPL body and accounting for water table fluctuations, LNAPL recharge rates at a given well can be expected to decline over time as mobile LNAPL is depleted in the formation around the well. However, hydraulic recovery of LNAPL will not result in elimination of all LNAPL in the formation outside the well bore. LNAPL will still be present at or below residual saturation in the pores. Even though the LNAPL body may be stable or all of the LNAPL within it below residual saturation, the remaining LNAPL may be a potent source of COCs in the potentially more mobile aqueous and vapor phases. If the risks posed by these LNAPL-dependent phases are high, more aggressive remediation methods beyond hydraulic recovery may be necessary in order to address the LNAPL below residual saturation.

III. LNAPL management strategy

The initial steps of the LNAPL management strategy include identifying and eliminating or preventing any evident hazardous conditions, then continuing LNAPL recovery and completing the required site investigation and risk evaluation. Continued LNAPL recovery activities must be approved by the MPCA and will be considered an interim corrective action. See Corrective action design and implementation. The site investigation includes delineating mobile LNAPL with wells.

The final steps of the LNAPL management strategy involve factoring identified risks and consequent corrective action into the strategy to make a site management decision. When no identified risks have been identified and the only corrective action reason is measurable LNAPL, the site management decision is guided by the LNAPL management decision requirements. The LNAPL management decision depends on LNAPL recovery to the maximum extent practicable.

A. LNAPL recovery as an interim corrective action

LNAPL recovery means action focused on physical removal of LNAPL only. LNAPL recovery activities include not only physical removal, but also measuring pre and post recovery LNAPL thicknesses and groundwater levels and evaluating LNAPL recharge rates and recovery trends. This information must be evaluated on an ongoing basis to determine appropriate recovery event frequency and adoption of alternative recovery methods, if necessary. The method and frequency of recovery events are based on criteria such as method-specific removal rates, recharge rates, and overall cost effectiveness during the interim period.

The schedule for recovery events must be approved by the MPCA. The MPCA does not anticipate approving remediation of the entire LNAPL body as an interim corrective action unless cost effectiveness can be demonstrated. When risks appear low, LNAPL recovery using manual methods will usually be required by the MPCA. Typically, manual LNAPL recovery will be sufficient until the site management decision is made. Continuing high LNAPL recharge rates indicate the need to consider the cost effectiveness of automated LNAPL recovery as an interim corrective action. In most cases, a pilot test using the specified automated equipment will be required to determine removal and recharge rates prior to MPCA approval to install a full-scale system. Automated LNAPL recovery is discussed below. Interim LNAPL recovery should continue until a final corrective action is implemented unless directed otherwise by the MPCA. It is important to note that the MPCA will not approve site closure if LNAPL recovery has not been attempted and recovery trends are not adequately documented.

B. LNAPL recovery methods

The following discussion focuses on commonly employed recovery methods used as interim corrective action, and is not considered a comprehensive list of available methods. Most LNAPL recovery methods usually result in some recovery of groundwater. The recovered volumes of LNAPL and groundwater must be measured separately. LNAPL recovery activities must be discussed with and approved by the MPCA.

1. Manual LNAPL recovery

The following manual LNAPL recovery methods are most commonly used:

- Hand bailing
- Ooleophilic and hydrophobic absorbent pads, tubes, or socks
- Passive specific gravity collectors
- Non-automated pumping

Manual methods will result in limited immediate hydraulic capture and removal of LNAPL exceeding residual saturation from the formation outside the well bore. Special methods and procedures may be necessary to differentiate recovered LNAPL from recovered groundwater, especially when absorbent methods are used. Generally, manual LNAPL recovery methods are used when there is no evidence of a migrating LNAPL body, risks appear low, and LNAPL recharge rates are low. Manual event frequency should be evaluated based on cost while also considering LNAPL recharge rates and method-specific removal rates.

2. Vacuum truck LNAPL recovery

Vacuum truck LNAPL recovery is considered a manual, non-automated pumping method when it is used to remove LNAPL from a well. Special methods and procedures may be necessary to differentiate recovered LNAPL from recovered groundwater due to emulsification. Except in emergency situations, the MPCA must approve the use of the vacuum truck method before it is employed at a site. The cost for a vacuum truck recovery event can be much higher than for an event using other manual, non-automated pumping methods. The MPCA does not consider numerous vacuum truck events to be a cost effective manual LNAPL recovery method.

Longer-term employment of the vacuum truck method using wells as extraction points can result in vacuum enhanced recovery of LNAPL, as well as aqueous and vapor phases from the formation pores. Employment of a vacuum enhanced, multi-phase recovery strategy requires collection of subsurface response and vacuum truck operation data to confirm effectiveness. In the case of a recent release, vacuum truck use under a vacuum enhanced strategy can result in contaminant mass removal to the point of sufficient risk reduction and possible regulatory closure after post-recovery monitoring. For a historical release, the MPCA will only approve vacuum truck use if it is supported by a clear strategy to achieve well-defined remediation end points while considering total life-cycle costs. For example, in the case where there is a limited amount of LNAPL exceeding residual saturation, a vacuum enhanced strategy may be capable of quickly eliminating visible or measurable LNAPL. In most cases, a proposal to use the vacuum truck method under a vacuum enhanced strategy will be considered a final corrective action.

3. Automated LNAPL recovery system

Under high LNAPL recharge rates, installing an automated LNAPL recovery system, such as a skimmer, can be more cost effective as a corrective action. A recommendation for its use as an interim corrective action should also consider the future site management decision regarding a final corrective action.

C. LNAPL removal and recharge rates

1. Data collection

LNAPL removal and recharge rates are used to determine the method and frequency of LNAPL recovery, respectively. The removal rate is based on the amount of time it takes to remove a measurable level of LNAPL from a well to a negligible amount. The recharge rate is based on the amount of time it takes for LNAPL to recover to the pre-removal level. The removal and recharge rates can be determined by completing a recovery test. A recovery test is completed in two phases.

The first phase consists of LNAPL removal to the point of negligible measurable product. The second phase consists of measuring LNAPL recharge immediately following the removal phase. The need for a recovery test must be discussed with and approved by the MPCA. Be prepared to discuss recovery test methods, procedures, data evaluation, and reporting requirements. A general, four-step LNAPL recovery test procedure for wells follows:

1. Measure the depths to LNAPL and groundwater in the well using an interface probe. Calculate the volume of LNAPL in the well.
2. Begin removing all or most of the LNAPL from the well as quickly as possible while preventing or minimizing the removal of groundwater. Record the volumes of both LNAPL and groundwater removed from the well and the length of time it took for removal.
3. After LNAPL removal, measure the depths to LNAPL and groundwater in the well until both levels achieve or closely approach pre-removal conditions, or up to a maximum of 24 hours after LNAPL removal. The timing of measurements should be based on the apparent pace of change but in general should be collected more frequently at first (e.g., every minute) and less frequently later on (e.g., every 10 minutes or hourly). It is equally important to capture the change in recharge rate throughout the test as well as the specific length of time it takes for complete recharge.
4. Following LNAPL recharge to near pre-removal levels, or no more than 24 hours after the initial removal phase, repeat steps 1 through 3. Repeat the test for each well containing LNAPL so there are two sets of data. The purpose of the second test is to better assess LNAPL recharge from the formation rather than recharge from the sand pack surrounding the well screen.

2. Data evaluation

Calculate the LNAPL removal rate in gallons per day using the removal phase data for each test and each well containing LNAPL. Calculate the recharge rate in gallons per day using the recharge phase data. Tabulate the data using the table provided in Light non-aqueous phase liquid recovery report and convert LNAPL recharge thicknesses to volumes for each measurement event. Graph cumulative recharge volume versus time for each test. The recharge rate should be based on the point at which recharge reaches asymptotic conditions. Pay particular attention to the second set of data from a given well and compare the recharge rates to see whether they are similar or if the recharge rate was significantly different after the second removal event. In most cases, the recharge rate data from the second event should be considered more conclusive.

Using the calculated removal and recharge rates, develop recommendations regarding the most cost effective LNAPL recovery method and schedule. Include contingency plans for adapting the method or schedule to changing recharge rates, especially in the case where rapidly declining LNAPL recharge rates can be expected. Submit the recovery test procedures, data, evaluation, and recommendations to the MPCA in the initial or an updated Light non-aqueous phase liquid recovery report as soon as practical after completing the test.

3. LNAPL delineation

The objective of LNAPL delineation is to define the lateral extent of mobile LNAPL and determine if the LNAPL is migrating. Migrating LNAPL is considered a high risk. Permanent monitoring wells should be used to define the lateral extent of mobile LNAPL. LNAPL delineation monitoring well locations and specifications should be discussed with the MPCA prior to installation. The MPCA does not anticipate approving the use of predictive modeling to define the LNAPL body or predict LNAPL migration.

Although subject to site-specific circumstances, permanent monitoring wells installed for LNAPL delineation should be located no more than 50 feet apart unless otherwise approved by the MPCA. Well construction specifications such as screen type, screened interval, and sand pack gradation need to be considered so that mobile LNAPL can efficiently enter the well, especially if high LNAPL recharge rates are expected and the well will be used for LNAPL recovery. All monitoring wells must be adequately developed to assure hydraulic connection with the formation since most drilling methods create what is commonly referred to as a borehole skin, a smearing of clay and silt on the borehole which can reduce the hydraulic conductivity in the vicinity of the well screen.

LNAPL monitoring activities should include measuring depth to LNAPL and depth to groundwater. If LNAPL is not detected in delineation wells, water level measurements should be taken during LNAPL recovery events. Unless directed otherwise by the MPCA, groundwater samples should be collected from the delineation wells without detectable LNAPL on a quarterly schedule and analyzed for petroleum parameters in accordance with Groundwater sample collection and analysis procedures. The appearance of LNAPL in a previously uncontaminated well or other structure is strong evidence of LNAPL migration. If LNAPL is discovered at a new location during the investigation, contact the MPCA immediately and begin LNAPL recovery. It is important to note that the MPCA will not approve site closure if the extent and magnitude of mobile LNAPL are not adequately characterized.

D. LNAPL management decision

A site management decision is made after Investigation report is reviewed. The site management decision is based on risks. If the site investigation indicates that risks are high, final corrective action must focus on cost effective risk reduction. If the final corrective action involves remediation, the entire LNAPL body should be considered a potential remediation target. If a corrective action such as water supply replacement has sufficiently reduced risks, or the only risk is the continued presence of mobile LNAPL, the MPCA will consider site closure when LNAPL recovery has been completed to the maximum extent practicable. LNAPL recovery to the maximum extent practicable is defined as:

1. The LNAPL body has been delineated and mobile LNAPL characterized.
2. LNAPL recharge rates decrease to and stabilize at some minimal levels due to sustained LNAPL recovery efforts under MPCA approved recovery method, schedule, and locations.
3. One year of post LNAPL recovery monitoring data confirm that mobile LNAPL is spatially stable and not migrating.
4. One year of post LNAPL recovery groundwater monitoring data confirm decreasing or stable trends in aqueous phase contaminant concentrations and extents.
5. One year of post LNAPL recovery vapor monitoring data confirm low risk to receptors.

If the above conditions have not been met at the time the site management decision is made, additional work will be necessary. Continued or additional LNAPL recovery will be considered a final corrective action.

E. Final corrective action

For sites where closure is contingent upon LNAPL recovery to the maximum extent practicable, the final corrective action goal is to meet the conditions above. Measurable corrective action objectives should be defined for each of the maximum extent practicable conditions defined in the LNAPL management decision. See Petroleum Remediation Program general policy and Conceptual corrective action design (CCAD) report for more information on corrective action goals and objectives.

Minimal LNAPL recharge rates should be based on site specific data, and in the case of known low recharge rates across the LNAPL body, practicality. LNAPL recovery objectives should be based on recharge rates and the recovery event method and schedule. Given efficient and effective LNAPL recovery, plotting cumulative removed volume over time can provide evidence of recharge rate decrease and stabilization upon displaying asymptotic trends. An evaluation of LNAPL recovery trends must account for groundwater elevation fluctuations.

If the area where LNAPL exceeds residual saturation is small and recharge rates are low at all wells, the MPCA will consider approving LNAPL recovery using manual recovery methods as a final corrective action. Manual LNAPL recovery is considered a simple corrective action unless additional characterization of the LNAPL body is required via a focused investigation. In that case, manual LNAPL recovery will be considered a complex corrective action. See Corrective action design and implementation for more information about simple and complex corrective actions.

Generally, an area less than 10,000 square feet with LNAPL exceeding residual saturation is considered small and a recharge rate less than one gallon per day per recovery location is considered low. Application of these two general criteria are subject to site-specific circumstances and may be overridden by the presence of nearby receptors, and LNAPL body characterization data such as its geometry, geologic complexity, potential for LNAPL migration, and effects of fluctuating water levels.

If the area where LNAPL exceeds residual saturation is large or recharge rates are high at some or all wells, continued LNAPL recovery should be proposed as a final corrective action. The cost effectiveness of various LNAPL recovery methods and schedules must be considered. The MPCA does not anticipate approving a complex corrective action targeting the entire LNAPL body to accomplish LNAPL recovery to the maximum extent practicable unless cost effectiveness can be demonstrated. In the case of high LNAPL recharge rates, the cost effectiveness of automated LNAPL recovery or other corrective actions should be considered using life cycle cost estimates. Automated LNAPL recovery systems, remediation systems, and subsurface LNAPL excavation are considered complex corrective actions. Achieving the corrective action goal under a complex corrective action may require additional information by completing a focused investigation in order to better define measurable objectives and to complete a detailed design. Relative LNAPL saturations across an LNAPL body can be an important characteristic when determining well placement to confirm the presence of LNAPL exceeding residual saturation and understanding LNAPL recovery and recharge rate trends. The MPCA does not anticipate approving the use of predictive modeling to define minimal LNAPL recharge rates.

F. Reporting requirements

A Light non-aqueous phase liquid recovery report must be submitted to the MPCA within 45 days of LNAPL discovery. If an LNAPL recharge test is completed after the initial report, an updated Light non-aqueous phase liquid recovery report must be submitted. A copy of this report must be included in Investigation report when applicable. Ongoing interim LNAPL recovery activities should be documented in the Investigation report or Monitoring report. The MPCA may require periodic reporting to document ongoing interim LNAPL recovery activities. An automated LNAPL recovery system is considered a remediation system, therefore, LNAPL recovery should be reported using Remediation system operation monitoring (RSOM) report.

VII. Additional resources

LNAPL concepts have been adapted from training and publications provided by the Interstate Technology & Regulatory Council (ITRC) and the American Society for Testing and Materials (ASTM). Please refer to the following publications for more detailed information on LNAPL characterization and recoverability:

ITRC. 2009a. *Evaluating Natural Source Zone Depletion at Sites with LNAPL*. LNAPL-1. Interstate Technology & Regulatory Council, Washington, D.C. http://www.itrcweb.org/Documents/LNAPL-1.pdf

ITRC. 2009b. *Evaluating LNAPL Remedial Technologies for Achieving Project Goals*. LNAPL-2. Interstate Technology & Regulatory Council, Washington, D.C. http://www.itrcweb.org/documents/LNAPL-2.pdf

ASTM. 2007. *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface*. ASTM E2531-06. ASTM International, West Conshohocken, PA. http://www.astm.org/Standards/E2531.htm