LIGHT NONAQUEOUS PHASE LIQUIDS (LNAPL) AND THE MCP: GUIDANCE for SITE ASSESSMENT AND CLOSURE Policy #WSC-14-450

This document provides guidance on investigating, assessing, understanding, and addressing the presence and migration of LNAPL at disposal sites regulated under the Massachusetts Contingency Plan (the "MCP" or 310 CMR 40.0000)

This document is intended solely as guidance. It does not create any substantive or procedural rights, and is not enforceable by any party in any administrative proceeding with the Commonwealth. This document provides guidance on approaches MassDEP considers acceptable for meeting the general requirements set forth in the MCP. Parties using this guidance should be aware that other acceptable alternatives may be available for achieving compliance with general regulatory requirements.

DRAFT

Table of Contents

DRAFT

1.0 PURPOSE AND SCOPE

The purpose of this document is to provide general guidance and a simplified approach to evaluate and address Light Nonaqueous Phase Liquids (LNAPL) at contaminated sites, in accordance with the 2014 Amendments to Massachusetts Contingency Plan ("MCP" at 310 CMR 40.0000).

This document is designed for a wide range of MCP users, *especially* those whose professional expertise is *not* in hydrogeology or sub-surface engineering. In order to enable all such users to effectively and efficiently understand and implement relevant MCP provisions, this guidance:

- summarizes the new LNAPL provisions and performance standards of the MCP;
- provides a simplified description of the LNAPL Conceptual Site Model (LCSM);
- details the relevant fundamental principles of fluid flow in porous media (FFPM) consistent with the LCSM;
- outlines tools and metrics for the evaluation of LNAPL-contaminated sites using a *multiple lines of evidence* approach;
- presents a simplified approach that may be voluntarily used to demonstrate compliance with MCP LNAPL performance standards; and
- provides recommended technical references for parties who elect to demonstrate compliance with MCP LNAPL performance standards using an alternative and/or more rigorous site-specific approach.

The scope of the guidance offered in this document is limited to the direct impacts related to the occurrence and bulk movement of LNAPL *in and through* porous media. Beyond these direct impacts are secondary concerns related to the partitioning of LNAPL constituents into environmental media, including sorption onto/into soil organic carbon, dissolution into groundwater and volatilization into soil gas. Refer to other agency documents for guidance on these secondary impacts.

This document is intended solely as guidance. It does not create any substantive or procedural rights, and is not enforceable by any party in any administrative proceeding with the Commonwealth. This document provides guidance on approaches MassDEP considers acceptable for meeting the general requirements set forth in the MCP. Parties using this guidance should be aware that other acceptable alternatives may be available for achieving compliance with general regulatory requirements.

2.0 APPLICABILITY

This guidance applies to disposal sites regulated under the Massachusetts Contingency Plan where LNAPL is present in porous media. As defined in the MCP, LNAPL is any oil or hazardous material that is present in the environment as a separate phase liquid, and which has a specific gravity equal to or less than one.

This document does not address disposal sites in which LNAPL is present in non-porous media (e.g., bedrock fractures), or Dense Nonaqueous Phase Liquid (DNAPL).

3.0 MCP PERFORMANCE STANDARDS FOR NAPL

Massachusetts General Law (MGL) c. 21E and the MCP address releases of oil and hazardous materials (OHM) to the environment, and require that all sites impacted by such releases achieve a *Permanent Solution*. A Permanent Solution is achieved when OHM at a site does not pose a Significant Risk to human health, safety, public welfare, or the environment, at present and for the foreseeable future. Both the statute and regulations also require that all releases of OHM be removed from the environment if and to the extent feasible.

The presence of OHM in the environment as a separate phase – whether lighter or denser than water - is of special concern, with respect to these mandates, as:

- the mass of contaminants within NAPL is orders of magnitude higher than the "µg/L" levels of OHM dissolved in water, $\mu g/m^3$of OHM present in air, and mg/kg of OHM sorbed onto soil; and
- the presence of NAPL represents not only a direct and current exposure concern, but also a long-term/future risk via movement through the environment as a separate phase liquid and/or via inter-media mass transfer.

From 1993 to 2014, the MCP attempted to address these concerns by specifying an *Upper Concentration Limit* for NAPL, which precluded achieving a Permanent Solution if the average thickness of NAPL at a disposal site was "equal to or greater than ½ inch in any environmental medium." Evolving scientific knowledge in this area, along with difficulties in ascertaining compliance with the ½ inch standard, led MassDEP to address NAPL with a new approach in MCP amendments that became effective in June 2014.

These new provisions eliminate the ½ inch Upper Concentration Limit, and instead focus on NAPL movement and recoverability. Two new mobility terms have been defined in the MCP at 310 40.0006:

> **Non-Stable NAPL:** a NAPL with a *footprint that is expanding laterally or vertically* by: (a) *migrating* along or within a preferred flow path; (b) *discharging* or periodically discharging to a building, utility, drinking water supply well, or surface water body; or (c) *spreading* as a bulk fluid through or from subsurface strata; and
>
> **NAPL with Micro-Scale Mobility**: a NAPL with a footprint that is not expanding, but which is visibility present in the subsurface in sufficient quantities to migrate or potentially migrate as a separate phase over a short distance and visibility impact an excavation, boring, or monitoring well.

While not defined terms in the MCP, there are two additional types of sites with respect to the presence of NAPL (i.e., in addition to sites with Non-Stable NAPL and NAPL with Micro-scale Mobility):

> ***Sites at which some amount of NAPL is present, but where such NAPL does not have Micro-Scale Mobility****, due to its limited mass, its properties, and/or the properties of the porous environmental media; and*
>
> ***Sites at which NAPL is not present at all*** *(i.e., all OHM are present in a sorbed, dissolved, or vapor state).*

Permanent and Temporary Solutions

The states of NAPL existence (or non-existence) and mobility have implications as to the type of closure that can be achieved under the MCP:

- Sites with **Non-Stable NAPL** cannot achieve a Permanent Solution, as specified at 40.1003(7)(a)(1.), but may qualify for a Temporary Solution, as specified at 40.1003(7)(b), if the Non-Stable NAPL and NAPL with Micro-Scale Mobility is removed and/or controlled to the extent feasible.
- Sites with **Micro-scale Mobility** may be able to achieve a Permanent Solution, but only after NAPL is removed or controlled to the extent feasible, as specified at 40.1003(7)(a)(2.), and all other MCP cleanup requirements relating to source and migration control and risk management are achieved. If remedial efforts are successful in removing all NAPL with Micro-Scale Mobility, there is no requirement to provide notice of the presence of any remaining NAPL with an Activity and Use Limitation (AUL). If NAPL with Micro-scale Mobility remains, an AUL is required, as specified at 40.1012(2)(d).
- Sites where NAPL is not/no longer present or where any remaining NAPL does not have Micro-Scale Mobility may be able to achieve a Permanent Solution, with no NAPL-related conditions or AUL.

While this document is focused on MCP performance standards in support of a Permanent or Temporary Solution for LNAPL disposal sites, other MCP requirements for notification and assessment specific to NAPL and LNAPL are important to note to ensure compliance with the MCP.

Notification

Two NAPL-related conditions require reporting to MassDEP within 2 hours:

- Oil or waste oil NAPL that constitutes a "sudden, continuous or intermittent release" that results in a sheen on a surface water (310 CMR 40.0311(5)); and
- NAPL that poses or could pose an Imminent Hazard (310 CMR 40.0311(7))

There are also two NAPL-related conditions that require reporting to MassDEP within 72 hours:

- **Equal to or greater than ½ inch** of NAPL in a groundwater monitoring well, excavation, or other subsurface structure **at any location** (310 CMR 40.0313(1)); and
- **Equal to or greater than 1/8 inch** of Volatile LNAPL in a groundwater monitoring well, excavation, or other subsurface structure **within 30 feet of a School, Daycare or Child Care Center or occupied residence** (310 CMR 40.0313(4)(f)3.).

Lastly, there is one NAPL-related condition that requires reporting to MassDEP within 120 days:

Equal to or greater than 1/8 inch of NAPL in a groundwater monitoring well, excavation, or other subsurface structure **at any location (310 CMR 40.0315(4))**.

As can be seen, the presence of subsurface NAPL equal to or greater than 1/8 inch can trigger a 120 day or 72 hour reporting obligation, depending on its proximity to sensitive receptors and on its volatility, as summarized in Figure 1.

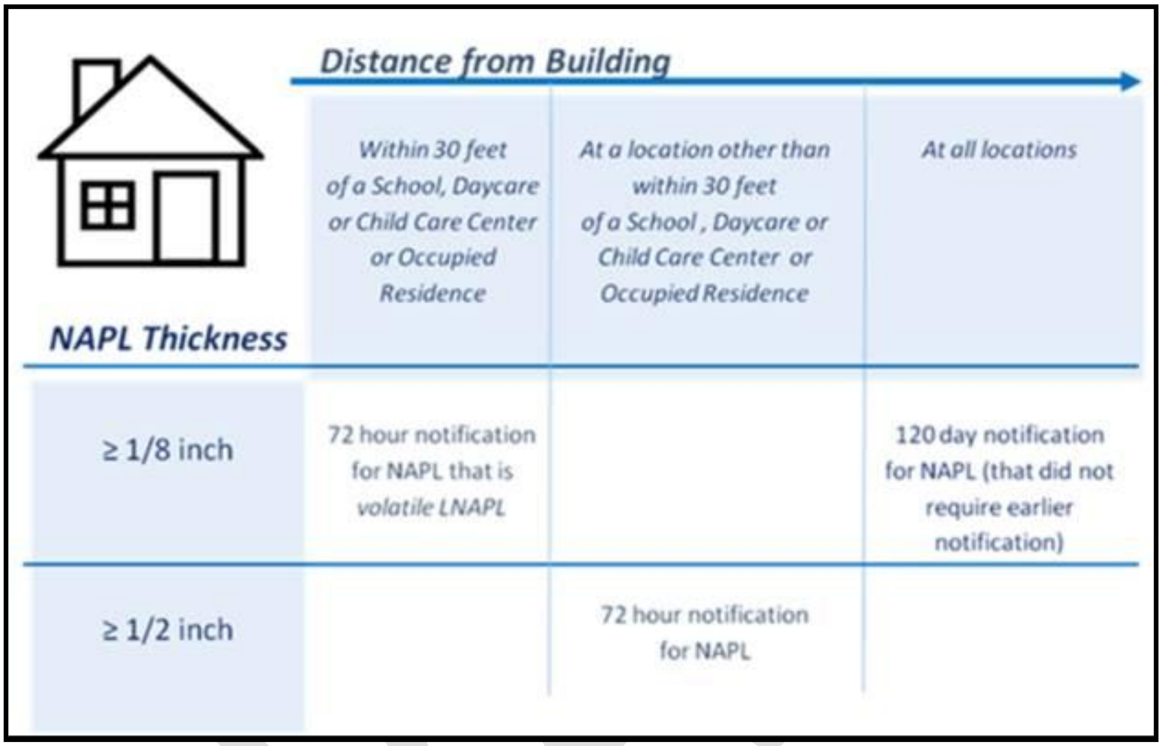

Figure 1 – Notification Requirements for NAPL in the Subsurface

In those cases where a NAPL condition triggers a 2- or 72-hour notification obligation, an Immediate Response Action must be conducted to assess the NAPL and, as appropriate, to implement immediate measures to contain the NAPL and prevent or mitigate exposures.

Conceptual Site Model (CSM) and Assessment

Conceptual Site Model development as a tool for organizing and analyzing information about disposal site conditions and designing and implementing sampling and remedial plans has become standard practice by environmental professionals and regulators on the state and national level. Use of the CSM is particularly important for understanding and successfully managing more complex sites, such as sites with potential vapor intrusion or NAPL. The MCP provides a CSM definition (310 CMR 40.0006) that includes a specific reference to sites where "NAPL is or may be present." **Section 6** provides further discussion of CSM at LNAPL sites.

In addition to the CSM definition, there are requirements to document the preliminary CSM at the conclusion of a Phase I Initial Site Investigation (310 CMR 40.0483(1)(h)); base the Conceptual Phase II Scope of Work on the preliminary CSM developed in Phase I (310 CMR 40.0834(2)(a)); and provide an updated CSM at the conclusion of the Phase II Comprehensive Site Assessment (310 CMR 40.0835(4)(i)).

A succinct summary of the CSM must also be provided in support of a Permanent or Temporary Solution (310 CMR 40.1056(2)(b) and 310 CMR 40.1057(2)(b), respectively). Each of these provisions makes specific reference to NAPL sites and, as applicable, specifies requirements to document the presence, distribution and stability of NAPL.

Other MCP references to CSM relevant to LNAPL include the provision at 310 CMR 40.1003(7) related to evaluating the feasibility of removing NAPL with Micro-Scale Mobility "based upon consideration of CSM principles."

> Conceptual Site Model or CSM means a site-specific description of how contaminants entered the environment, how contaminants have been and may be transported within the environment, and routes of exposure to human and environmental receptors that provides a dynamic framework for assessing site characteristics and risk, identifying and addressing data gaps and managing uncertainty, eliminating or controlling contaminant sources, developing and conducting response action strategies, and evaluating whether those strategies have been effective in achieving desired endpoints. ***At sites at which NAPL is or may be present, this includes the body of fundamental scientific principles describing the behavior of fluid flow in porous media necessary to assess NAPL in subsurface strata.***

A flowchart summarizing these MCP Performance Standards for NAPL is provided in **Figure 2**.

4.0 COMPLYING WITH MCP PERFORMANCE STANDARDS FOR LNAPL

Any scientifically justified approach may be used to demonstrate compliance with the LNAPL mobility and recoverability standards in the MCP, as long as it is based upon and/or consistent with the fundamental principles of Fluid Flow in Porous Media (FFPM) and the LNAPL Conceptual Site Model.

Many organizations have published excellent comprehensive technical documents for assessing LNAPL behavior in the sub-surface, and MassDEP's preferred and recommended references in this regard are provided in Section 13.0 with Internet Hyperlinks for ready access. Repeating the extensive technical details from these works is beyond the scope of this document. However, familiarity with these references is recommended and sometimes necessary.

Regardless of the approach used, of paramount concern is the level of effort and amount of data needed to adequately demonstrate compliance with MCP provisions. While decisions of this nature are inherently site-specific and involve professional judgment, as a general rule, data needs will be greatest for sites:

- where the LNAPL is gasoline or another material with significant toxicity, mobility, solubility, and/or volatility;
- where the LNAPL is located in complex fill or geological conditions; and/or
- where the LNAPL is proximate to drinking water supplies, homes, schools, surface waters and/or other sensitive receptors.

DRAFT

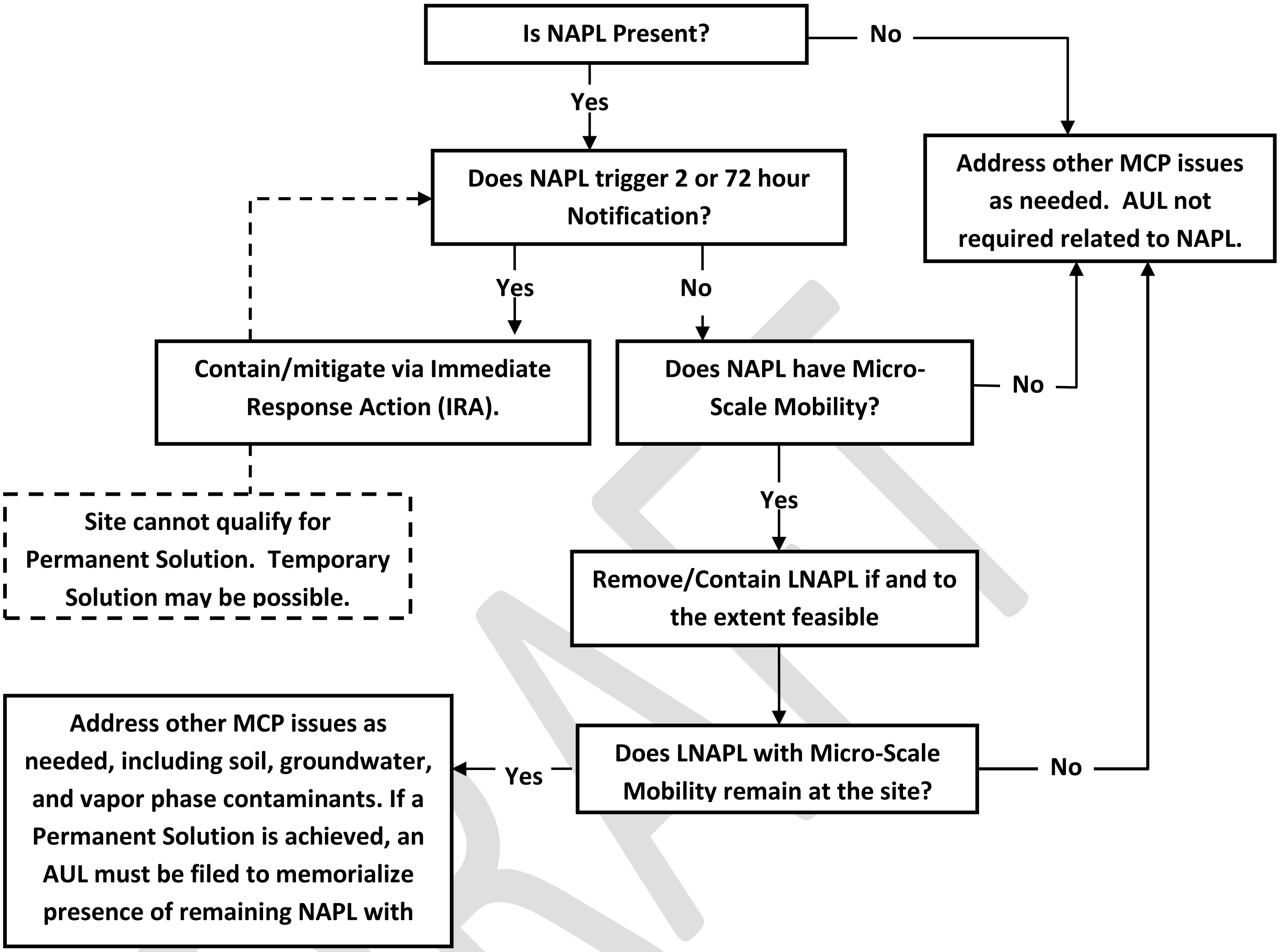

Figure 2: MCP Performance Standards for LNAPL

5.0 SIMPLIFIED CONCEPTUAL SITE MODEL FOR LNAPL

Soil is a porous media. At uncontaminated sites, above the water table (the *Vadose Zone*), the void (*pore*) spaces between soil particles are filled with a mixture of air and water. Below the water table (the *Saturated Zone*), void spaces are completely filled with water.

LNAPL (e.g., gasoline, fuel oils, and certain chemical products) spilled onto or into the ground travels downward due to the force of gravity, moving through the void spaces in the Vadose Zone. The LNAPL will follow the path(s) of least resistance, preferentially following any interconnected air-space “finger” structures that way be present. Water droplet present in larger pore areas may be dislodged by the migrating LNAPL globules, but the water present in smaller pore areas will be held tightly in place by capillary forces, forcing the LNAPL globules to travel in a different direction (see Figure 3).

Some of the LNAPL traveling downward through the Vadose Zone gets "stuck" in the pore spaces, leaving behind a trail of LNAPL globules (*Residual Saturation*). If enough LNAPL has been spilled, globules will eventually reach the water table, where void spaces between the soil particles are completely filled with water. At this point, the (less dense) LNAPL will initially not be able to "push" the water out of the void spaces in the Saturated Zone, and further downward movement of the LNAPL ceases, at least temporarily.

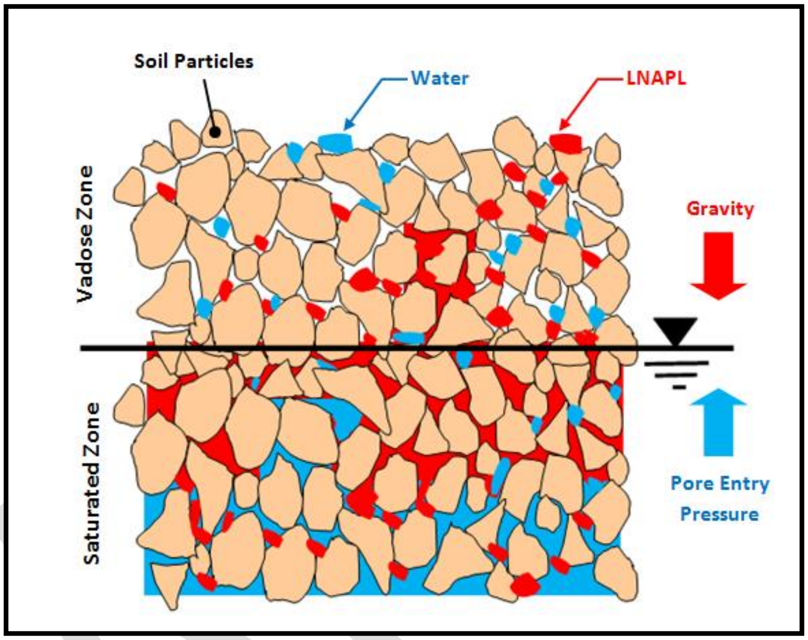

Figure 3: NAPL Movement through Porous Media

If additional LNAPL continues to travel downward to the water table, its collective mass will eventually become large enough to create a gravitational force that is greater than the opposing density/capillary forces (*Pore Entry Pressure*) arresting the movement of the globules, and some LNAPL will enter into the pore, displacing some (but not all) of the water. Additional transport of LNAPL to the water table interface will continue to push more LNAPL into the Saturated Zone pore spaces, vertically and laterally, based upon these force dynamics.

In theory, an equilibrium condition would be reached when further transport of LNAPL to the water table is halted (i.e., the spill/release of LNAPL is terminated). In reality, a continuously rising and falling water table will alter pore and LNAPL forces and pressure conditions, resulting in the ongoing movement of LNAPL and water in and out of pore spaces. However, absent preferred flow paths, a quasi-equilibrium condition will generally become established within 1 to 2 years after the LNAPL spill, in that the overall footprint of the LNAPL globules will cease to expand laterally and vertically, even though some movement of globules will continue within this footprint. At this point, the LNAPL is considered to be in a state of *Macro-Scale Stability.*

In previous decades, it was theorized that LNAPL that made its way to the water table would displace all water in the impacted Saturated Zone void spaces, creating a so-called "pancake" of pure LNAPL at the water table. This is now known to be incorrect, and a gross oversimplification of a complex process and condition, in which pore spaces at and below the water table are in fact filled with a mixture of LNAPL and water, while the pore spaces above the water table are filled with a mixture of LNAPL, water, and air – with most of the LNAPL eventually becoming concentrated in the area just above and below the water table (*Smear Zone*).

Although the exact shape and nature of this dynamic multi-phase condition is complex, variable, and site-specific, it is often visualized as a "shark fin", straddling the water table interface in a perpendicular orientation (see **Figure 4**).

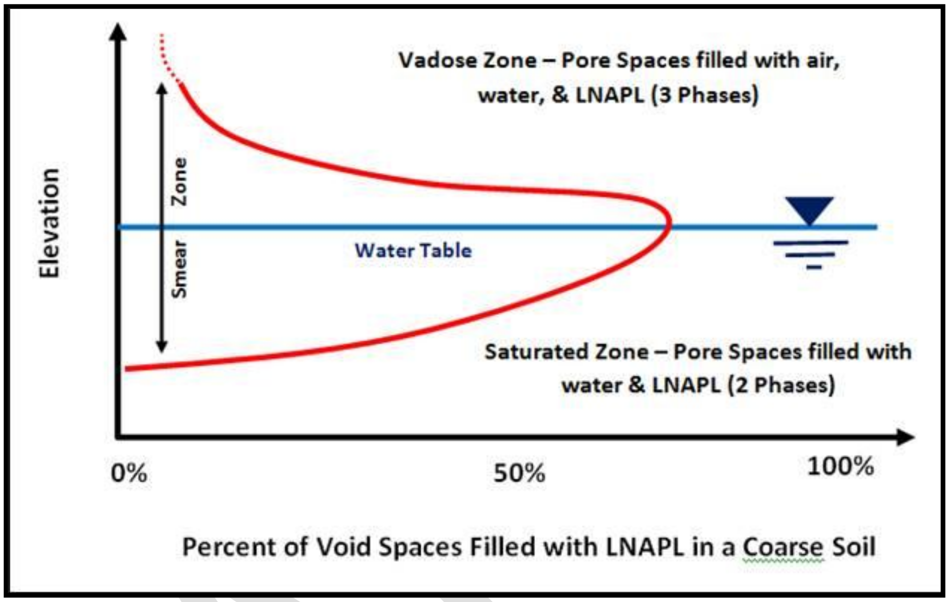

Figure 4: LNAPL Saturation at Water Table Interface

In this model, the outline of the shark fin represents the percentage of soil void spaces filled with LNAPL. The tip of the fin occurs near the water table interface (i.e., where the largest accumulation of LNAPL occurs). Pore LNAPL saturation sharply decrease with distance above and below the water table interface, until it reaches zero percent at the lower extent of the Smear Zone (in the Saturated Zone), and approaches Residual Saturation levels in the upper extent of the Smear Zone (in the Vadose Zone). In coarse soils (with large pore spaces), up to 70% of the void spaces at and just below the water table interface could be filled with LNAPL, with the remaining 30% filled with water that could not be "pushed out" by the migrating LNAPL globules. In finer grained soils, the maximum LNAPL saturation value will be less than 70%, as water present in smaller void spaces is more closely held in place via capillary forces, making it harder for migrating LNAPL globules to dislodge.

Theoretical and empirical methods and models have been developed to qualitatively and quantitatively evaluate this phenomenon on a semi-generic and/or site-specific nature, based upon the properties of the LNAPL (e.g., specific gravity, viscosity), the properties of the porous media (e.g., porosity, grain size distribution), and the resulting interactions (e.g., interfacial forces).

While achievement of a state of LNAPL Macro-Scale Stability is an important milestone in controlling contaminant migration at a site, it may only be the first step. Even after the bulk movement of the separate phase OHM is halted, additional migration of contaminants can occur as constituents within the LNAPL (e.g., benzene in gasoline) partition out of the LNAPL globule. This includes sorption onto/ into soil organic carbon, dissolution into groundwater and volatilization into soil gas. Of particular concern is the subsequent migration of these constituents in groundwater and soil gas, which can impact drinking water supplies and indoor air.

6.0 IMPORTANT TECHNICAL CONCEPTS, TERMS AND METRICS

Subsurface LNAPL behavior in soils is governed by the fundamental principles of multi-phase fluid flow in porous media (or "FFPM," which includes Darcy's Law,) used for decades in the oil industry, which have been developed and used in recent years in environmental applications. A number of states and regulatory authorities have published guidelines based heavily on FFPM concepts to more accurately describe the nature, extent and behavior of LNAPL contamination in the subsurface. The foundation of this work is commonly called the LNAPL Conceptual Site Model (or "LCSM").

While a detailed description and discussion of all technical concepts, terms, and metrics in this area is beyond the scope of this document, certain items warrant mention:

6.1 Soil Saturation Concentration or "C_{sat}"

OHM within LNAPL released to the environment will partition into soil organic carbon, soil pore water, and soil air spaces, based upon the properties of the OHM and the soil. Eventually, an equilibrium condition will be established. Mathematical models and empirical data can be used to calculate/estimate this equilibrium condition, and resultant concentration levels. These equilibrium levels represent a "saturation" concentration, in that no additional contaminant molecules can be accommodated in the soil organic carbon, soil pore water, or soil air space. Accordingly, a measured concentration in excess of these saturation levels is suggestive of the presence of an LNAPL (i.e., a separate phase of OHM not sorbed/dissolved/vaporized).

For most LNAPL sites, the most important data set in this regard is for the concentration of hydrocarbons (or other LNAPL materials) in soil, as this is the media compartment where most of the partitioned mass will generally reside. Soil Saturation Concentration values (C_{sat}) have been developed by researchers for a number of common LNAPL materials and soils. A helpful summary tool in this regard published by the Massachusetts LSP Association is provided in **Figure 5**. This graphic indicates that for most common LNAPLs, a concentration of OHM (e.g., Total Petroleum Hydrocarbons) in soil above about 100 mg/kg (C_{sat}) indicates the likely presence of LNAPL.

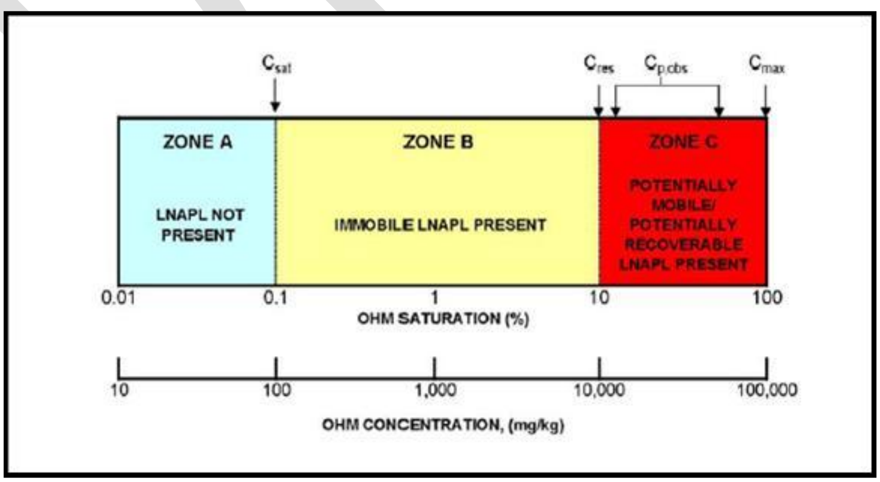

Figure 5: LNAPL in Soil (LSPA, 2008)

DRAFT

The idea that LNAPL can be present in a soil with as little as 100 mg/kg (or less) of hydrocarbons may come as a surprise to many people who have traditionally understood LNAPL to be present only if it is visually observed as droplets in soil or groundwater.

6.2 LNAPL Saturation and Residual Saturation

LNAPL Saturation refers to the amount of LNAPL contained in a volume of subsurface porous media at a given point in time, usually measured as the percent of void space filled. In the near-term aftermath of a significant release of LNAPL to the environment, this value will generally be no more than 70% for coarse, pervious soils, and significantly less in fine grain soils.

An important sub-universe of LNAPL Saturation is *LNAPL Residual Saturation*. Similar to LNAPL Saturation, it is expressed in terms of percent, but can also be converted to units of mg/kg, to express an *LNAPL Residual Concentration* value. It is important to note, however, that there appear to be subtle variations in the exact meaning, measurement, and application of this term and metric in available literature.

Basically, LNAPL Residual Saturation/Concentration is meant to describe the amount of LNAPL that will be immobile in subsurface soils, and, by implication/extension:

- the *maximum* level of LNAPL that can exist in soil and not be mobile; and
- the *minimum* level of LNAPL that will remain in soil after the completion of conventional remedial recovery efforts (i.e., it is theoretically not possible to get the site any cleaner using these technologies).

Various researchers have published values for these metrics. It can however be difficult to ascertain the assumptions and conditions inherent in these presentations to ensure an "apples to apples" comparison. Of particular concern are:

- whether the data/values apply to the Vadose Zone or the Saturated Zone (some researchers have maintained that these values are somewhat or even substantially higher in the Saturated Zone);
- the amount of LNAPL that was present or was assumed at a site (large amounts of LNAPL – as observed in the oil industry – will "push" LNAPL deep into soil void spaces, which will result in high LNAPL Residual Saturation values not relevant to environmental LNAPL applications).

6.3 LNAPL Transmissivity (T_n)

LNAPL Transmissivity (or T_n) is a measure of how much and how quickly LNAPL can flow through soil, and it has become a popular metric as an indicator of LNAPL "recoverability." T_n values, expressed in units of ft^2/day, are determined on a site-specific basis using recovery/bail-down data from wells installed through an LNAPL smear zone. Results can vary with seasonal water table fluctuations, and familiarity with hydrogeology or sub-surface engineering may be necessary to obtain and apply these data in a competent manner.

The LNAPL Transmissivity metric provides a discrete numerical value that: (1) has nationwide regulatory precedent and acceptance; (2) has been confirmed and/or endorsed by a number of researchers; and (3) can indicate a point at which recovery (or further recover) of LNAPL may be considered "infeasible. The API and ASTM T_n methods listed in Section 13.0 – which include a method for direct-push micro-wells - are among the more recognized for determining LNAPL Transmissivity.

Regulatory programs in a number of states have closed or granted no further action status to sites that have demonstrated or achieved a T_n value of between 0.1 and 0.8 ft^2/day.

7.0 APPROACHES TO EVALUATE THE OCCURRENCE/MOBILITY OF LNAPL

The simplest indicators of the presence of LNAPL are visual observations of LNAPL/LNAPL discharge in structures, utilities, excavations, water bodies and/or wells. While such observations can confirm the existence of mobile LNAPL at a site or portion of a site, they cannot rule out the existence of mobile or potentially mobile LNAPL in other areas. To accomplish this objective, proactive steps must be taken to search for LNAPL. Traditional approaches in this regard typically focus on the advancement of subsurface borings, followed by the installation of monitoring wells and/or retrieval and subsequent evaluation of core samples. While many practitioners rely upon on monitoring wells to detect and evaluate LNAPL, others, concerned with perceived anomalies in well gauging data, advocate an approach focused primarily on the testing of soil/core samples.

Each approach has its own benefits and limitations, however, *both* can and usually do add value to characterizing LNAPL sites and assessing LNAPL behavior using LCSM/FFPM principles.

7.1 Use of Monitoring Well/Groundwater Data

Monitoring wells have been used for decades to document and evaluate the presence of LNAPL at contaminated sites. Until recently, however, these data have been widely misunderstood and misapplied.

Most researchers now believe that while observed/apparent LNAPL thickness in a well provides an approximation of the amount of *potentially* mobile LNAPL in the surrounding formation, this metric – in and of itself - is not a reliable indicator of the *actual* amount, mobility, or recoverability of LNAPL. In general, the observed/apparent thickness of LNAPL in a well exaggerates the amount of LNAPL that is in fact mobile and recoverable, especially in fine-grained soils.

Further complicating matters are fluctuating groundwater levels, which often lead to increased LNAPL thickness in wells during a low or falling water table condition. Some researchers have suggested that this effect is more pronounced in coarser-grained soils, because LNAPL drains more freely from larger pore spaces when transitioning from a two phase LNAPL-water system to a three phase LNAPL-water-air system.

The utility and limitations of monitoring well data are further summarized below:

DRAFT

Benefits

- While LNAPL well thickness measurements are not a reliable indicator of the amount, mobility, or recoverability of the LNAPL at a site, the presence of measurable LNAPL, regardless of thickness, in an excavation, boring or monitoring well does have important meaning: It indicates OHM concentrations are high enough to exist as separate-phase OHM and mobile enough as a separate-phase to migrate at least a short distance. Monitoring well installation is common, cost-effective, and necessary in any event at virtually all sites to characterize groundwater quality (e.g., dissolved phase contamination) as well as LNAPL physical properties used in applying FFPM/LCSM principles (e.g., density, viscosity). Moreover, permanent monitoring well installations allow for temporal monitoring programs over time to better characterize dynamic conditions (e.g., seasonal water table fluctuations).
- Monitoring well installations can be used to evaluate and/or institute LNAPL recovery (e.g., one time or long-term multiphase extraction efforts).
- When installed correctly (e.g., screen intervals extending through the entire smear zone into the water table), monitoring wells may be representative of a much greater area/volume of a formation than discrete cores or soil samples obtained from within the same zone.
- In the last several years, a number of regulatory agencies and other organizations have begun to publish guidelines on LNAPL characterization based upon LCSM/FFPM principles, most notably Texas, Alaska, British Columbia, ITRC, API, ASTM, among others listed in Section 13.0. All involve the use of LNAPL measurements in monitoring wells.

Limitations

- Many monitoring wells may not have been properly installed, developed, or maintained, which can lead to erroneous or unreliable results.
- Using well data and testing results for some of the more detailed analyses and determinations (e.g., recoverability and saturation distribution profiling) often involve complex calculations and/or computer modeling.
- LNAPL thicknesses may differ significantly in neighboring wells, possibly due to the inherent heterogeneities that limit any approach, and/or issues with well construction and maintenance.
- Uncertainties continue to exist on the affects of well diameter and installation techniques on representativeness and data comparability.

7.2 Use of Soil Borings/Core Samples/OHM Concentration Data

Similar to groundwater monitoring wells, soil borings have also been used for decades to evaluate LNAPL contaminated sites. Traditionally, these LNAPL characterization efforts have focused on obtaining and examining core samples and/or obtaining and quantifying LNAPL or LNAPL constituents in soil samples. The development of specialized direct push technologies incorporating Laser Induced Fluorescence (LIF), Membrane Interface Probes (MIPs), and Cone Penetrometer Technology (CPT) have

DRAFT

added further capabilities in this area, as have approaches to more fully characterize undisturbed core samples to obtain site-specific information on LNAPL saturation and mobility.

The biggest limitations with the use soil cores and/or samples are concerns over representativeness. Even at sites without fill and with relatively uniform soil conditions, heterogeneities and macro-features can create LNAPL "fingers" which are detectable only by a robust boring program. The relatively small volume and representativeness of soil cores are further reduced in cases where characterization relies upon OHM soil concentration data, given the small size of soil samples that are analyzed (e.g., typically only 10 grams), as depicted in **Figure 6**.

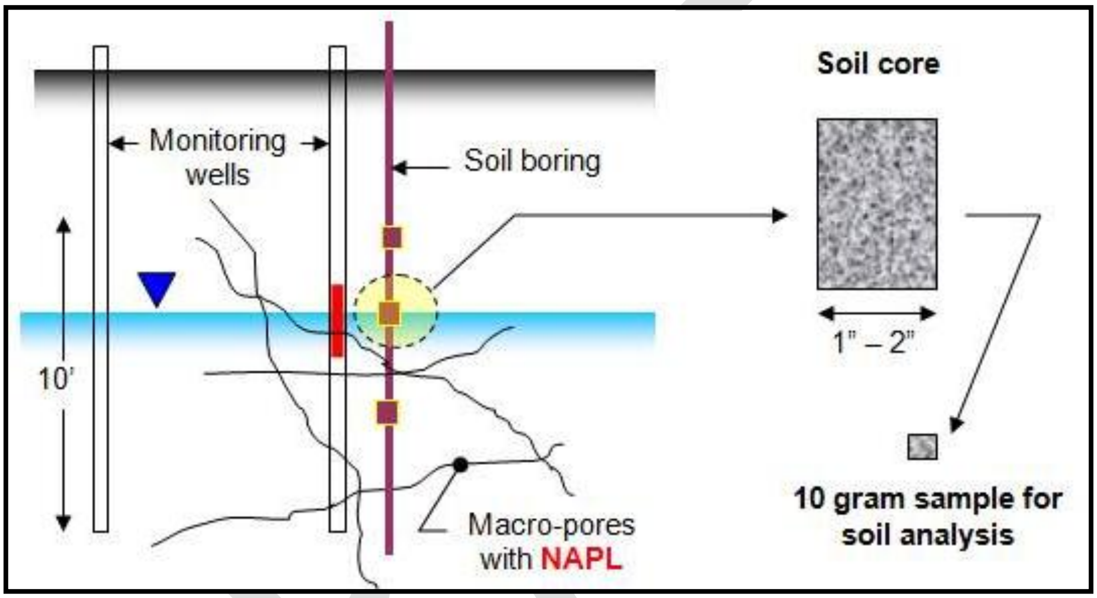

Figure 6: Representativeness Concerns for Soil Samples

The utility and limitations of approaches that rely on soil borings are further summarized below:

Benefits

- Actual site-specific soil data (e.g., TPH) often have already been obtained (and hence are available at no additional cost).
- Inexpensive and reliable field test methods are available to test for common LNAPL constituents (e.g., TPH).
- Soil data can provide a direct vertical profile of LNAPL saturation which exists in zones of variable saturation throughout the vertical column, including the Vadose Zone and the smear (or fluctuating) zone within the water table itself, where the highest LNAPL saturations usually exist.
- Soil sampling can provide a direct measure of physical soil properties necessary for applying FFPM/LCSM principles (e.g., porosity, grain size distribution and density).
- Comparing soil data to residual saturation is a simple indicator of potential LNAPL mobility.

Limitations

- A substantial amount of core/soil data may be needed to adequately characterize a site.
- Soil boring/sample data is specific to a point in time, and cannot be used to monitor variations in LNAPL conditions over time, which can be a key issue in the evaluation of mobility.
- Representative core samples for quantitatively evaluating LNAPL saturation conditions (particularly in the Saturated Zone) can be difficult and costly to obtain.

8.0 LINES OF EVIDENCE FOR LNAPL OCCURRENCE, MOBILITY, AND RECOVERABILITY

In Massachusetts, the fundamental nature of FFPM science combined with our tens of thousands of heterogeneous LNAPL sites - usually having shallow and seasonally varying groundwater elevations and/or decades-old urban development remnants - creates an unavoidable degree of complexity and uncertainty. Therefore, in many cases, *there may be no single definitive compliance criterion*. Rather, *the best evaluation of environmental protection* using this science often *depends on multiple lines of evidence*, which collectively form an improved and more informed professional opinion.

Below are summaries of the most widely acknowledged and simplest Lines of Evidence with regulatory precedent which can and should be used to assess LNAPL behavior for MCP-specific purposes. References for all of these Lines of Evidence (as well as others that also are suitable but more complex) are provided in Section 13.0, and familiarity with these references is recommended.

8.1 Release Date and Volume, LNAPL type, soil type

Basic and easily available information can provide a Line of Evidence in the evaluation of LNAPL occurrence and mobility/stability:

Release Date and Volume: Most LNAPL releases generally approach a condition of Macro-scale stability (often for both the LNAPL plume as well as the dissolved groundwater plume) within 1 to 2 years from when the release was terminated, absent preferred flow paths. It is informative to know the date of the release termination, at least to the extent of whether the release is “new” (e.g., less than two years) or “old” (e.g., more than five years). In addition, all other factors being equal, larger releases spread and migrate more than smaller releases.

LNAPL Type: LNAPL viscosity is inversely proportional to its mobility (a principle of Darcy’s Law.) Therefore, more viscous LNAPLs such as No. 4 and No. 6 oil are less mobile than diesel or gasoline in similar soils under similar conditions.

Soil Type: Because soil permeability is proportional to grain size, LNAPL flows more easily through larger grained soils than smaller grained soils. Therefore, absent preferred flow paths, LNAPL releases to low permeability/fine grained soils, such as clay, will migrate less than identical releases to coarse sand under the same conditions. Soil type also significantly affects pore entry pressures and residual saturation. Soil grain size testing (ASTM sieve analysis) and classification (Unified Soil Classification System or USCS) are usually inexpensive and should be considered, as appropriate.

8.2 Soil Concentration Data

In concept, if the concentration of OHM in soil does not exceed its Soil Saturation Concentration (C_{sat}), LNAPL will not be present. Even if LNAPL is present, it will not, in theory, be mobile if the LNAPL concentration (e.g., TPH) in soil is less than its Residual Concentration (C_{res}) value. When used properly, this comparison can be an inexpensive and valuable line of evidence for assessing LNAPL stability and recoverability.

One of the most widely referenced collections of C_{sat} and C_{res} data is by Brost et. al., in API Soil and Groundwater Bulletin No. 9, June, 2000. A summary table from this publication is reproduced, in part, in Table 1. As can be seen, C_{res} values reported in literature can vary significantly, even for the same petroleum product in similar soil types. This is reflective of the various assumptions/parameters/test conditions used to develop these values.

Reported values for Residual LNAPL Saturation often over-estimate values seen at MCP LNAPL sites, sometimes by orders of magnitude. This happens because Residual Saturation is directly proportional to Initial LNAPL Saturation, and many of the literature values reflect conditions in oilfield petroleum reservoirs where depths, pressures and initial oil (or LNAPL) saturations far exceed those at typical shallow environmental LNAPL sites.

For this reason, absent definitive knowledge on the origin and relevance of a published metric, only the most conservative values should be used when applying these data to MCP sites. Moreover, even when applying the most conservative values, it is important to carefully considered the representativeness of existing site data, given site/soil heterogeneity issues, sampling procedures, and small (e.g., 10 gram) sample sizes.

Although soil concentration data alone may not be sufficient to rule out the presence of mobile LNAPL at most sites, a robust data set with all soil concentration levels well below conservative Residual Concentration values would be a significant line of evidence in support of such a finding.

8.3 Product Thickness Measurements (Spatial and Temporal)

Possibly the most direct, reliable and simplest tool for demonstrating LNAPL (and dissolved phase) plume stability is with the use of groundwater monitoring wells. Defining the LNAPL “footprint” and demonstrating that it is not expanding are requirements in the 2014 MCP amendments. Valid use of these data as a Line of Evidence depends on: (1) proper well installation techniques (e.g., well screen intervals extending through the entire smear zone into the lowest water table elevation); (2) an adequate number and spatial distribution of wells to surround and define the “footprint” boundary; and (3) adequate sampling/gauging frequency to account for seasonal groundwater table fluctuations, which can affect the measured thicknesses (and the occurrence) of LNAPL significantly.

While data from a low and high groundwater table condition may be sufficient to rule out a LNAPL mobility issue, an adequate sampling frequency to evaluate and document the stability of a significant LNAPL plume is generally quarterly sampling/gauging over a two-year period, with events occurring at

Table 1: C_{sat} and Residual Saturation (C_{res}) Values in Soil (API, 2000)				
LNAPL	Soil Type	Theoretical	Measured	
		$C_{sat.\ soil}$ (mg/kg)	S_r (cm^3/cm^3)	$C_{res.\ soil}$ (mg/kg)
Gasoline	coarse gravel	57	0.01	1,000
Gasoline	coarse sand and gravel	102	0.01	1,697
Gasoline	medium to coarse	143	0.02	3,387
Gasoline	fine to medium sand	215	0.03	5,833
Gasoline	silt to fine sand	387	0.05	10,000
Middle distillates	coarse gravel	2	0.02	2,286
Middle distillates	coarse sand and gravel	4	0.02	3,879
Middle distillates	medium to coarse	5	0.04	7,742
Middle distillates	fine to medium sand	9	0.06	13,333
Middle distillates	silt to fine sand	18	0.1	22,857
Fuel oils	coarse gravel	2	0.04	5,143
Fuel oils	coarse sand and gravel	4	0.05	8,727
Fuel oils	medium to coarse	6	0.08	17,419
Fuel oils	fine to medium sand	9	0.1	30,000
Fuel oils	silt to fine sand	18	0.2	51,429
Light oil & gasoline	soil	9	0.18	40,800
Diesel & light fuel oil	soil	-	0.15	34,000
Lube & heavy fuel oil	soil	-	0.2	53,067
Gasoline	coarse sand	106	0.15 to 0.19	24,954 to 31,609
Gasoline	medium sand	106	0.12 to 0.27	19,767 to 44,476
Gasoline	fine sand	106	0.19 to 0.6	31,065 to 98,100
Gasoline	graded fine-coarse	106	0.46 to 0.59	80,500 to 103,250
Mineral oil	Ottawa sand	3	0.11	20,116
Mineral oil	Ottawa sand	3	0.14	25,602
Mineral oil	Ottawa sand	3	0.172	31,454
Mineral oil	Ottawa sand	3	0.235	42,975
Mineral oil	glacial till (NA)	3	0.15 to 0.28	13,500 to 25,200
Mineral oil	glacial till	3	0.12 to 0.21	10,800 to 18,900
Mineral oil	alluvium (NA)	3	0.19	61,071
Mineral oil	alluvium	3	0.19	61,071
Mineral oil	loess (NA)	3	0.49 to 0.52	154,000 to 163,800
Paraffin oil	coarse sand	-	0.12	27,000
Paraffin oil	fine sediments	-	0.52	147,086
Paraffin oil	Ottawa sand	-	0.11 to 0.23	20,382 to 42,618
O-Xylene	coarse sand	143	0.01	1,936
Gasoline	sandy loam	-	0.42 to 0.59	94,500 to 132,750

DRAFT

both high and low water table conditions. Determining adequate spatial coverage depends on the quality of site characterization and the site Conceptual Site Model, including the presence of heterogeneities and/or preferred flow paths.

8.4 Pore Entry Pressure Correlations

A well-known and referenced correlation is the relationship between soil type, LNAPL type, and "pore entry pressure" (which equates to the height of a column of LNAPL). Exceeding this pressure (or measured height of LNAPL) can indicate potential LNAPL migration. While "real world" site conditions are variable, this theory is sound and its use (with appropriate caution) as a Line of Evidence is simple and has regulatory precedent. Examples and applications of this approach have been published by Golder Associates (2008).

8.5 Recovery Decline Curve Analysis

Decline Curve Analysis is a formal and systematic method of recording and interpreting LNAPL well removal quantities over time (by bailing or pumping) to estimate the limit of recoverability. LNAPL recovery rates typically decline over time, as the volume of LNAPL in the ground decreases and its saturation approaches Residual Saturation. Eventually, an asymptotic limit of recovery or "point of diminishing returns" can be observed by graphs of: (1) recovery rate versus time; or (2) recovery rate versus cumulative recovery. Random periodic bailing of small quantities of LNAPL from a monitoring well may not generate enough data to perform this analysis, but if a trend can be observed, it could provide a valuable Line of Evidence.

Appendix I provides a LNAPL Screening Checklist and a Lines of Evidence Matrix that indicates the applicability of the different Lines of Evidence to evaluating the MCP LNAPL requirements for a Permanent or Temporary Solution.

9.0 FEASIBILITY EVALUATIONS

The 2014 Amendments to the MCP have established two new NAPL-related feasibility requirements:

- Per 310 CMR 40.1003(7)(a)(2.), in order to achieve a Permanent Solution, all NAPL with Micro-scale Mobility at a site must be removed if and to the extent feasible.
- In cases where a Permanent Solution cannot be achieved due to the presence of Non-Stable NAPL, in order to achieve a Temporary Solution, all Non-Stable NAPL and NAPL with Micro-scale Mobility at a site must be removed and/or controlled if and to the extent feasible (310 CMR 40.1003(7)(b)).

In both cases, feasibility evaluations must be conducted in accordance with the provisions of 310 CMR 40.0860, which specifies the procedures and criteria used to conduct feasibility evaluations at all MCP sites. Under this process and paradigm, a feasibility evaluation considers technical practicability *and* economics, integrated into a benefit/cost evaluation.

The benefits involved in removing LNAPL from the environment are clear: eliminating or reducing the possibility of future separate-phase mobility, eliminating or mitigating a potential source/continuing source of groundwater, soil gas, and indoor air contamination; eliminating or mitigating risks to human and ecological receptors. However, the costs of achieving these objectives can be high and at times disproportionate to the benefit, as documented by historic examples of costly LNAPL recovery systems that were only able to extract a few gallons of petroleum.

While acknowledging the inherent difficulties and uncertainties in these areas, under certain conditions, the need and benefit of attempting and continuing LNAPL recovery are high, and outweigh even significant costs. This includes sites where LNAPL:

- Is Non-Stable and/or
- is creating a vapor pathway that presents a significant risk of harm to human health, safety, or public welfare.

It is MassDEP's position that the feasibility evaluations conducted at these and similar sites of high concern consider the full range of NAPL remedial options, including excavation and conventional (hydraulic/vacuum recovery) technologies as well as alternative/innovative technologies (e.g., ISCO, soil flushing, soil heating), and that remedial operations deemed to be feasible are maintained for as long as it is necessary to achieve MCP standards.

In contrast to the above, many sites contain relatively small quantities of oil or waste oil LNAPL, where (i) the LNAPL has Micro-scale Mobility (only), (ii) the LNAPL is not creating vapor pathways of concern nor posing any other significant exposure threats, and (iii) the Source Elimination and Migration Control requirements of the MCP have otherwise been achieved. When these lesser concerns are combined with the long-term biodegradation potential of petroleum LNAPLs, the benefit/cost considerations are significantly altered. At these sites, it is MassDEP's position that:

- Feasibility evaluations may be limited to excavation of hot spots and conventional hydraulic/vacuum extraction technologies, although parties are encouraged to consider alternative techniques, where appropriate, for effectiveness and cost-effectiveness. Moreover, these recovery operations need not be attempted at sites where the amount and type of petroleum products and hydraulic conductivity of site soils suggest that only *a de minimis* quantity of LNAPL is likely to be recovered.
- Where instituted, remedial operations at these sites may be terminated when LNAPL Transmissivity decreases to a de minimis level and/or when asymptotic recovery conditions are observed and documented.

10.0 LNAPL RECOVERY

Conventional LNAPL recovery systems typically involve hydraulic and/or vacuum extraction technology with standardized "off the shelf" modular components. These include:

- Floating LNAPL Extraction/Skimming
- Dual Pump Liquid Extraction

- Soil Vapor Extraction
- Dual/Multi-phase Extraction

Excavation of "hot spots" can also be an effective conventional approach, especially for more viscous oils.

The selection of any particular system/combination of systems is dependent on a number of factors, including LNAPL fluid properties, soil properties, site conditions, remedial timeframes, and site/logistical constraints. There are many excellent references available on the evaluation/design/operation of these systems, including those cited in Section 13.0

In addition to these conventional approaches are a number of alternative/innovative technologies that often rely upon chemical transformations and/or modifications of LNAPL or media properties to enhance and maximize LNAPL recovery or destruction. These include:

- Soil Flushing;
- Steam/Hot Air Injection
- Electrical Resistance/Radio Frequency Heating
- In-Situ Oxidation (ISCO);

While often (though not always) more costly than conventional systems, these technologies can generally achieve a higher level of LNAPL recovery or control.

11.0 ACTIVITY AND USE LIMITATIONS (AULs)

A Permanent Solution may be achieved at a disposal site where some NAPL remains in the environment, provided a level of No Significant Risk has been achieved, Non-Stable LNAPL is not present (i.e., the overall LNAPL footprint is not expanding) and all LNAPL with Micro-Scale Mobility has been removed to the extent feasible. As required at 310 CMR 40.1012(2)(d), where the remaining LNAPL exhibits "Micro-scale Mobility", an AUL is required as part of the Permanent Solution.

The purpose of the AUL where there is NAPL with Micro-scale Mobility is to provide notice to the current and future property owners about the presence of NAPL so that appropriate measures can be taken to manage future exposure to the NAPL (e.g., to protect construction workers and/or to establish management plans for any NAPL that may flow into future excavations in the event of construction activities in the area of the NAPL that exhibits Micro-scale Mobility).

It is MassDEP's position that the presence of LNAPL in a groundwater monitoring well at an observed thickness equal to or greater than ½ inch is evidence of NAPL with Micro-Scale Mobility, necessitating the implementation of an AUL. This ½ inch metric applies to the maximum observed thickness in any monitoring well at a site during the 12 month period preceding the filing of a Permanent Solution, particularly during a period of a low or falling groundwater table.

At those sites where Micro-scale Mobility does not exist, an AUL could still be necessary to address other exposure/risk concerns related or unrelated to any LNAPL remaining at the site.

DRAFT

12.0 RECOMMENDED SIMPLIFIED APPROACH FOR PETROLEUM LNAPL SITES

The vast majority of LNAPL sites in Massachusetts are petroleum, with the most common petroleum spills being gasoline, diesel/#2 fuel oil, jet fuel, #4-#6 fuel oil, (automotive) waste oil, and lubricating oil. A relatively small number of LNAPL sites are chemical in nature (e.g., toluene). The simplified approach described in this section pertains only to oil and waste oil LNAPL. While voluntary, absent unusual site-specific factors, this approach will satisfy MCP performance standards to assess and address LNAPL mobility and recoverability. Parties electing to use other approaches are required to demonstrate that such techniques are scientifically valid.

12.1 Simplified Approach: Basis and Limitations

The recommended simplified approach consists of a series of investigatory and/or remedial steps with specified levels of efforts, data needs, and evaluation metrics. All decisions and conclusions shall be based on a preponderance of the evidence, i.e., that a condition is more likely than not.

To maximize its utility and application, the specific procedures and metrics incorporated into this simplified approach are designed to be applicable and protective at the vast majority of LNAPL sites. However, there may be unusual site conditions where these guidelines may not be sufficiently protective. The Department may, upon review of the use of this approach in such cases, require additional documentation and/or response actions to demonstrate that the requirements of the MCP are met.

The overall approach is summarized in **Figure 6**. Additional details on individual elements are provided below in Sections 12.2 though 12.8.

12.2 Simplified Approach: Characterization Methods and Level of Effort

The simplified approach relies upon site history research, observations, LNAPL thickness in groundwater monitoring wells, and conservative metrics obtained or adapted from other regulatory agencies and researchers.

- Site history information must be obtained for the area under investigation, including information and data on past storage or uses of petroleum products and petroleum spills.
- The installation of semi-permanent monitoring wells is required to allow repeated gauging over time. These monitoring wells must be screened across the groundwater fluctuation zone in overburden unconfined formations. After installation, all groundwater monitoring wells must be thoroughly developed.
- LNAPL thickness measurements must be made using an oil/water interface probe to eliminate accuracy concerns associated with measuring the thickness of LNAPL observed in a bailer. Each time a well is gauged for LNAPL thickness, the elevation of the groundwater/LNAPL interface must be observed and recorded, to ensure that the well screen is not above the groundwater table. Following a gauging event, at least one well volume of any LNAPL must be evacuated from the well and properly disposed or recycled.

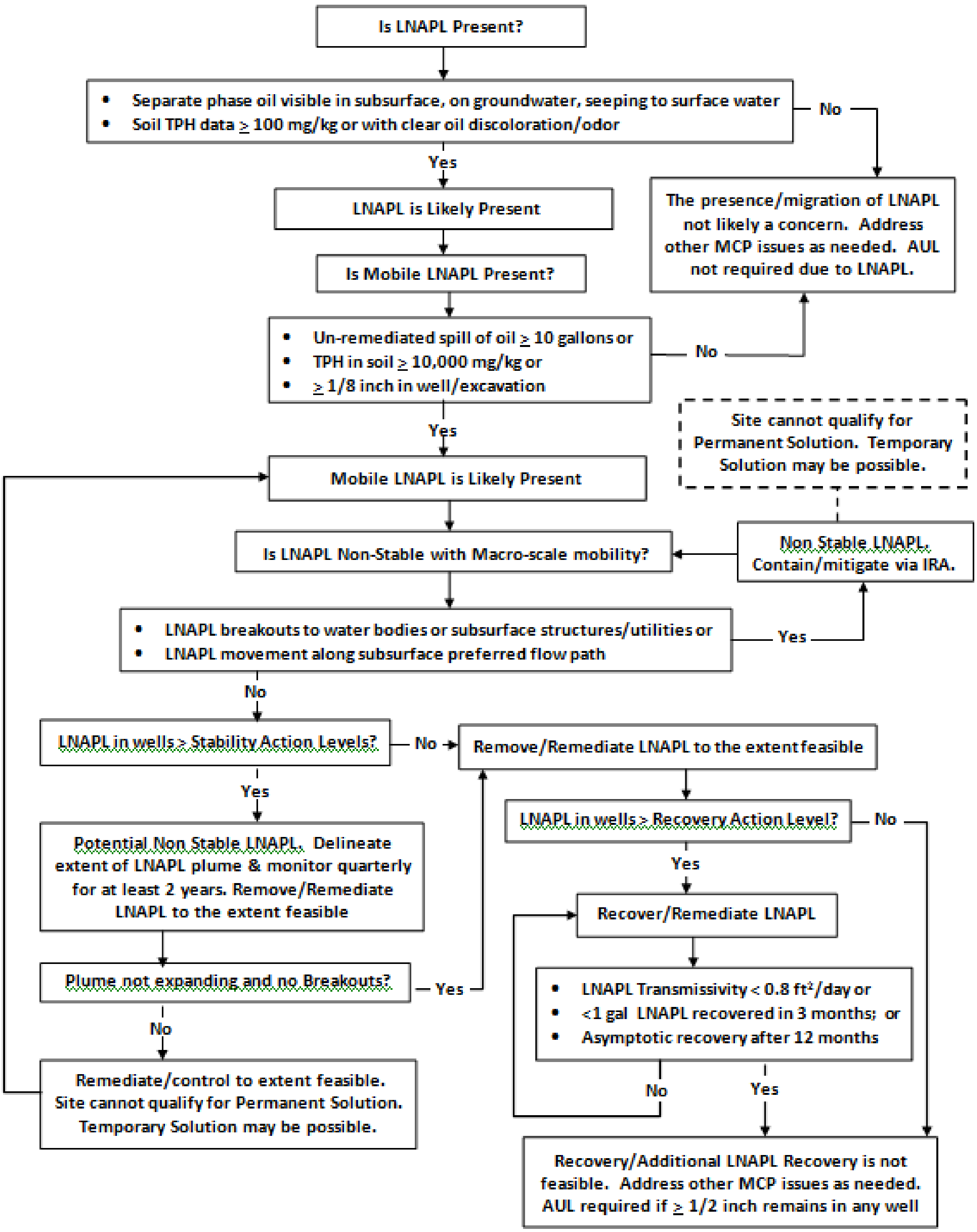

Figure 7: Recommended LNAPL Simplified Approach

- Baring unavoidable site constraints, the spacing of a monitoring well network must be in the range of 15 to 30 feet within the core and at the perimeter of the LNAPL plume. The placement of wells shall reflect the existence of sensitive LNAPL receptors, which include surface waters and buildings, sumps, utilities/subsurface structures within the groundwater fluctuation/LNAPL smear zone.
- At sites where Non-Stable LNAPL is present or potentially present, wells within and just downgradient of an identified LNAPL plume must be gauged on at least a monthly basis for a minimum of two years. At sites where Non-Stable LNAPL is not present or potentially present, wells within and just downgradient of an identified LNAPL plume must be gauged on at least a quarterly basis for a minimum of one year.
- For the purpose of obtaining soil data for comparison to Residual Soil Concentration metrics, the use of a GC/FID "Total Petroleum Hydrocarbon (TPH)" test method is acceptable for non-gasoline LNAPLs, as long chromatographic integration is to baseline, and the carbon range covered is at least C_9 through C_{24} for diesel/#2 Fuel, and C_9 thorough $_{36}$ for heavier oils. A "TPH" value can also be obtained by summation of Target Analytes and hydrocarbon ranges in the Massachusetts Extractable Petroleum Hydrocarbon (EPH) method.

12.3 Simplified Approach: Determining Whether LNAPL is Present

Visual observation of any amount of oil or waste oil in a subsurface excavation or monitoring well, or seeping into a proximate surface water body or building structure, is proof of the presence of LNAPL at a disposal site. Additionally, for the purposes of complying with this approach, a concentration of total hydrocarbons in soil in excess of 100 mg/kg (dry weight) shall be assumed to constitute proof of the likely presence of LNAPL.

At sites where LNAPL is not visually observed, proactive steps should be taken to determine its possible presence if:

- soils at the site are discolored with a clear petroleum odor;
- the site was previously used to store more than household quantities of petroleum products (i.e., quantities of petroleum use and storage beyond a home heating oil tank, and gasoline/oil used for lawn/yard/car maintenance);
- credible evidence exists that a release of an LNAPL occurred or likely occurred at the site; or
- available groundwater, soil gas, or indoor air data at the site exceed MCP reporting thresholds for petroleum constituents.

These proactive investigatory steps may include soil borings, test pits, groundwater monitoring wells, and/or soil cores/samples. The level of effort in this regard should reflect the nature and quantities of petroleum products of interest, site complexity, and presence of sensitive receptors, consistent with the Conceptual Site Model.

If it is determined that LNAPL is not present at a site, other MCP concerns and requirements must be addressed as applicable.

DRAFT

12.4 Simplified Approach: Determining Whether Mobile LNAPL is Present

At sites where LNAPL is present or likely present, investigatory actions must taken to ascertain its potential mobility. For the purposes of this approach, an LNAPL is or is likely to be mobile if:

- A spill of a total of 10 or more gallons of oil/waste occurred or likely occurred at the site in the previous 10 years which was not promptly and adequately remediated via removal of the LNAPL, applied sorbents, and/or impacted soils;
- Total hydrocarbons in soil exceed 10,000 mg/kg (via a TPH test method or via the summation of fractions and Target Analytes from a VPH or EPH test method); or
- Equal to or greater than 1/8 inch of LNAPL is identified any groundwater monitoring well or in any excavation at the site.

A finding that mobile LNAPL is present or likely present at a site necessitates an evaluation of its mobility per Section 12.5 and recoverability per Section 12.6

12.5 Simplified Approach: Determining Whether Mobile LNAPL at a Site is Non-Stable

At sites where mobile LNAPL is present or likely present, initial investigatory actions must be promptly taken to determine whether it is Non-Stable.

These initial efforts shall focus on proactive and systematic observations in proximate (< 50 – 100 feet) buildings, utilities, and surface water bodies. At sites at which a significant (>100 gallons) release of LNAPL had occurred within the previous 2 years, subsurface explorations must be undertaken to determine if the LNAPL plume is expanding. These explorations must include, as appropriate, the advancement of soil borings, installation of groundwater monitoring wells, and/or excavation of test pits.

As a result of these efforts, or any other available observational/site assessment data, an LNAPL present in the subsurface shall be deemed Non-Stable if:

- It is discharging or periodically discharging to a Surface Water;
- It is discharging or periodically discharging into a building, including drainage sumps within such building;
- It is discharging or periodically discharging into a utility structure, including manholes, vaults, and piping/conduits;
- It is observed to be present within a preferred flow path, including in the pervious backfill of utility conduits or in bedrock fracture; and/or
- Its footprint is expanding as described below.

For the purposes of this approach, “periodically” means any discharge that occurs one or more times within a 12 month period.

DRAFT

Even when LNAPL is not actively discharging to surface waters or other receptor of concern, it may still meet the MCP definition of Non-Stable if it is moving as a separate phase through subsurface porous media (i.e., the LNAPL footprint is expanding, and Macro-Scale stability has not been achieved). This is most likely to occur when the amount of oil/waste oil within a subsurface LNAPL plume is sufficient to overcome pore entry pressures within adjacent impacted media. While not a perfect instrument, the measured thicknesses of LNAPL in a monitoring well network is generally the most readily available surrogate to judge whether this condition may exist, and researcher have developed well thickness criteria as a means to evaluate this concern.

Accordingly, for the purposes of this approach, a condition of Non-Stable LNAPL may exist at a site if, during the course of investigating an LNAPL spill or obtaining data for other site assessment purposes, LNAPL is observed/measured in any boring, excavation, or groundwater monitoring well at any time at a thickness equal to or greater than the Stability Action Levels contained in **Table 2**.

Table 2: Stability Action Levels (Golder Associates, 2008)

Soil Type*	Characteristic Fraction	Percent Fines (silt and clay)	LNAPL Thickness (inches)
Coarse sand or gravel	> 20% Coarse sand	< 3	**1.2 inch**
Coarse sand or gravel	> 20% Coarse sand	3-10	**2 inches**
Medium sand	Medium sand	< 10	**4 inches**
Fine sand	Fine sand	< 10	**8 inches**
Silty sand	Sand	> 10	**12 inches**

*If soil at a site does not match any of the listed types, judgment shall be used to select an available category and metric that is a reasonably conservative approximation.

If an appropriate Stability Action Level in Table 2 is exceeded, two years of quarterly monitoring is required to determine whether a condition of Non-Stable LNAPL is present. This monitoring effort shall include the installation of additional monitoring wells if:

- a thickness value is exceeded by more than a factor of 2 in any well/excavation within 50 feet of a potential subsurface LNAPL receptor if no additional wells are already present in this zone, with potential subsurface LNAPL receptors defined as Surface Waters and building/building sumps and utility structures located within the groundwater fluctuation (LNAPL smear) zone; or
- one or more key monitoring wells in the area of interest are not screened over the water table fluctuation (smear) zone.

LNAPL above the notification threshold at 310 CMR 40.0311(5) shall be reported to MassDEP within 2 hours and above the notification thresholds at 310 CMR 40.0313(1) or (4)(f)3. within 72 hours. All such notifications require the implementation of Immediate Response Actions to assess the condition and, as appropriate, to implement immediate measures to contain the LNAPL and prevent or mitigate exposures. See the Summary of LNAPL-related notification requirements in **Section 3**.0.

Quarterly monitoring of wells shall consist of gauging wells for the present and thickness of LNAPL. Only wells that straddle the groundwater fluctuation (smear) zone have relevance in this evaluation effort. Following each gauging round, at least one well volume of LNAPL must be evacuated from each well, in an attempt to maintain reasonable communication with the surrounding formation.

In addition to gauging monitoring wells, assessment efforts shall also include the inspection of potential subsurface receptors within 50 feet of the presumed edge of the LNAPL plume.

Following this two-year monitoring program, it can be concluded that there is no current indication of Non-Stable LNAPL if:

- Subsurface LNAPL did not discharge to surface waters, buildings, building sumps, or subsurface utility conduits and/or structures; and
- Observed LNAPL thickness levels did not consistently or significantly increase in downgradient monitoring/sentinel wells.

12.6 Simplified Approach: Determining the Feasibility of Removing or Containing Mobile LNAPL

A feasibility evaluation must be conducted in accordance with the provisions of 310 CMR 40.860, as further discussed in Section 9.0.

In applying this simplified approach at sites where the feasibly evaluation is appropriately limited to conventional hydraulic/vacuum LNAPL recovery technologies, the graph contained in **Figure 8** may be used to conclude that such LNAPL recovery efforts are infeasible.

In applying the criteria in **Figure 8**:

- The Hydraulic Conductivity value selected for the site shall be based upon the most pervious/ transmissive soils present within the LNAPL plume. Conservative (i.e., more permeable) values shall be assumed at sites where this determination is based upon soil type, not site-specific testing data.
- The Dynamic Viscosity value (C_p) value may be selected on the basis of the type of oil/waste oil present, with conservative (lower) values assumed when a mixture of products is present or when the identity of the LNAPL is not conclusively established.
- The maximum observed thickness of LNAPL in any monitoring wells over a 1-2 year gauging cycle shall be determined and be used as the basis for determining the thickness level in the graph.
- Values between the indicated inches may be extrapolated, within the range of 0.125 to 5.0 inches.
- A condition of infeasibility may be assumed in cases where the intersection of the Hydraulic Conductivity (cm/sec) and Dynamic Viscosity (cP) values is above the indicated or extrapolated thickness line.

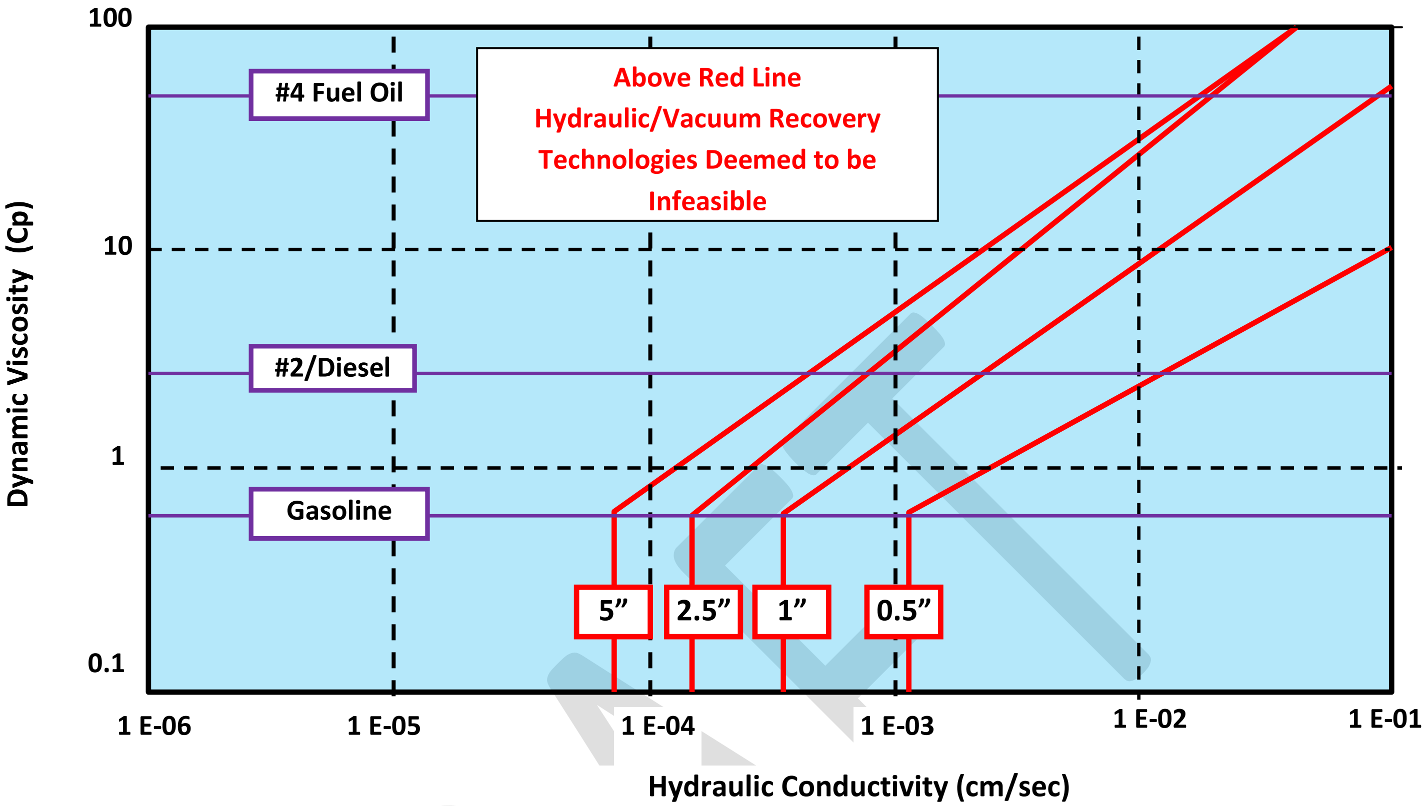

Figure 8: Conditions of Infeasibility of LNAPL Recovery by Conventional Technologies (based on API, 2007)

- Thickness levels less than 1/8 (0.125) inch are deemed to be infeasible to recover for all petroleum products in all media. Under the terms of this simplified approach, it is not possible to conclude that it is infeasible to recover LNAPL at sites where the maximum LNAPL thickness level is greater than 5 inches.

At those sites where remedial actions are not required to address stability, vapor, or other critical LNAPL concerns, a finding that it is not feasible to institute conventional recovery operations may allow the achievement of a Permanent Solution, assuming all other (non-LNAPL) MCP requirements and standards have been satisfied.

12.7 Simplified Approach: Determining when it is No Longer Feasible to Continue Conventional LNAPL Recovery Operations

The continued operation of a properly designed, constructed, and operated conventional LNAPL recovery system can be deemed infeasible if and when:

- The LNAPL Transmissivity value (T_n) in all recovery wells is shown to be less than 0.8 ft^2/day; or
- The total volume of LNAPL recovered at a site is less than 1 gallon in any 3 month period; or

- A decline curve analysis of at least 12 months of cumulative LNAPL recovery data demonstrates an asymptotic condition.

At sites where conventional LNAPL recovery operations are being conducted to address stability, vapor, or other critical LNAPL concerns, such a finding would necessitate the need to evaluate and implement alternative/innovative technologies.

At all other sites, such a finding may allow the achievement of a Permanent Solution, assuming all other (non-LNAPL) MCP requirements and standards have been satisfied.

12.8 Simplified Approach: Achieving a Permanent Solution

An LNAPL site can achieve a Permanent Solution if:

- Non-Stable LNAPL is not or longer present, as articulated in Section 12.5;
- LNAPL has been recovered or removed to the extent feasible, as articulated in Section 12.6; and
- all other MCP requirements and standards have been met, including those related to Source Elimination or Control, Migration Control, site characterization and risk assessment.

In accordance with the provisions of 40.1012(2)(d), an Activity and Use Limitation (AUL) is required for sites where a Permanent Solution has been achieved and LNAPL with Micro-Scale Mobility is present. The presence of LNAPL with Micro-scale Mobility shall be assumed if the maximum observed thickness in any groundwater monitoring well was equal to or greater than ½ inch, at any time in the 12 months previous to the filing of the Permanent Solution, including during times of a low or falling water table.

13.0 RECOMMENDED SUPPORTING TECHNICAL REFERENCES

MassDEP's Recommended Supporting Technical References for some of the more comprehensive detailed and technically sound works from other regulatory agencies, organizations and experts are listed below. Familiarity with these references is recommended and may be necessary to properly assess complex LNAPL sites. While MassDEP does not necessarily or explicitly endorse (or even agree with) each and every single conclusion or thesis in these works collectively they clearly represent "accurate and up-to-date methods, standards and practices, equipment and technologies which are appropriate, available and generally accepted by the professional and trade communities conducting response actions in accordance with M.G.L. c. 21E and 310 CMR 40.0000 under similar circumstances" as articulated by the MCP's Response Action Performance Standard 310 CMR 40.0191(2)(b).

MassDEP LNAPL Workgroup
http://www.state.ma.us/dep

Licensed Site Professionals Association (LSPA)
LNAPL and The Massachusetts Contingency Plan Part II; Prepared by: LSPA Technical Practices Committee; July, 2008.
http://www.LSPA.org

MassDEP:

Characterizing Risks Posed by Petroleum Contaminated Sites: Implementation of the VPH/EPH Approach; Policy #WSC-02-411; October 31, 2002.

Interstate Technology & Regulatory Council (ITRC)

Archived On-Line Classes: http://cluin.org/live/archive/default.cfm?display=all&group=itrc#

LNAPL Training Part 1: An Improved Understanding of LNAPL Behavior in the Subsurface - State of Science vs. State of Practice
http://www.itrcweb.org/Training#LNAPLPart1

LNAPL Training Part 2: LNAPL Characterization and Recoverability - Improved Analysis - Do you know where the LNAPL is and can you recover it?
http://www.itrcweb.org/Training#LNAPLPart2

LNAPL Training Part 3: Evaluating LNAPL Remedial Technologies for Achieving Project Goals
http://www.itrcweb.org/Training#LNAPLpart3

Tech/Reg Guidance Document:
Evaluating LNAPL Remedial Technologies for Achieving Project Goals; December 2009.
http://www.itrcweb.org/Documents/LNAPL-2.pdf

American Petroleum Institute (API)

Brost et al.; *Non-Aqueous Phase Liquid (NAPL) Mobility Limits in Soil*; API Bulletin No. 9; June 2000. (API changing web site, use their search box with "Bulletin 9")
http://www.api.org/ehs/groundwater/upload/09_bull.pdf
http://www.clu-in.org/conf/itrc/iuLNAPL/030513_residual.pdf

Light Non-Aqueous Phase Liquid (LNAPL) Resource Center (including: *Interactive LNAPL Guide; LNAPL Distribution and Recovery Model (LDRM); and LNAPL Transmissivity Workbook - Calculation of LNAPL Transmissivity from Baildown Test Data.)*
http://www.api.org/environment-health-and-safety/clean-water/ground-water/lnapl

American Society for Testing and Materials (ASTM International)

ASTM E2856-13 *Standard Guide for Estimation of LNAPL Transmissivity*
http://www.astm.org/Standards/E2856.htm

DRAFT

ASTM D7242/D7242M-06(2013)e1 Standard Practice for Field Pneumatic Slug (Instantaneous Change in Head) Tests to Determine Hydraulic Properties of Aquifers with Direct Push Groundwater Samplers http://www.astm.org/Standards/D7242.htm

Adamski, Mark, P.G.

Adamski, Mark, Kremesec, Victor, and Charbeneau, Randall, Charbeneau *Residual Saturation: What is it? How is it Measured? How Should We Use it?*, National Ground Water Association and American Petroleum Institute, 20th Conference, Petroleum Hydrocarbons and Organic Chemicals in Groundwater, 2003.
http://www.clu-in.org/conf/itrc/iuLNAPL/030513_residual.pdf

Adamski, et. al., *LNAPL in Fine-Grained Soils: Conceptualization of Saturation, Distribution, Recovery, and Their Modeling*, Groundwater Monitoring and Remediation, Vol 25, no.1, Winter 2005 pages 100–112

Johnston, C., Adamski, M., 2005, Relationship Between Initial and Residual LNAPL Saturation for Different Soil Types, 2005 Petroleum Hydrocarbons and Organics Chemicals in Ground Water Conference, Costa Mesa, CA, August 18-19, 2005, Proceedings.
http://www.ngwa.org/_bdc/http___www_ngwa_org/GWOL%20Data_1.aspx?RecordID=653494

Applied NAPL Science Review "*Applied NAPL Science Review* (ANSR) is a scientific ejournal that provides insight into the science behind the characterization and remediation of non-aqueous phase liquids (NAPLs) using plain English"; Hawthorne, Adamski, Charbeneau, Garg, Johnson, Kirkman, Malander.
http://www.h2altd.com/ansr

British Columbia Ministry of Environment

PROTOCOL 16 FOR CONTAMINATED SITES: Determining the Presence and Mobility of Nonaqueous Phase Liquids and Odorous Substances; May 2010.
http://www.env.gov.bc.ca/epd/remediation/policy_procedure_protocol/protocols/pdf/protocol-16.pdf

Report on: Approaches and Methods for Evaluation of Light non-Aqueous – Hydrogeological Assessment Tools Project; Submitted to: Ministry of Environment; February 2006.
http://www.sabcs.chem.uvic.ca/LNAPL%20Guidance%2002-15-06%20rev.pdf

Alaska Department of Environmental Conservation (ADEC)

Maximum Allowable Concentration, Residual Saturation, and Free-Product Mobility Technical Background Document and Recommendations; Prepared for Alaska Statement of Cooperation Working Group; September 2006 http://dec.alaska.gov/spar/csp/docs/soc/4_max_allow_conc.pdf

Texas Commission on Environmental Quality

Risk-Based NAPL Management; RG-366/TRRP-32; Revised July 2013.
http://www.tceq.texas.gov/publications/rg/rg-366_trrp_32.html/at_download/file

DRAFT

DRAFT

APPENDIX I
LNAPL SCREENING CHECKLIST & LINES OF EVIDENCE MATRIX

LNAPL SCREENING CHECKLIST

Date/age of release:
LNAPL type:
LNAPL volume:
Soil Type:
Max Soil TPH range

- ☐ Do monitoring wells adequately cover the LNAPL footprint?
  Spatially:__________ wells/SF
  Temporally: __________ sampling events over ______ years
  Represent both High and Low water Table elevations
  Well completion/screen through entire smear zone into GW table?

- ☐ Existing soil TPH Data:
  Spatially: ______ locations over ______ SF
  Vertically: sample depth intervals______
  Samples in Vadose Zone? Smear Zone? GW table?

- ☐ Have CSM requirements (including LNAPL CSM) been met?

- ☐ Is the LNAPL plume stable?
  Based on what Line(s) of Evidence?

- ☐ Has LNAPL been "removed if and to the extent feasible?"
  Based on what Line(s) of Evidence?

- ☐ Does LNAPL with Micro-scale mobility remain?
  Based on what Line(s) of Evidence?

- ☐ Is an AUL Required? (1/2 inch criterion exceeded)

- ☐ Have all other MCP Source Control and risk-based closure requirements been met (including soil, groundwater and vapor phases)?

DRAFT

LINES OF EVIDENCE	**MCP PERMANENT and TEMPORARY SOLUTION REQUIREMENTS**			
	LNAPL presence & characterization using LCSM	Non-Stable LNAPL (or macro-scale mobility)	LNAPL Removal "if and to the extent feasible"	LNAPL Micro-scale Mobility and AULs
Site/release history, LNAPL type, soil type, TPH data	**X**	**X**		**X**
Product Thickness Measurements (spatial and temporal)	**X**	**XX**		**XX**
Pore Entry Pressure Correlations		**X**		
Recovery "Decline Curve"			**X**	
Transmissivity (ASTM)	**X**		**XX**	
Comparison of TPH to Residual Saturations	**X**	**X**	**X**	
Supporting References	**X**	**X**	**X**	**X**

LINES OF EVIDENCE MATRIX

X indicates the Line of Evidence is relevant in the evaluation of the MCP Performance Standard

XX indicates the Line of Evidence is relevant and favorably weighted in the evaluation of the MCP Performance Standard

DRAFT