Commonwealth of Massachusetts
Executive Office of Energy & Environmental Affairs

Department of Environmental Protection

One Winter Street Boston, MA 02108 • 617-292-5500

Charles D. Baker
Governor

Karyn E. Polito
Lieutenant Governor

Matthew A. Beaton
Secretary

Martin Suuberg
Commissioner

LIGHT NONAQUEOUS PHASE LIQUIDS (LNAPL) AND THE MCP: GUIDANCE for SITE ASSESSMENT AND CLOSURE
Policy #WSC-16-450

This document provides guidance on investigating, assessing, understanding, and addressing the presence and migration of Light Nonaqueous Liquid (LNAPL) at disposal sites regulated under Massachusetts General Law chapter 21E and 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.

Paul W. Locke
Assistant Commissioner
Bureau of Waste Site Cleanup

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LIST OF ACRONYMS & ABBREVIATIONS

ASTM	American Society for Testing and Materials
API	American Petroleum Institute
AUL	Activity and Use Limitation
C_{res}	Residual LNAPL Concentration (mg/kg)
C_{sat}	Soil Saturation Limit (mg/kg)
CPT	Cone Penetrometer Technology
CSM	Conceptual Site Model
DNAPL	Dense Nonaqueous Phase Liquid
EPH	Extractable Petroleum Hydrocarbons
FID	Flame Ionization Detector
FFPM	Fluid Flow in Porous Media
GC/FID	Gas Chromatography/Flame Ionization Detector
ITRC	Interstate Technology and Regulatory Council
IRA	Immediate Response Action
ISCO	In-Situ Chemical Oxidation
LCSM	LNAPL Conceptual Site Model
LNAPL	Light Nonaqueous Phase Liquid
LIF	Laser Induced Fluorescence
LSP	Licensed Site Professional
LSPA	LSP Association
MCP	Massachusetts Contingency Plan

MassDEP	Massachusetts Department of Environmental Protection
MIP	Membrane Interface Probes
NAPL	Nonaqueous Phase Liquid
NSR	No Significant Risk
OHM	Oil or Hazardous Material
PID	Photo-ionization Detector
S_o	LNAPL Saturation (volume/volume fraction)
S_{or}	Residual LNAPL Saturation (volume/volume fraction)
TPH	Total Petroleum Hydrocarbons
T_n	LNAPL Transmissivity
UST	Underground Storage Tank
VPH	Volatile Petroleum Hydrocarbons

1.0 PURPOSE, SCOPE, AND APPLICABILITY

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 Massachusetts General Law chapter 21E (M.G.L c. 21E) and the Massachusetts Contingency Plan (MCP) at 310 CMR 40.0000.

This document is designed to assist a wide range of MCP users with varying degrees of expertise in hydrogeology or sub-surface engineering in implementing MCP requirements related to LNAPL site evaluation and closure. Specifically, this guidance:

- provides a description of LNAPL science and behavior in the subsurface;
- provides details of applicable parameters that are based on the fundamental principles of Fluid Flow in Porous Media (FFPM), consistent with the LNAPL Conceptual Site Model (LCSM);
- summarizes MCP provisions and performance standards related to LNAPL;
- outlines tools and metrics for the evaluation of LNAPL-contaminated sites using a *multiple Lines of Evidence* approach to assess regulatory compliance;
- 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 alternative site-specific approaches.

This guidance applies to disposal sites regulated under the MCP where LNAPL is or may be 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).

The scope of this guidance is limited to the direct impacts of LNAPL and its bulk movement in and through porous media. Beyond these direct impacts, LNAPL has secondary impacts 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. These secondary impacts must also be adequately addressed in compliance with the MCP. Refer to other agency documents for guidance on these secondary impacts.

2.0 LNAPL SCIENCE AND BEHAVIOR IN THE SUBSURFACE

Subsurface LNAPL behavior in soils is governed by the fundamental principles of multi-phase Fluid Flow in Porous Media (FFPM), which are based primarily on Darcy's Law. Used for decades in the oil industry, FFPM principles have been developed and applied in recent years to the evaluation of oil contaminated sites. 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. This work informs what is commonly called the LNAPL Conceptual Site Model (LCSM).

While a detailed description and discussion of all concepts, terms, and metrics in this area is beyond the scope of this document, a summary of key terms is provided in **Appendix I** and a general overview of LNAPL behavior and parameters is provided below.

2.1 General Overview

Soil is a porous media. At uncontaminated sites, the void (*pore*) spaces between soil particles above the water table in the *Vadose Zone* are filled with a mixture of air and water. In the *Saturated Zone* below the water table, pore 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 pore spaces in the Vadose Zone. LNAPL follows the path(s) of least resistance, preferentially moving into any interconnected air-space “finger” structures that may be present. Water droplets 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, inhibiting LNAPL migration into these smaller pores (see **Figure 1.**)

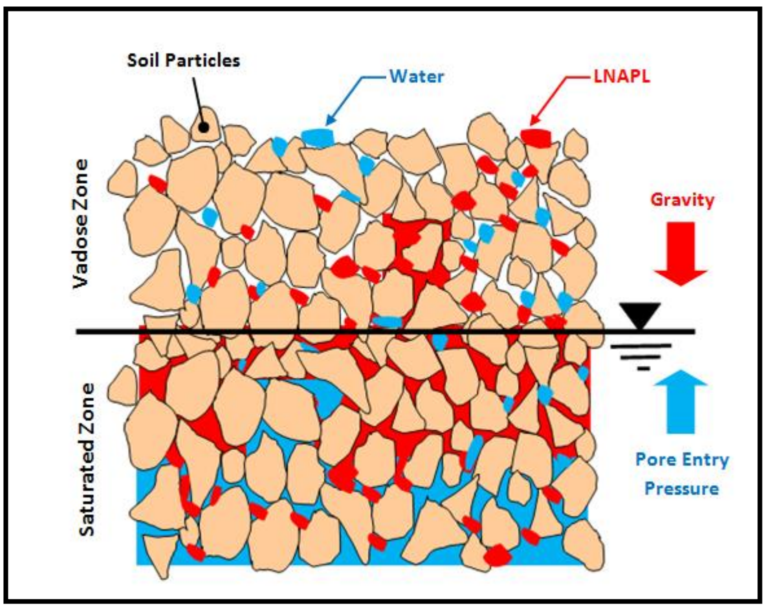


Figure 1: NAPL Movement through Porous Media

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

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*) that are arresting the movement of the globules, and some LNAPL will enter into the pore spaces, displacing some, but not all, of the water. Additional transport of LNAPL to the water table interface will continue to displace more LNAPL into the Saturated Zone pore spaces, vertically and laterally, based upon these force dynamics.

Within 1 to 2 years from the time that an LNAPL spill/release is halted, (e.g., no additional petroleum product is entering the environment), a quasi-equilibrium condition will generally be established where, absent the presence of preferred flow paths (e.g., in fill material, around underground utilities), the overall LNAPL footprint will cease expanding laterally or vertically. At this point, the LNAPL will be in what is sometimes referred to as a state of *macro-scale stability.* On a localized scale, however, LNAPL movement into and out of pore spaces (and possibly into and out of wells) within the stable LNAPL footprint may persist largely due to fluctuations in hydraulic conditions. That is, LNAPL may continue to exhibit micro-scale mobility within an LNAPL plume that is stable on a macro-scale.

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 pore spaces, creating a so-called "pancake" of pure LNAPL at the water table. This is now known to be an incorrect and oversimplified description 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.

Although the exact shape and nature of this dynamic multi-phase condition is variable and site-specific, it is often described as a "shark fin" straddling the water table interface in a perpendicular orientation (see **Figure 2).**

The vertical interval from the bottom of the LNAPL-impacted zone to the highest groundwater elevation level in the impacted area following the release of the LNAPL is known as the Smear Zone.

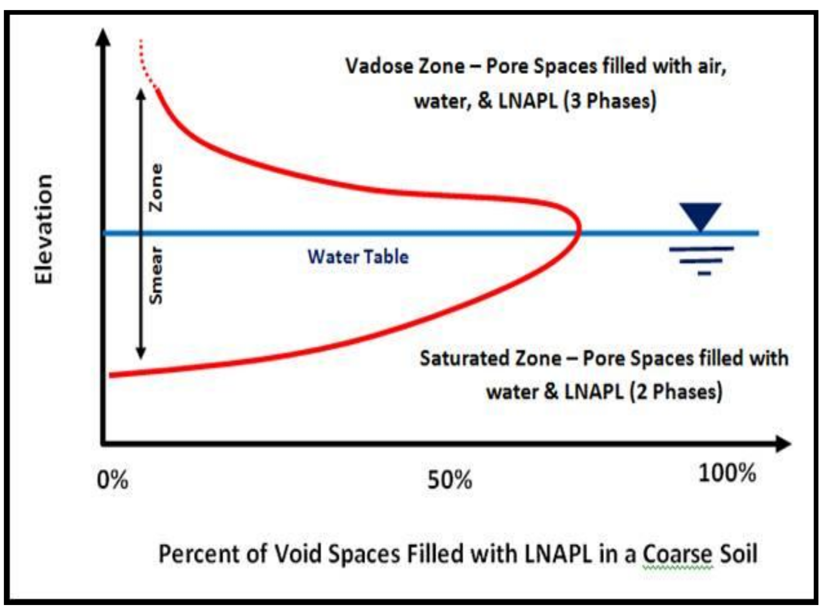


Figure 2: LNAPL Saturation at Water Table Interface

In this model, the outline of the shark fin represents the percentage of soil pore spaces filled with LNAPL. The tip of the fin occurs near the water table interface (i.e., where the largest accumulation of

LNAPL occurs). Even the most heavily LNAPL-impacted soil pore spaces are typically no more than 70% filled with LNAPL, with the remaining 30% filled with water and/or air. Pore LNAPL saturation sharply decreases 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 pore 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 displaced by the migrating LNAPL globules. In finer grained soils, the maximum LNAPL saturation value could be less than 70%, as water present in smaller pore spaces is more closely held in place via capillary forces, making it harder for migrating LNAPL globules to displace.

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 (i.e., specific gravity, viscosity), the properties of the porous media (i.e., porosity, grain size distribution), and the resulting interactions (i.e., interfacial forces).

While halting the bulk movement (or macro-scale mobility) of LNAPL is an important milestone in controlling contaminant migration at a site, it may only be the first step. Additional migration of contaminants can continue to 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.

2.2 Soil Saturation Limit (C_{sat})

Oil or hazardous material (OHM) chemical constituents in 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 estimate this equilibrium condition and corresponding maximum OHM "saturation" concentrations at which no additional contaminant molecules can be accommodated in the soil organic carbon, soil pore water, or soil air space. Accordingly, a measured OHM 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 the concentration of hydrocarbons (or other LNAPL materials) in soil, as this is the medium where most of the partitioned mass will generally reside. Soil Saturation Limit concentration values (C_{sat}) have been developed by researchers for a number of common LNAPL materials and soils. The LSP Association (LSPA) published a helpful graphic, provided here as **Figure 3,** that depicts approximate correlations between OHM concentrations and soil saturation levels and 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.

While C_{sat} values are typically orders of magnitude below those required for LNAPL mobility, 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 understood LNAPL to be present only if it is visually observed as droplets in soil or groundwater.

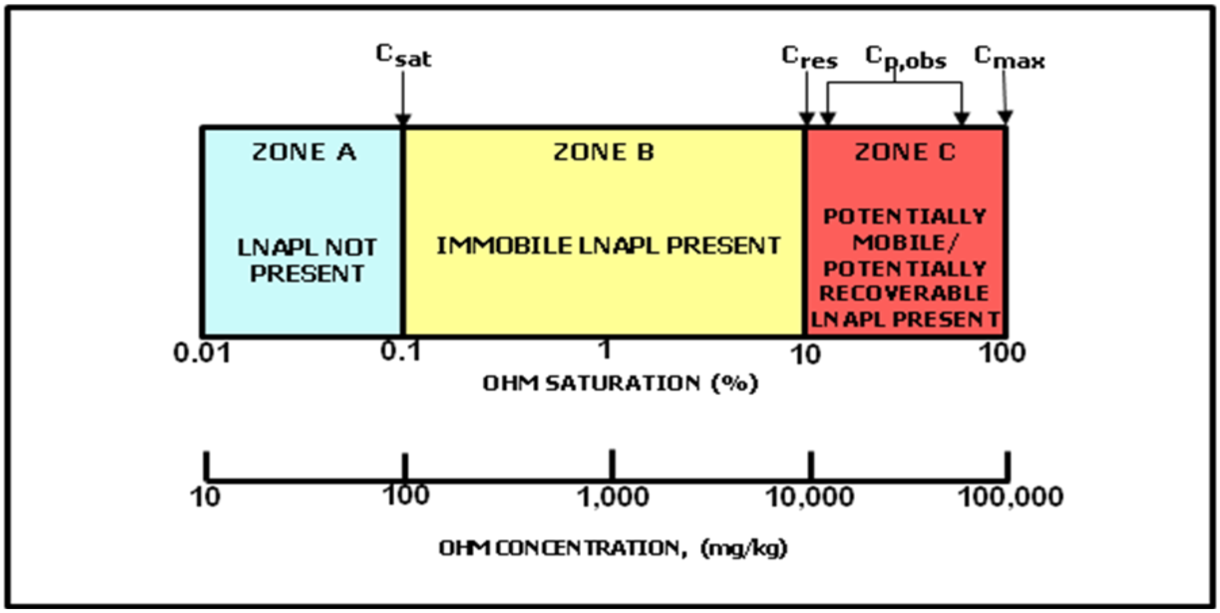


Figure 3: LNAPL Continuum in Soil (LSPA, 2008)

NOTE: correlations shown here between concentrations and saturations are approximate and depend on specific soil and LNAPL physical properties

2.3 LNAPL Saturation (S_o) and Residual LNAPL Saturation (S_{or})

LNAPL Saturation (S_o) refers to the amount of LNAPL contained in a volume of subsurface porous media at a given point in time, usually reported as the percent or fraction of pore space filled with LNAPL. 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 LNAPL Saturation threshold is *Residual LNAPL Saturation (S_{or}),* which is the LNAPL saturation below which LNAPL is theoretically immobile in subsurface soils, and, by 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 conventional technologies, discussed further in Section 4.2).

Residual LNAPL *Saturation* can be converted to Residual LNAPL *Concentration* in units of mg/kg (shown as C_{res} in Figure 3) and compared, as a Line of Evidence, to traditional TPH data as described in Section 4.1.4. This conversion depends on specific soil and LNAPL physical properties (e.g., soil porosity, soil bulk density, LNAPL density,) and therefore the correlated values of concentration and saturation shown in Figure 3 are only approximate (e.g., 10,000 mg/kg is approximately equal to 10% S_o.) This conversion is more accurately presented in equation, tabular and graphical form in *Applied NAPL Science Review* (January 2012 edition) and as an electronic "calculator" in The American Petroleum Institute (API) *Interactive LNAPL Guide's* "TPH to NAPL Saturation Conversion Tool." Both of these references are provided in Section 6.

Various researchers have published values for these metrics since the early 1960s. A collection of these values appears in API's *Soil and Groundwater Bulletin No. 9* (Brost et al., 2000) which has been referenced, expanded, and re-published numerous times for industrial and environmental purposes. A summary table from this publication is reproduced, in part, as **Table 1** below.

Table 1: Soil Saturation Limit (C_{sat}), Residual LNAPL Saturation (S_{or}), and Residual LNAPL Concentration (C_{res}) Values in Soil (API, Brost et al., 2000)

LNAPL	Soil Type	Theoretical	Measured	
		C_{sat} soil (mg/kg)	S_{or} (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

These data illustrate that, in general, Residual LNAPL Saturation (S_{or}) and hence Residual LNAPL Concentration (C_{res}) decreases with increasing soil grain size and with decreasing LNAPL specific gravity and viscosity. For example, coarse grained soils with gasoline would tend to have lower Residual Saturation values than fine grained soil with No. 2 fuel oil. This relationship, represented in a graphic published by the LSPA is provided below in **Figure 4**.

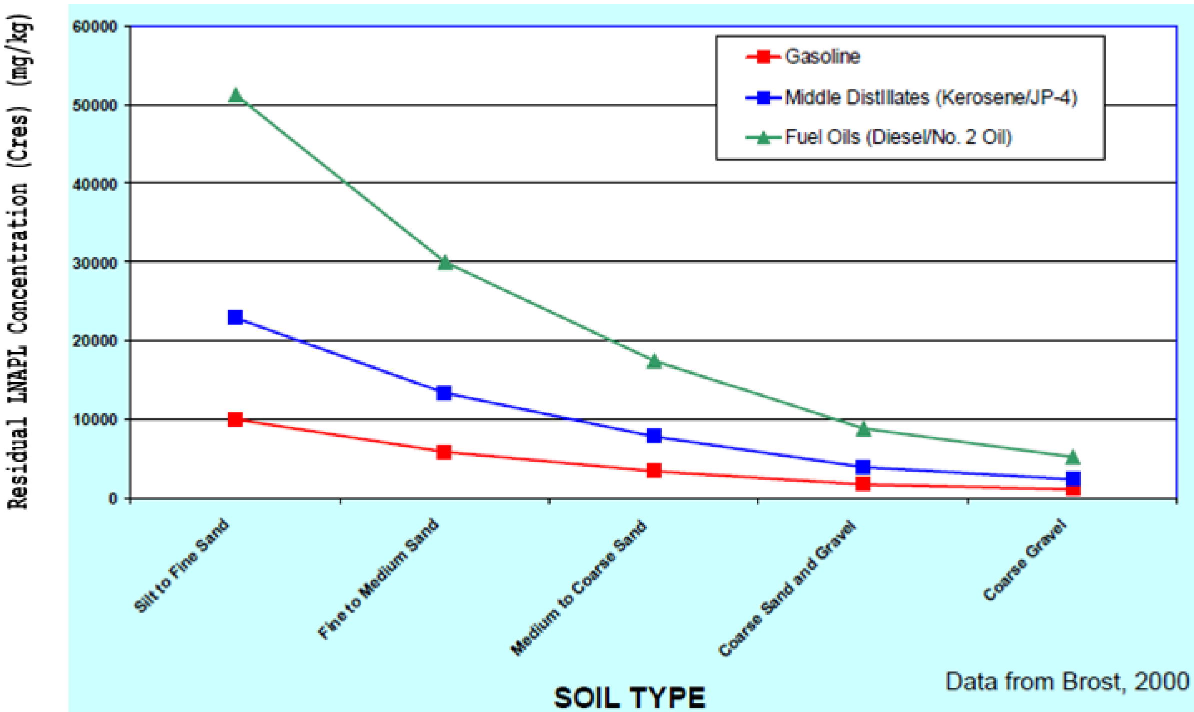


Figure 4: Typical Residual Saturations as a Function of Soil Type and LNAPL Type (LSPA, 2008)

However, there is little or no background information provided on how several of the "Residual" values in Table 1 were determined, and there appear to be subtle but significant variations in the exact meaning, measurement, and application of this term and metric in scientific literature and actual practice. Therefore, it can be difficult to ensure an "apples to apples" quantitative comparison, not only among the historical data sets themselves but also between them and LNAPL (or TPH) data from present day LNAPL site assessments. Of particular concern:

- The measurement and use of Residual Saturation originated in the oil industry for evaluating potential production from petroleum reservoirs where significant factors such as depths, pressures and initial oil (or LNAPL) saturations far exceed those at LNAPL-contaminated sites regulated under the MCP. Such differences, if not taken into account, can limit the usefulness of these comparisons. In addition, recent studies applying Residual Saturation concepts to LNAPL site cleanups have indicated that "Residual" values for identical soil and LNAPL types can vary by up to an order of magnitude, or more, depending on "initial" LNAPL saturations. This principle applies to BOTH laboratory and actual field saturations.

- Residual Saturation is a function of several hydrogeologic and fluid dynamics factors as well as the saturation history of the soil. The greater the degree of initial LNAPL Saturation, the greater the Residual LNAPL Saturation can be expected to be, particularly for fine-grained soils. Thus, Residual LNAPL Saturation values can vary across an affected area both laterally and vertically.

- There is uncertainty over the origin and appropriate use of various data/values in the Vadose Zone versus the Saturated Zone (e.g., while some researchers have maintained that Residual values are somewhat or even substantially higher in the Saturated Zone, there are differing opinions on the representativeness of various sampling and laboratory methods.)

There are a variety of analytical methods for determining saturation and TPH concentration, which are included in the references in Section 6.0 (e.g., Adamski, ITRC, API, and MassDEP). MassDEP has published a protocol for quantifying petroleum hydrocarbons using MassDEP's Volatile Petroleum Hydrocarbon (VPH) and Extractable Petroleum Hydrocarbon (VPH) Methods (#WSC-10-320, Compendium of Quality Control Requirements and Performance Standards for Selected Analytical Protocols, 2010). Approximate TPH concentrations can be obtained for gasoline-contaminated soil samples in the VPH method by summing the Unadjusted C_5-C_8 Aliphatic Hydrocarbon and Unadjusted C_9-C_{12} Aliphatic Hydrocarbon ranges. For #2 fuel oil/diesel samples, approximate TPH concentrations can be obtained using the EPH method by calculation of the method-defined “unadjusted TPH” concentration. In all cases, it is incumbent of the data user to account for the assumptions and limitations in all sample collection and analyses relative to the accuracy, precision, sensitivity, representativeness and overall usability of all analytical data pursuant to the requirements of 310 CMR 40.0017, 40.0191(2), and 40.1056(2)(k). (Additional guidance related to evaluating and documenting data usability and representativeness in support of MCP closure decisions is provided in #WSC-07-350, MCP Representativeness Evaluations and Data Usability Assessments, 2002.)

2.4 LNAPL Transmissivity (T_n)

LNAPL Transmissivity (T_n) is a measure of how much and how quickly LNAPL can flow through soil and is typically expressed in units of ft^2/day. T_n has become a popular science-based metric that correlates more reliably with LNAPL mobility and recoverability than in-well LNAPL thickness. It has been confirmed and/or endorsed at the state and national level as a point at which conventional recovery (or further recovery) of LNAPL may be considered infeasible.

Tn is best determined by testing wells using the methods described in ASTM 2856 and referenced in Section 6.0. However, well testing results assume and rely on several factors including: (1) proper well completion and screening throughout the Smear Zone; (2) equilibrium well conditions before testing; (3) steady-state flow during testing; (3) quantification of any effects of perched and/or confined aquifer conditions; and (4) application of appropriate quantitative models. Familiarity with hydrogeology or sub-surface engineering may be necessary to obtain and apply these data in a competent manner.

3.0 MCP PERFORMANCE STANDARDS FOR NAPL

M.G.L. c. 21E and the MCP address releases of 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 poses No Significant Risk to human health, safety, public welfare, and the environment, at present and for the foreseeable future. Both the statute and MCP require that releases of OHM be remediated if and to the extent feasible. Where a Permanent Solution is not currently feasible, one or more Temporary Solutions must be implemented prior to such time that a Permanent Solution is 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, µg/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 science related to NAPL behavior in the environment as well as difficulties in ascertaining compliance with the ½ inch standard led MassDEP to address NAPL with an updated approach in MCP amendments that became effective in June 2014.

The 2014 provisions eliminated the ½ inch Upper Concentration Limit, and instead focused on NAPL movement and recoverability. Two mobility terms have been added and 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 visibly 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

Note: For purposes of this document, “stable” (as opposed to “Non-stable”) and “macro-scale” (as opposed to “Micro-scale”) are sometimes used when discussing the mobility concepts behind the above MCP-defined terms.

While not specifically identified in the MCP, there are two additional possibilities to consider with respect to characterizing NAPL contamination (i.e., in addition to Non-stable NAPL and NAPL with Micro-scale Mobility):

> **Some amount of NAPL is present but it does not have either macro- or micro-scale mobility**, due to its limited mass, its properties, and/or the properties of the porous environmental media; and
>
> **No NAPL is present** (i.e., all OHM are present only in a sorbed, dissolved, or vapor state).

<u>Permanent and Temporary Solutions</u>

The forms of NAPL existence (or non-existence) and NAPL mobility at a disposal site have implications as to the type of closure that can be achieved under the MCP.

- At sites with **Non-stable NAPL, *a Permanent Solution cannot be achieved***, as specified at 40.1003(7)(a)(1.), but a Temporary Solution, as specified at 40.1003(7)(b), may be achieved if the Non-stable NAPL and NAPL with Micro-scale Mobility is removed and/or controlled if and to the extent feasible.

- At sites where the remaining NAPL is limited to **NAPL with Micro-scale Mobility, *a Permanent Solution may be achieved***, but only after NAPL is removed if and to the extent feasible, as specified at 40.1003(7)(a)(2.) and described in Section 4.2, and all other MCP cleanup requirements relating to source and migration control and risk management are achieved. If NAPL with Micro-scale Mobility remains, ***an AUL is required***, as specified at 40.1012(2)(d) and described in Section 4.3.

- At sites where NAPL is not/no longer present or where **remaining NAPL does not have Micro-scale Mobility, *a Permanent Solution may be achieved without an AUL.***

Beyond these bulk mobility concerns, an additional MCP closure consideration that is particularly relevant to sites where NAPL is present involves an evaluation of the degree to which the NAPL is acting as a continuing source of contamination to surrounding environmental media via dissolution or volatilization processes.

- Under the "Source Elimination and Control" provisions of 310 CMR 40.1003(5), ***a Permanent Solution cannot be achieved*** unless NAPL constituting a Source of OHM Contamination, as that term is defined at 310 CMR 40.0006, is eliminated, or if not eliminated, eliminated to the extent feasible and controlled. For a Temporary Solution, NAPL that constitutes a Source of OHM Contamination must be eliminated or controlled to the extent feasible.

- Under the "Migration Control" provisions of 310 CMR 40.1003(6), ***a Permanent Solution cannot be achieved*** unless plumes of dissolved OHM in groundwater and vapor phase OHM in the Vadose Zone are stable or contracting. For a Temporary Solution, such plumes must be stable or contracting or otherwise controlled or mitigated to the extent feasible.

The achievement of the requirements at 310 CMR 40.1003(5), (6) and (7) with respect to LNAPL must be documented in a Permanent Solution Statement as required by 310 CMR 40.1056(2)(c), (d) and (e), and in a Temporary Solution Statement as required by 310 CMR 40.1057(2)(c), (d) and (e).

Notification

The required timeframe (2-hour, 72-hour or 120 day) for providing notification to MassDEP of NAPL in the environment depends on its location, mobility, observed thickness and volatility.

There are two NAPL-related conditions that require reporting to MassDEP **within 2 hours**:

- A sudden, continuous, or intermittent breakout or discharge of oil or waste oil NAPL that results in the appearance of 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**:

- **NAPL equal to or greater than ½ inch** in a groundwater monitoring well, excavation, or other subsurface structure **at any location** (310 CMR 40.0313(1)); and

- **Volatile NAPL equal to or greater than 1/8 inch** in a groundwater monitoring well, excavation, or other subsurface depression **within 30 feet of a School, Daycare or Child Care Center or occupied residence** (310 CMR 40.0313(4)(f)3.).

MassDEP considers volatile NAPL to include gasoline, petroleum napthas, mineral spirits, kerosene, jet fuels and any petroleum mixture where more than 25 percent of component hydrocarbons (by mass) have a boiling point below 218°C (424°F), and any single component (or predominantly single-component) LNAPL with a boiling point below 218°C. Diesel fuels, #2 fuel oils and heavier fuels oils (#3 - #6), waste oils, and lubrication oils are not considered volatile LNAPL.

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

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

In those cases where a NAPL condition triggers a 2- or 72-hour notification obligation, an Immediate Response Action (IRA) must be conducted to assess the NAPL and, as appropriate, to implement immediate measures to contain the NAPL and prevent or mitigate exposures (310 CMR 40.0412(3) and (4)).

<u>**Conceptual Site Model (CSM) and Assessment**</u>

It is standard practice among environmental professionals to use a Conceptual Site Model to organize site information and to develop site assessment and remedial plans. 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 CSM definition at 310 CMR 40.0006 includes a specific reference to sites where "NAPL is or may be present" to emphasize the necessity of understanding and applying the principles of Fluid Flow in Porous Media to characterize and remediate NAPL sites. The CSM for an LNAPL site that takes into consideration these principles is also referred in this guidance as the LNAPL CSM or LCSM.

> 310 CMR 40.0006 (12)
>
> **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.***

The MCP contains the following specific requirements related to documenting or considering the CSM:

- 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));

- provide an updated CSM at the conclusion of the Phase II Comprehensive Site Assessment (310 CMR 40.0835(4)(i)); and

- provide a succinct summary of the CSM in support of a Permanent or Temporary Solution (310 CMR 40.1056(2)(b) and 310 CMR 40.1057(2)(b), respectively).

For NAPL sites, the CSM documentation requires addressing FFPM principles in describing the presence, distribution, behavior 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.”

A flowchart summarizing these MCP Performance Standards for NAPL is provided in **Figure 5**.

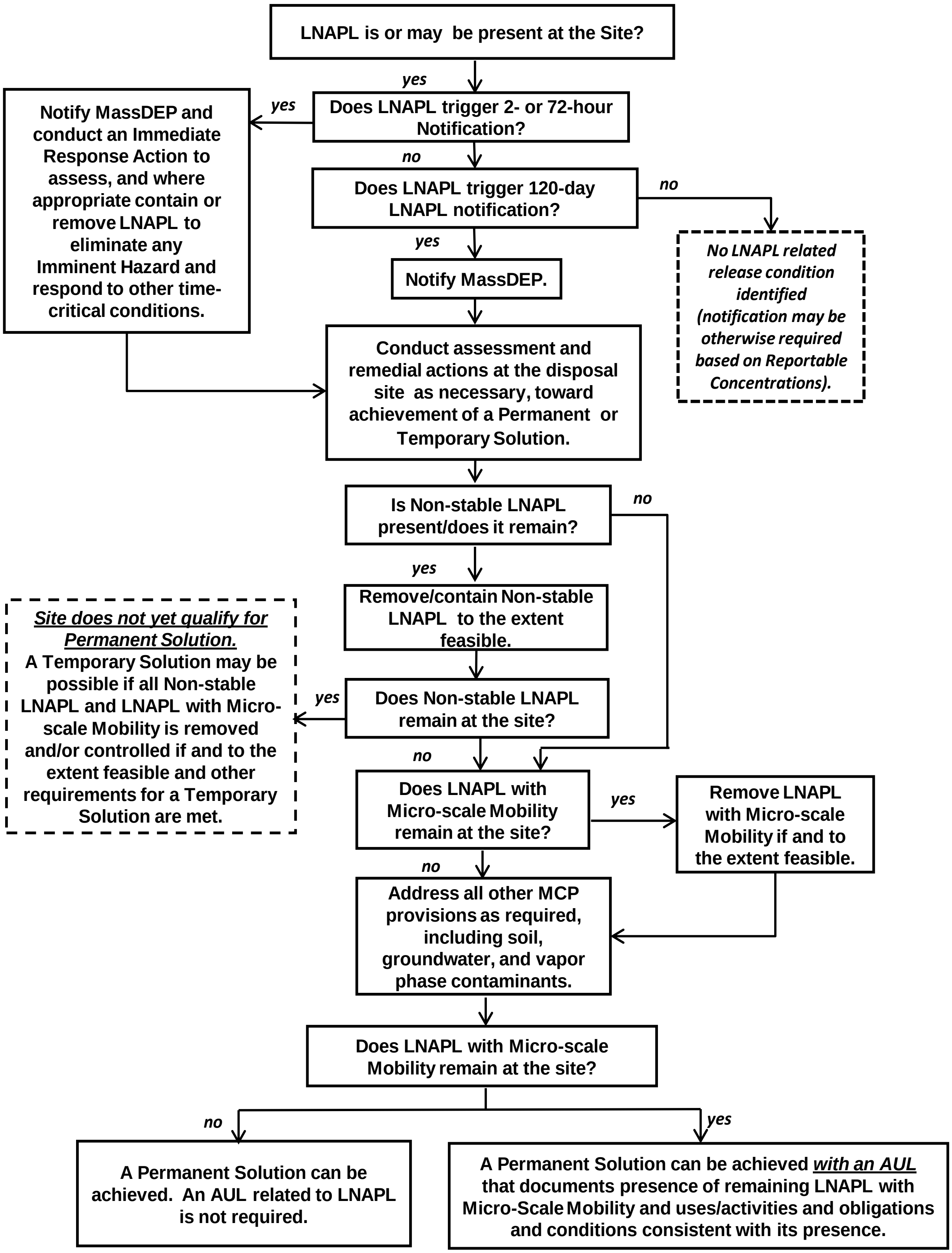
4.0 COMPLYING WITH MCP PERFORMANCE STANDARDS FOR LNAPL

Any scientifically justified approach may be used to demonstrate compliance with the MCP requirements related to mobility and recoverability at LNAPL-contaminated sites, as long as it is consistent with the fundamental principles of Fluid Flow in Porous Media and the LNAPL Conceptual Site Model.

At LNAPL sites in Massachusetts, heterogeneous subsurface conditions, typically shallow and seasonally variable groundwater elevations and/or the remnants of urban development often create an unavoidable degree of complexity and uncertainty for site characterization and the evaluation of LNAPL mobility and recoverability. Moreover, LNAPL site characterization may include well data (e.g., LNAPL thicknesses, Transmissivity, Decline Curve Analysis) and/or soil data (e.g., hydrocarbon concentrations, LNAPL Saturation, core observations, direct-push testing). While well and soil data each have limitations (as described further in Section 4), **both can be and usually are necessary to characterize LNAPL sites and assess LNAPL behavior using LCSM/FFPM principles.** Therefore, evaluating compliance and supporting closure decisions for LNAPL sites often *depends on multiple Lines of Evidence* using a variety of data types which address the complexity of such sites and collectively form an improved and more informed professional opinion.

Many organizations, experts and regulatory agencies have published comprehensive technical documents for assessing LNAPL behavior in the sub-surface, including those publications recommended by MassDEP in Section 6.0. General familiarity with these references is recommended and is particularly important in the case of sites where compliance is not evaluated and supported using the Simplified Approach in Section 5.0.

Figure 5 MCP Performance Standards for LNAPL



Regardless of the approach used, the level of effort and amount of data needed to adequately demonstrate compliance with MCP provisions must be commensurate with disposal site conditions (310 CMR 40.1004) and include review and discussion of representativeness and data usability in the Permanent or Temporary Solution (310 CMR 40.1056(2)(k) and 40.1057(2)(k), respectively). While decisions of this nature are inherently site-specific and involve professional judgment, as a general rule, data needs will be greatest for LNAPL 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, day care/child care centers, surface waters and/or other sensitive receptors.

Below are summaries of widely acknowledged Lines of Evidence that MassDEP recognizes as appropriate for assessing LNAPL behavior and supporting closure decisions for LNAPL sites under the MCP.

Appendix II provides an 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.

4.1 Lines of Evidence for LNAPL Occurrence, Mobility, and Recoverability

4.1.1 Basic Information

Basic release information, described below, can provide useful Lines of Evidence in the evaluation of LNAPL occurrence and mobility/stability.

Release Date: Most LNAPL releases generally stabilize (i.e., the LNAPL footprint stops expanding) within 1 to 2 years from when the active release was terminated, absent preferred flow paths. With some notable exceptions, such as when MtBE is present, this often applies to the dissolved groundwater plume as well. Therefore, it is informative to know the date of the release termination to ascertain whether or not the release is “new” (i.e., less than two years).

Release Volume: 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). The 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.

Visual Evidence: The past or current appearance of LNAPL (including sheens) in the subsurface, sumps, groundwater and/or surface water or odors/discolorations clearly related to LNAPL are simple indicators of the past or current presence or potential presence of LNAPL in the environment.

4.1.2 Presence/Potential Presence of LNAPL

Visual observations of LNAPL anywhere in the subsurface or on surface water, both current and in the past, indicate the presence or potential presence of LNAPL which warrants additional assessment.

At sites where separate-phase LNAPL has not been visually observed, assessment to determine its possible presence in the subsurface is indicated where:

- there is knowledge of LNAPL releases;
- soil odors consistent with LNAPL are observed; or
- available groundwater, soil gas, or indoor air data at the site exceed MCP reportable conditions for the LNAPL constituents.

Proactive investigatory steps include, as appropriate, soil borings, test pits, groundwater monitoring wells, groundwater samples, soil cores/samples, and/or other scientifically sound site characterization technologies. The level of effort must reflect the nature and quantities of LNAPL, site complexity, and presence of sensitive receptors, consistent with the Conceptual Site Model.

As described in Section 2, petroleum LNAPL may be present in the soil matrix at TPH concentrations as low as 100 mg/kg (or less,) although it is usually immobile at concentrations below approximately 10,000 mg/kg**.** Generally, for the purpose of planning and conducting assessments for the potential presence of mobile petroleum LNAPL, TPH data less than 1000 mg/kg can be considered insignificant.

4.1.3 Well Data

One of the most direct, reliable and common approaches for identifying the presence, extent, and mobility of LNAPL at a site and demonstrating that its footprint is not expanding is the use of groundwater monitoring wells. LNAPL parameters obtained from monitoring wells include measured LNAPL thickness, LNAPL recovery rates, and LNAPL Transmissivity. While some types of well data have been widely misunderstood and misapplied, a number of LNAPL assessment techniques using these data are recognized for their specificity and regulatory precedent as Lines of Evidence in environmental applications.

Product Thickness Measurements (Spatial and Temporal): 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. Regardless of its thickness, the presence of measurable LNAPL in an excavation, boring or monitoring well does have significant 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 (i.e., LNAPL with Micro-scale Mobility).

Valid use of these data as an LNAPL characterization 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 LNAPL "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 low and high groundwater table conditions may be sufficient to rule out an LNAPL mobility issue, ***an adequate sampling frequency to evaluate and document the stability of a significant LNAPL plume is generally quarterly sampling/gauging over at least a one-year period, with sampling events occurring at both high and low water table conditions, and where water table measurements are not influenced by significant recent rainfall***. Acceptable methods to assess groundwater elevation range include well gauging and evaluation of redoxymorphic features.

Determining adequate spatial coverage depends on the site Conceptual Site Model and the complexity of site conditions, including the presence of heterogeneities and/or preferred flow paths. Ideally, an LNAPL plume worst-case stable boundary would be delineated by monitoring wells that *never* contain LNAPL. However, periodic appearance of LNAPL near the edge of the plume does not necessarily mean that the LNAPL plume is Non-stable NAPL. While surrounding the LNAPL plume (at least the down-gradient side) with monitoring wells that never show LNAPL would provide the most decisive indicator of stability, installing additional wells solely for this purpose is generally not necessary. However, if such additional sentinel and/or down-gradient wells already exist and/or are otherwise needed for groundwater quality or other assessment objectives, their inclusion in an LNAPL plume monitoring program would generally be expected.

Pore Entry Pressure Correlations: Another well-known and referenced use of measured LNAPL thicknesses in a well is the correlation between soil type, LNAPL type, and "pore entry pressure," which equates to the height of a column of LNAPL (i.e., LNAPL thickness). 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. While in-well LNAPL thicknesses exceeding these criteria may indicate a need for further investigation, they do not necessarily indicate non-stability (i.e., there may be other site-specific reasons reflected in the LCSM for such exceedances). However, thicknesses below these criteria can serve as one possible Line of Evidence to help support a conclusion that the LNAPL is stable. Examples and applications of this approach, prepared by Golder Associates, were published by the British Columbia Ministry of Environment (2006 and 2010) and are referenced in Section 6.

Recovery Decline Curve Analysis: Decline Curve Analysis is a formal and systematic method of recording and interpreting LNAPL well removal quantities over time to estimate the limit of recoverability. It is important to note that LNAPL recovery is NOT necessarily required to demonstrate that LNAPL has been recovered to the extent feasible (i.e., the infeasibility of further recovery). Using actual recovery data, however, can be an effective method for this demonstration.

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; (2) recovery rate versus cumulative recovery; or (3) cumulative recovery versus time.

To demonstrate that the LNAPL recovery has achieved a "point of diminishing returns," data should show that the recovered volume of LNAPL for a given duration of treatment/recovery has stabilized and the graph of the recovered volume versus time of operation should fit a curve generally defined by the equation $Q_t = Q_f + Q_0\ e^{-kt}$, where:

- Q_t is the recovery rate at time t;
- Q_f is the final recovery rate which the curve approaches asymptotically;
- Q_0 is the recovery rate at time of initial treatment/recovery;
- e is 2.710, the base of natural logarithms;
- k is the coefficient representing the exponential factor which indicates how fast the recovered volume approaches Q_f; and
- t is the time from some fixed starting point.[1]

In applying Recovery Decline Curve Analysis, the following points may be helpful:

- The lower limb of the curve should be substantially linear, and the slope of the final portion of the curve should approach zero. The x and y axes should be of a scale that minimizes data distortion and appropriate statistical methods should be applied to support the conclusion that the monitoring data fit the curve.

- The x-intercept of a linear best-fit line through the latter portion of the Recovery Decline Curve represents the maximum volume of LNAPL that is theoretically recoverable via a given system operating under a given set of conditions.

- A semi-log plot of cumulative recovery versus time can allow a projection of how much longer a given system may need to operate in order to recover the volume of LNAPL predicted by the Recovery Decline Curve.

- The difference between the cumulative recovery at a given point in time and the theoretical maximum predicted via the Recovery Decline Curve provides an estimate of the fraction of the remaining LNAPL that might be mobile/recoverable.

It is important to note that achievement of an asymptotic condition of LNAPL recovery does not categorically mean that continuing or additional remedial actions are no longer feasible; this is especially true in cases where substantial amounts of LNAPL continue to be recovered, or in cases where the need to address Non-stable LNAPL or Imminent Hazard conditions may require

[1] This demonstration reflects the same logarithmic behavior described in MassDEP's Background Feasibility policy (http://www.mass.gov/eea/docs/dep/cleanup/laws/04-160.doc) substituting LNAPL recovery rates for contaminant concentrations.

initiation of other remedial approaches. Other considerations for achieving or determining asymptotic limits include:

- Random periodic removal of small quantities of LNAPL from a monitoring well is not likely to generate enough data to perform this analysis. An observed trend, however, may be a supporting Line of Evidence relative to recovery feasibility, provided an appropriate level of effort is applied to such removal efforts.
- Steady state conditions, which are ideal for determining asymptotic limits, are virtually impossible to maintain at minimal recovery rates.
- Steady state conditions and asymptotic limits may be observed at high recovery rates (e.g., 100 gallons/day) at which recovery efforts remain feasible. Therefore, using this approach to support recovery infeasibility should include the establishment of an asymptotic recovery rate endpoint which is no higher than a minimal recovery rate based on the feasibility provisions in 310 CMR 40.0860 (which are discussed further in Section 4.2).

LNAPL Transmissivity (T_n): The ITRC has reported that regulatory programs in a number of states have closed or granted no further action status to sites where a T_n value of between 0.1 and 0.8 ft^2/day has been demonstrated or achieved. The supporting evidence for these decisions also included: (1) LNAPL recovery was asymptotic and small; (2) no significant risk to receptors via vapor or dissolved phase transport; (3) remaining LNAPL was stable and not migrating; (4) institutional controls were in place to prevent exposure. Use of properly determined T_n in this range may be appropriate to support LNAPL assessment and closure decisions provided that all of other MCP requirements related to LNAPL assessment and closure decisions (which correspond to the supporting evidence described above) are met. More information on supporting evidence for the use of T_n values can be found in the 2015 ASTM course materials, *Estimating LNAPL Transmissivity: A Guide to Using ASTM Standard Guide E2856*, referenced in Section 6.0.

Merits and Limitations of Well Data

Merits

- The presence of measurable LNAPL, regardless of thickness, in an excavation, boring or monitoring well 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 nearly 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., specific gravity, viscosity). Moreover, permanent monitoring well installations allow for temporal monitoring programs over time to better characterize dynamic conditions (e.g., seasonal water table fluctuations).
- T_n is a discrete numerical parameter that has been and can be used as recoverability metric.
- 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.

- Since the late 1990s, a number of regulatory agencies and other organizations have begun to publish environmental guidelines on LNAPL characterization based upon LCSM/FFPM principles, most notably Texas, Alaska, British Columbia, ITRC, API, ASTM, among others listed in Section 6.0. All of these guidelines include 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 more detailed analyses and determinations (e.g., LNAPL Transmissivity, recoverability and saturation distribution profiling) often involves complex calculations and/or computer modeling. Confined and perched aquifer conditions affect well testing measurements and require additional data manipulation. Familiarity with hydrogeology or sub-surface engineering may be necessary to obtain and apply these data in a competent manner. Well testing for T_n still may still require soil sampling for necessary LCSM properties (e.g., grain size distribution, porosity, bulk density, specific gravity, viscosity.)
- 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 effects of well diameter and installation techniques on representativeness and data comparability. For example, anecdotal reports indicate measured LNAPL thicknesses in small diameter wells are sometimes greater than in larger diameter wells (at least initially), possibly due to differences in sand-pack volumes and their "sink effects" particularly near the plume boundaries.

4.1.4 Soil Data (Soil Borings/Core Samples/OHM Concentration)

Similar to groundwater monitoring wells, soil borings have also been used for decades to evaluate LNAPL contaminated sites. Traditionally, these LNAPL characterization efforts have relied on obtaining soil samples for determining TPH concentrations in mg/kg and/or obtaining and analyzing core samples for determining LNAPL saturations as a percent of pore space filled, and have typically focused on TPH-to-LNAPL saturation conversions and comparisons. The development of specialized direct push technologies incorporating Laser Induced Fluorescence (LIF), Membrane Interface Probes (MIP), and Cone Penetrometer Technology (CPT) have 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.

Soil TPH Concentration: TPH concentration (mg/kg) is a long-established characterization parameter at petroleum sites, which constitute the vast majority of LNAPL sites in Massachusetts. Field screening methods used in combination with laboratory-analyzed samples can be a relatively inexpensive and effective way to define the areal LNAPL "footprint" when assessing plume stability. In addition, these data can provide vertical LNAPL profiles and the volume of LNAPL present at a site

LNAPL Saturation (S_o) and Residual LNAPL Saturation (S_{or}): While these can be potentially significant Lines of Evidence, understanding the meanings and complexities of these terms, summarized in Sections 2.1 and 2.3, is necessary for their determinations and uses. LNAPL

Saturation can be calculated using soil TPH concentration, or it can be measured in a laboratory using an undisturbed "core" sample by a variety of differing analytical methods which may produce differing results depending on which type of saturation is present (i.e., saturations vary, sometimes significantly, vertically through the Smear Zone and into the water table.) With the appropriate laboratory analysis, saturation results from samples taken from the depth(s) that best represent "residual" conditions are good measures of Residual Saturation. However, such undisturbed samples can be difficult to obtain below the top of the water table, where field saturations are highest and where determining the minimum or Residual Saturation matters most.

Comparison of S_o to S_{or} (or TPH to C_{res}): In concept, LNAPL is present only if the concentration of OHM in soil (e.g., TPH) exceeds its theoretical Soil Saturation Limit (C_{sat}), as described in Section 2.2. Even if LNAPL is present, it will not, in theory, be mobile unless TPH in soil exceeds its Residual LNAPL Concentration (C_{res}) or Residual LNAPL Saturation (S_{or}) value, as described in Section 2.3. With certain significant limitations, comparing site-specific soil TPH concentration or LNAPL Saturation (S_o) to Residual LNAPL Concentration (C_{res}) or Residual LNAPL Saturation (S_{or}) can be an inexpensive and valuable Line of Evidence for assessing LNAPL stability and recoverability (i.e., "how much total LNAPL is present in the soil" versus ""how much of that LNAPL is theoretically immobililzed"). This comparison can be done using either TPH concentrations (typically mg/kg) or volumetric saturations (fraction of pore volume containing LNAPL). Algebraic conversions between concentrations and saturations are usually necessary and depend on specific soil and LNAPL physical properties (e.g., soil porosity, soil bulk density, LNAPL density.) The API Interactive LNAPL Guide, referenced in Section 6, includes a useful converter ("TPH to NAPL Saturation Conversion Tool") for this purpose.

One of the most widely referenced collections of C_{sat}, S_{or} and C_{res} data was published in API's *Soil and Groundwater Research Bulletin No. 9* (Brost et al., 2000). A summary table from this publication reproduced in part in Table 1 of Section 2.3, shows S_{or} 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.

Literature 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, even the most conservative literature values can overestimate the amount of immobilized LNAPL when applied to MCP sites. Moreover, even when applying the most conservative values, it is important to carefully consider 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 an LNAPL mobility issue at most sites, a robust data set with all soil TPH concentration levels well below conservative Residual LNAPL Concentration values and which accounts for the limitations presented here and in Section 2.3 could be a significant Line of Evidence in support of such a finding.

Continuous Soil Cores and Direct Push Technologies: Visual observation of continuous soil cores along with in-situ testing techniques (e.g., LIF, MIP, and CPT) performed using direct push technologies can facilitate the development of the LNAPL CSM by providing a greater understanding of (1) subsurface heterogeneities, (2) physical soil properties, and (3) the extent of LNAPL based on visual and olfactory observations and screening for Total Organic Vapors with a photo-ionization detector (PID) or a flame ionization detector (FID) or heavier petroleum hydrocarbons using LIF.

Merits and Limitations of Soil Data

Merits

- 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 (including continuous cores and direct push testing technologies) can provide a direct vertical profile and distribution of LNAPL saturation across zones of variable saturation in 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. These data can also provide information regarding preferred flow paths, potential presence of macro-pores and/or other heterogeneities within the soil matrix.
- Soil data can be used to calculate the volume of LNAPL at a site.
- Soil sampling can provide a direct measure of physical soil properties necessary for applying FFPM/LCSM principles including well testing for T_n (e.g., porosity, grain size distribution and density.)
- Comparing soil TPH data to Residual LNAPL Saturation can be a simple indicator of potential LNAPL mobility.

Limitations

- A substantial amount of core/soil data may be needed to adequately characterize a site. 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 or test pit 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**.
- 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.
- Recent studies applying Residual Saturation concepts to LNAPL site cleanups have indicated that "residual" values for identical soil and LNAPL types can vary by up to an order of

magnitude, or more, depending on "initial" LNAPL saturations as well as several hydrogeologic and fluid dynamics factors, thereby limiting the usefulness of these comparisons if such differences are not accounted for when using historical literature, laboratory and/or field data.

- Representative core samples for quantitatively evaluating LNAPL saturation conditions (particularly in the Saturated Zone) sometimes are difficult and/or costly to obtain.

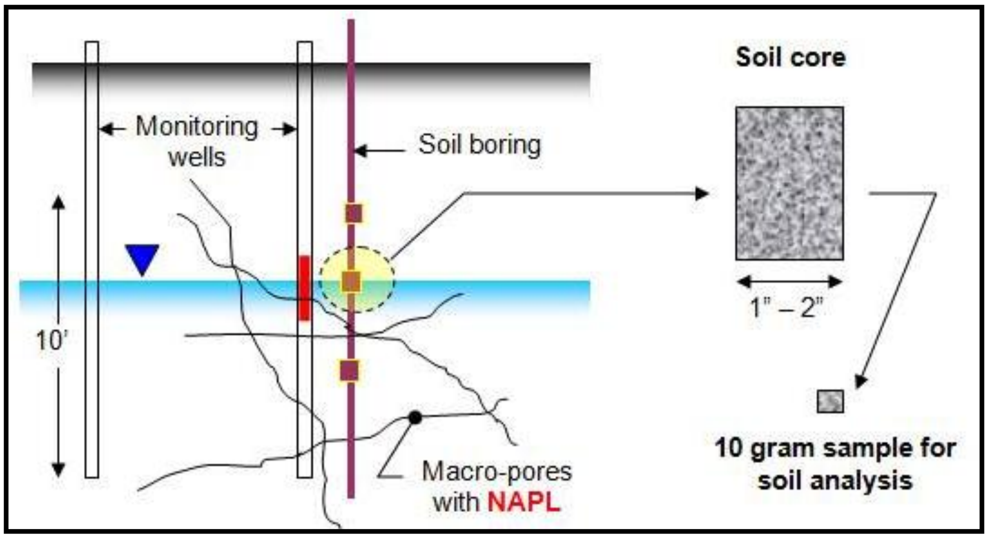


Figure 6: Representativeness Concerns for Soil Samples

4.2 Feasibility Evaluations

The 2014 Amendments to the MCP established two 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)).

It is important to note that "…removed if and to the extent feasible" does NOT mean attempts at removal, past or present, are required. Rather, this provision means that an evaluation must be done to determine if removal is feasible, and if it is, then actions must be conducted to remove NAPL to the extent feasible. Attempting recovery may be one way of demonstrating feasibility or infeasibility (e.g., Decline Curve Analysis), but recovery is not always required if other information provided in the feasibility evaluation is used to support the conclusion that NAPL removal is infeasible.

For both Permanent and Temporary Solutions, feasibility evaluations must be conducted in accordance with the procedures and criteria of 310 CMR 40.0860. Under these provisions, a feasibility evaluation considers technical practicability (including the use of FFPM principles) *and* economics, integrated into a benefit/cost evaluation. As an approximate cost reference, MassDOR's Petroleum Product Cleanup Fund (M.G.L. c. 21J) Reimbursement Fee Schedule and Guidelines applicable to gasoline and diesel sites has been included as **Appendix III** of this document. This fee schedule is provided as a general reference and is not intended as a definitive source of cost information.

The benefits of removing LNAPL from the environment are clear and include eliminating or reducing: risks to human and ecological receptors, its potential as a continuing source of groundwater, soil gas, and indoor air contamination, and the potential negative impacts and limitations that its separate-phase mobility poses upon property use and redevelopment. However, the costs of achieving these objectives can be high and at times disproportionate to the benefit, as documented by real world examples of costly LNAPL recovery systems that were only able to extract a few gallons of petroleum.

While acknowledging the inherent difficulties and uncertainties of LNAPL removal, under certain conditions, the benefits of attempting and continuing LNAPL recovery are high, and outweigh even significant costs. These **conditions of high concern** include sites where LNAPL is:

- Non-stable;
- impacting a current drinking water supply; or
- 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 for these and similar sites with conditions of high concern consider the full range of LNAPL 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 to be maintained for as long as it is necessary to eliminate these conditions.

In contrast to the discussion above regarding sites of high concern, many sites contain smaller quantities of oil or waste oil LNAPL, where (i) the LNAPL mobility is limited to Micro-scale Mobility, (ii) the LNAPL is not impacting drinking water, creating vapor pathways of concern or posing any other significant exposure threats, and (iii) the Source Elimination or Control (310 CMR 40.1003(5)) and Migration Control (310 CMR 40.1003(6)) requirements of the MCP have otherwise been achieved. When these less serious and less time-critical conditions are considered along with the long-term biodegradation potential of petroleum LNAPLs, the balance of the benefit/cost evaluation for remedy selection is significantly shifted. At sites with these conditions, it is MassDEP's position that:

- Feasibility evaluations may be limited to excavation of hot spots and the use of 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 minimal quantity of LNAPL is likely to be recovered.

- Where instituted, remedial operations at these sites may be terminated when LNAPL Transmissivity and/or asymptotic recovery decreases to a minimal level not commensurate with costs, as determined by feasibility analyses specified at 310 CMR 40.0860.

Recovery Technology Considerations

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” or possibly all LNAPL impacted soil 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, as well as site/logistical constraints. There are many excellent references on evaluating these systems, including those cited in Section 6.0.

In addition to these conventional approaches, there 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 Chemical Oxidation (ISCO)

While these treatment technologies may be more costly and/or require higher levels of oversight than conventional systems, they often achieve a higher level of LNAPL recovery or control and may be appropriate or required in some cases depending on site circumstances.

Lastly, there may be cases where Bioremediation or Monitored Natural Attenuation (MNA) may be an appropriate LNAPL remedy, generally for lighter-molecular-weight fuel products (e.g., gasoline/diesel/jet fuel/kerosene), and only in cases where time-critical conditions are not present (e.g., Non-stable LNAPL or Imminent Hazard/Critical Exposure Pathways). In such cases, an adequate case must be made to justify the suitability of the site for such an approach.

4.3 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 NAPL is not present (i.e., the overall LNAPL footprint is not expanding), and all LNAPL with Micro-scale Mobility has been removed if and to the extent feasible. As specified at 310 CMR 40.1012(2)(d), where the remaining NAPL 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 and to establish through the "Consistent" and "Inconsistent" Activities and Uses and "Obligations and Conditions" of the AUL appropriate measures to be taken to manage potential future exposure to the NAPL (e.g., to protect construction workers and/or to establish management/contingency 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). The obligation to develop and adhere to such "NAPL Management Plans" would be included in the Obligations and Conditions of the AUL in the same manner as Health and Safety and Soil Management Plans, and as appropriate, these plans may be combined. The objectives, scope and general provisions of the NAPL Management Plan should be outlined in the Obligations and Conditions of the AUL (e.g., NAPL containment, collection, recovery, storage and removal, worker protection measures related to the NAPL consistent with the Health and Safety Plan, monitoring, excavation safety).Note it is not necessary to a attach a detailed NAPL Management Plan to the AUL; detailed Plans that better reflect actual construction plans can be developed prior to any work occurring in the AUL area.

As a matter of its enforcement discretion, MassDEP will not expect or require that an AUL be implemented as part of the Permanent Solution pursuant to 310 CMR 40.1012(2)(d) if the thickness of visible NAPL in an excavation, boring or monitoring well remaining at a disposal site for "any foreseeable period of time" as described at 310 CMR 40.1005 is less than ½ inch. This lower limit is intended to focus AULs on conditions that are more likely to warrant measures to manage NAPL as the result of future excavation or other activities affecting subsurface conditions. If it is demonstrated that remaining visible NAPL will remain for any foreseeable period of time below ½ inch thickness, consistent with 310 CMR 40.1005(2)(a), then *relative to the presence of LNAPL*, the disposal site can be closed as a Permanent Solution with No Conditions. Note that at those sites where NAPL with Micro-scale Mobility does not exist, an AUL could still be necessary to address other exposure/risk concerns (e.g., TPH or other OHM concentrations in soil) related or unrelated to any LNAPL remaining at the site.

5.0 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). This section of the document describes a "Simplified Approach" for evaluating and supporting the closure of LNAPL sites that pertains only to petroleum-based oil and waste oil releases. Absent unusual site-specific factors where these guidelines may not be sufficiently protective, proper application of the Simplified Approach will satisfy MCP performance standards to assess and address LNAPL mobility and recoverability.

Use of the Simplified Approach is voluntary. In outlining a Simplified Approach, it is not the Department’s intention to limit or prevent use of alternative approaches for evaluating and supporting the closure of LNAPL sites.

Parties electing to use other approaches are required to demonstrate that such techniques are scientifically valid and demonstrate compliance with all applicable MCP performance standards. The guidance provided in the other sections of this document should be considered as relevant to both the Simplified Approach and any alternative approach. Likewise, parties using an alternative approach can apply the underlying principles and relevant elements of the Simplified Approach as supporting Lines of Evidence in such alternative approach. However, each action in this regard must be adequately justified, and *in no case shall a party indicate or infer that the Simplified Approach was followed unless it was implemented in its entirety*.

5.1 Simplified Approach: Basis and Limitations

The Simplified Approach consists of a series of investigatory and, where applicable, remedial steps with specified levels of effort, data needs, and evaluation metrics. It lays out decision criteria that not only “screen in” sites of potential concern, but also “screen out” sites where further evaluation of LNAPL mobility and/or recoverability are not necessary.

The elements of the Simplified Approach are presented in a sequential manner to encourage logical and systematic consideration of scientific principles and regulatory mandates and to progressively address the key questions surrounding releases of petroleum at sites regulated by the MCP:

- How and to what degree should sites be assessed for the possible presence of LNAPL?
- Based upon these assessments, is LNAPL present or likely present?
- If LNAPL is or is likely present, does it have Micro-scale Mobility?
- If LNAPL is or is likely present, is it Non-stable LNAPL, as defined in the MCP?
- When and to what extent must LNAPL be removed from the environment?
- When and how can a site where LNAPL is present qualify for a Permanent Solution?

It is incumbent on users of the Simplified Approach to ensure that ***<u>all</u>*** required elements and considerations of the approach are addressed for the entire disposal site.

As the Simplified Approach is designed to be reasonably conservative and protective when implemented in its totality, ***users of the Simplified Approach are not permitted to "pick and choose" among provided steps and metrics (as described in Sections 5.2 through 5.7); <u>all</u> must be implemented if the Simplified Approach is applied to the site in question***. Conclusions for each element of the Simplified Approach are based upon 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 criteria incorporated into the 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 details of the individual elements of the Simplified Approach are provided in Sections 5.2 through 5.7. The overall Simplified Approach is summarized in **Figure 7**.

5.2 Simplified Approach: Characterization Methods and Level of Effort

The Simplified Approach focuses on site history research, site observations, LNAPL thickness in groundwater monitoring wells, and the use of reasonably conservative metrics obtained or adapted from other regulatory agencies and researchers. Key components of the Simplified Approach are summarized below to provide an overall understanding of procedures and expectations; more detail on each of these components is given in the sections that follow.

- 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. Parties who elect to use monitoring wells that are less than 2 inches in diameter shall include with relevant submittals a discussion of the steps that were taken during the installation, development, and gauging process to ensure the validity of LNAPL thickness measurements.

- 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.

  An LNAPL thickness measurement may not be used to support a conclusion under the Simplified Approach if the measurement was made within a 7 day period following a significant rainfall event. While the significance of a rainfall event depends on site-specific factors, an explicit justification on the use and relevance of such data is required when more than 2 inches of total rainfall occurred in this preceding 7 day period.

- Barring 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 must reflect the location of any 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 until stability is demonstrated. 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, with gauging events occurring at both high and low water table conditions.

- 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, as long as chromatographic integration is to baseline, and the carbon range covered is at least C_5-C_{12} for gasoline, C_9 through C_{24} for diesel/#2 Fuel, and C_9 thorough C_{36} for heavier oils. See Section 2.3 for additional guidance on this subject.

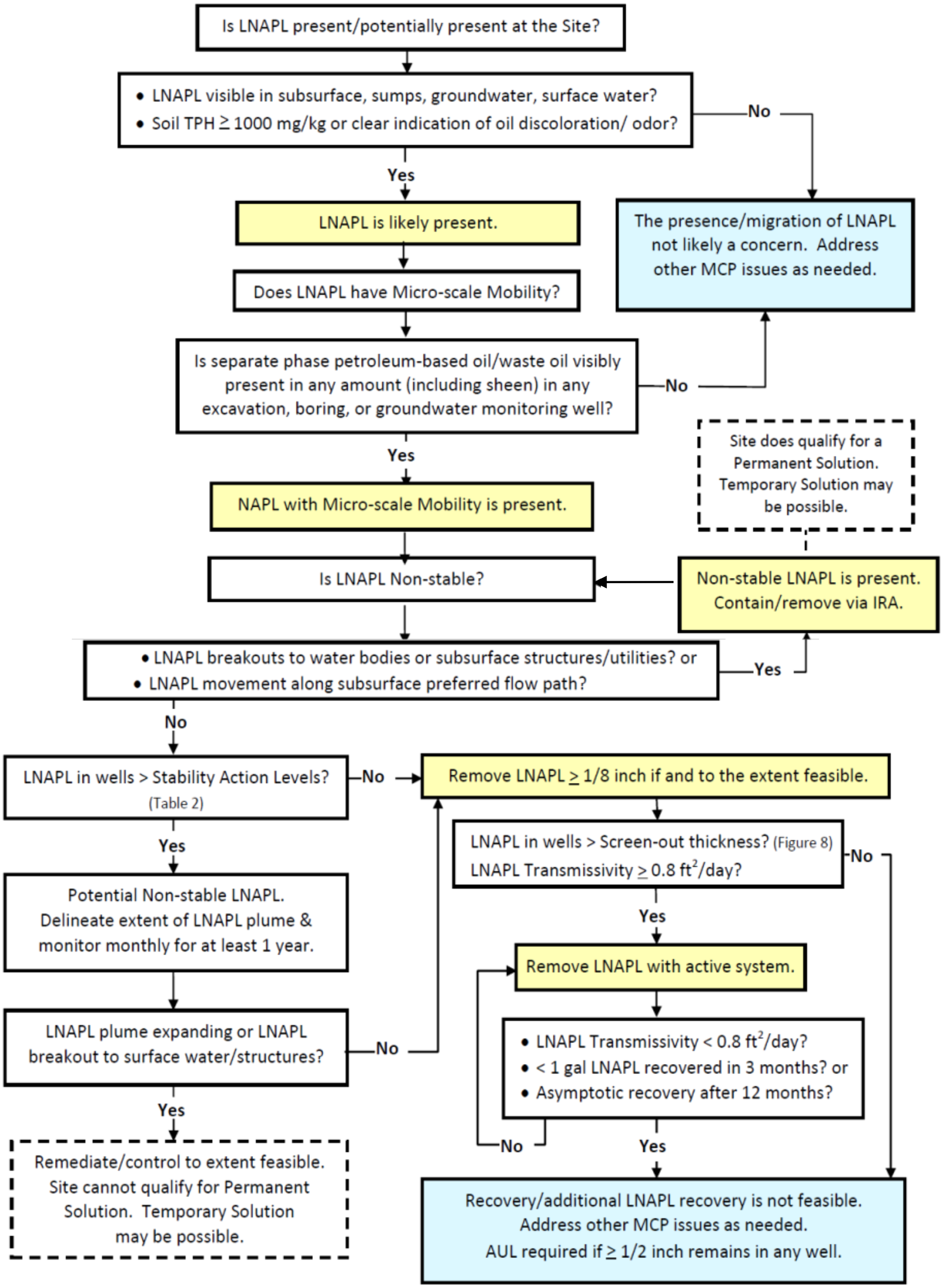
5.3 Simplified Approach: Determining Whether LNAPL is Present at a Disposal Site

When using the Simplified Approach, LNAPL shall be presumed to be present at a disposal site if, at any time in the past, separate-phase petroleum-based oil or waste oil was visibly present in any amount (including a sheen) in any

- subsurface excavation, boring or monitoring well at the disposal site;
- subsurface utility, building sump, or other subsurface structure at or immediately downgradient of the disposal site; or
- surface water body immediately downgradient of the disposal site.

This presumption may be rebutted by a showing that the separate-phase petroleum-based oil or waste oil in question did not originate from/travel through subsurface environmental media at the disposal site.

Figure 7: LNAPL Simplified Approach



At sites where separate-phase petroleum-based oil or waste oil has not been visually observed, proactive steps must be taken to determine its possible presence in the subsurface 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);
- spills/releases totaling 10 or more gallons of oil/waste occurred or are likely to have occurred at the site in the previous 10 years; or
- available groundwater, soil gas, or indoor air data at the site exceed MCP reportable conditions for petroleum constituents.

These proactive investigatory steps shall include, as appropriate, soil borings, test pits, groundwater monitoring wells, soil cores/samples, and/or other scientifically sound site characterization technologies. The level of effort in this regard must reflect the nature and quantities of petroleum products of interest, site complexity, and presence of sensitive receptors, consistent with the Conceptual Site Model.

A disposal site with a total petroleum hydrocarbons concentration in soil in excess of 1000 mg/kg shall be presumed to contain LNAPL, with the understanding that such LNAPL is unlikely to be mobile at concentrations less than 10,000 mg/kg.

At all sites at which LNAPL is or presumed to be present, as described above, additional actions or considerations are required, as detailed in Section 5.4. For all other sites, no further actions specifically to assess LNAPL mobility or recoverability issues are necessary, provided that such findings are based upon an adequate investigatory effort.

5.4 Simplified Approach: Determining Whether LNAPL with Micro-scale Mobility is Present or Likely Present

In some cases it can be presumed that LNAPL with Micro-scale Mobility is present at a site, and users of the Simplified Approach may proceed to Section 5.5. This shall include sites where, at any time in the preceding 10 year period, LNAPL originating from/traveling through subsurface media was visibly present in any amount (including a sheen) in a:

- subsurface excavation, boring, or monitoring well at the disposal site;
- subsurface utility, building sump, or other subsurface structure at or immediately downgradient of the disposal site; or
- surface water body immediately downgradient of the disposal site.

To rebut this presumption, or to further explore this concern at disposal sites with no past history of visible LNAPL, test pits, borings, and/or water table monitoring wells must be installed and/or gauged for a minimum of one year on a quarterly basis in those suspect areas identified in Step 5.3, and in areas where soil concentrations of total petroleum hydrocarbons exceed 10,000 mg/kg.

In order to rule out the presence of LNAPL with Micro-scale Mobility, all test pits and water table wells must be free of any amount of LNAPL. If this conclusion cannot be reached, users of the Simplified Approach must proceed to Section 5.5.

5.5 Simplified Approach: Determining Whether LNAPL at a Disposal Site is Non-stable

At sites where LNAPL with Micro-scale Mobility is present or likely present, investigatory actions must be promptly taken to determine whether the LNAPL is Non-stable LNAPL, as that term is defined in the MCP.

These 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 subsurface exploration efforts, or any other available observational/site assessment data, an LNAPL present in the subsurface shall be deemed Non-stable LNAPL 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 and migrating along or within a preferred flow path, including in the pervious backfill of utility conduits ; and/or
- its footprint is expanding as described below.

For the purposes of the Simplified Approach, "periodically" means any discharge that occurred one or more times in the preceding 12 months.

Even when LNAPL is not actively discharging or periodically discharging to surface waters or other receptors of concern, it may still meet the MCP definition of Non-stable LNAPL if it is moving as a separate phase through subsurface porous media (i.e., the LNAPL footprint is expanding). 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 researchers have developed well thickness criteria as a means to evaluate this concern.

Accordingly, for the purposes of this Simplified 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, professional judgment shall be used to select an available category and metric that is a reasonably conservative approximation.

If an appropriate Stability Action Level (i.e., LNAPL thickness) in Table 2 is exceeded, one year of monthly 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:

- An LNAPL thickness value in Table 2 is exceeded by more than a factor of 2 in any well/excavation within 50 feet of a potential subsurface LNAPL receptor and no additional wells are already present in this zone; potential subsurface LNAPL receptors are 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.

Monthly monitoring shall include gauging wells for the presence and thickness of LNAPL. Only wells that straddle the groundwater fluctuation (smear) zone have relevance in this evaluation effort.

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

Upon completion of this one year monthly monitoring program, it may be concluded under the Simplified Approach that there is no current indication of Non-stable LNAPL if:

- subsurface LNAPL was not observed to be migrating along or within a preferred flow path;
- subsurface LNAPL did not discharge into a building, utility, drinking water well, or surface water body; and
- observed LNAPL thickness levels did not consistently or significantly increase in downgradient monitoring wells.

5.6 Simplified Approach: Determining the Feasibility of Removing LNAPL

In addition to the general provisions for feasibility evaluations at 310 CMR 40.0860, there are two LNAPL feasibility-related requirements specified in the MCP at 310 CMR 40.1003(7):

- Non-stable NAPL must be removed and/or controlled if and to the extent feasible in order to achieve a Temporary Solution;
- NAPL with Micro-scale Mobility must be removed if and to the extent feasible in order to achieve a Permanent Solution.

A robust and comprehensive evaluation of all conventional and innovative remedial options and technologies is necessary when considering the feasibility of:

- removing and/or controlling Non-stable LNAPL in order to achieve a Temporary Solution; or
- removing LNAPL with Micro-scale Mobility at disposal sites where the LNAPL is creating or contributing to a vapor intrusion pathway or impacting a drinking water well to a degree that presents a significant risk of harm to health, safety, or public welfare.

Absent such conditions, the feasibility of removing LNAPL with Micro-scale Mobility may be limited to the consideration of conventional hydraulic/vacuum LNAPL removal technologies. Under the Simplified Approach, this feasibility evaluation is conducted by sequentially evaluating the applicability of the following:

Categorically Infeasible - It may be considered categorically infeasible to initiate removal operations in cases where:

- the thickness of visible LNAPL at a disposal site *never* exceeded the reporting threshold in 310 CMR 40.0300 of equal to or greater than 1/8 inch; or
- LNAPL thickness in any excavation, boring, or monitoring well was at one time equal to or greater than 1/8 inch and a monitoring program conducted on at least a quarterly basis has demonstrated that all excavations, borings, and monitoring wells had less than 1/8 inch thickness of LNAPL for a preceding period of at least 12 months.

Conditionally Infeasible - For sites where LNAPL thickness is equal to or greater than 1/8 inch but no greater than 5 inches in the previous 12 month period, it may be considered infeasible to initiate LNAPL removal operations if the maximum LNAPL thickness in all excavations, borings, and monitoring wells is less than the "screen out" thickness plotted in **Figure 8**, Conditions of Infeasibility of LNAPL Recovery by Conventional Technologies, for the given site/soil condition and petroleum product.

In applying the criteria in Figure 8:

- The LNAPL thickness value (in red) shall be the maximum thickness observed in any excavation, boring, or monitoring well in the preceding 12 month period based upon gauging on at least a quarterly basis.
- 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., higher Hydraulic Conductivity) 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.

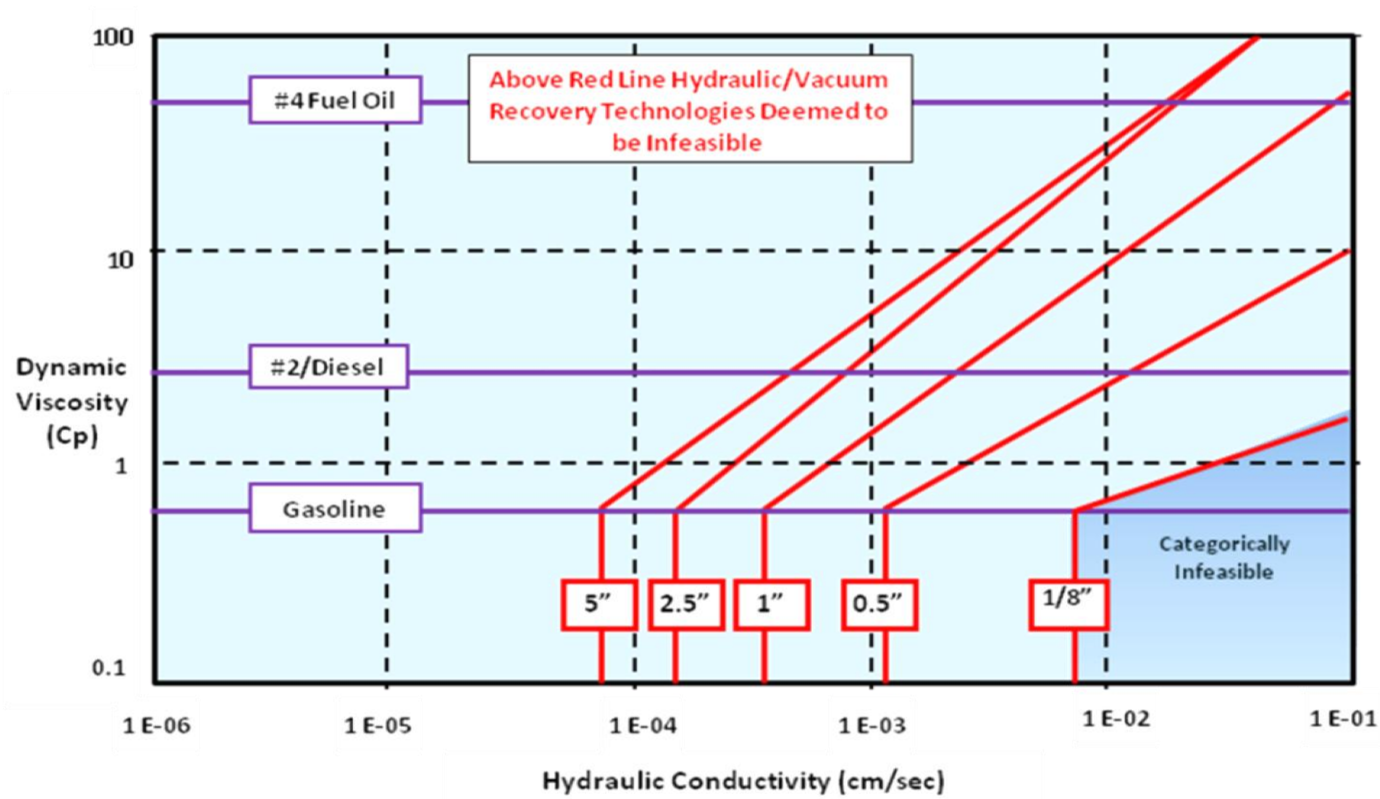


Figure 8: Conditions of Infeasibility of LNAPL Recovery by Conventional Technologies (based on a modification of modeling results from API, 2007)

- Values between the indicated inches may be extrapolated, within the range of 1/8 to 5 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.
- 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.

In lieu of using the generic criteria contained in Figure 8, users of the Simplified approach may chose to conduct a site-specific LNAPL Transmissivity test to demonstrate the infeasibility of commencing LNAPL removal operations. In such cases, the initiation of removal operations may be considered infeasible if the LNAPL Transmissivity value (T_n) in suitable recovery locations are less than 0.8 ft^2/day.

No Longer Feasible - The *continued operation* of a properly designed, constructed, and operated conventional LNAPL recovery system can be deemed infeasible if and when:

- Subsequent to the initiation of LNAPL recovery operations, the LNAPL Transmissivity value (T_n) in all recovery wells as determined by using the well testing methods described in ASTM 2856 and referenced in Section 6.0 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 plotted on a monthly basis demonstrates an asymptotic condition.

Under the Simplified Approach, the removal of LNAPL with Micro-sale Mobility will be considered feasible if it is not demonstrated to be Categorically Infeasible, Conditionally Infeasible or No Longer Feasible as described above.

5.7 Simplified Approach: Achieving a Permanent Solution

A Permanent Solution may be supported for an LNAPL site if:

- Non-stable LNAPL was never or is no longer present, as articulated in Section 5.5;
- LNAPL with Micro-scale Mobility has been removed if and to the extent feasible, as articulated in Section 5.6; 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. As previously stated in Section 4.3, MassDEP will not require an AUL as part of the Permanent Solution pursuant to 310 CMR 40.1012(2)(d) if the thickness of visible LNAPL in any excavation, boring or monitoring well remaining at a disposal site during "any foreseeable period of time" as described at 310 CMR 40.1005 is less than ½ inch.

6.0 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

Characterizing Risks Posed by Petroleum Contaminated Sites: Implementation of the VPH/EPH Approach; Policy #WSC-02-411; October 31, 2002.
http://www.mass.gov/eea/docs/dep/cleanup/laws/02-411.pdf

Compendium of Quality Control Requirements and Performance Standards for Selected Analytical Protocols; Policy WSC #10-320); July 1, 2010.
http://www.mass.gov/eea/agencies/massdep/cleanup/regulations/wsc10-320-compendium--quality-control-reqs.html

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

Interstate Technology & Regulatory Council (ITRC)

LNAPL Training Part 1: *An Improved Understanding of LNAPL Behavior in the Subsurface - State of Science vs. State of Practice*; 2016.
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?*; 2016.
http://www.itrcweb.org/Training#LNAPLPart2

LNAPL Training Part 3: *Evaluating LNAPL Remedial Technologies for Achieving Project Goals;* 2016.
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

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

American Petroleum Institute (API)

Brost et al.; *Non-Aqueous Phase Liquid (NAPL) Mobility Limits in Soil*; API Soil & Groundwater Research Bulletin No. 9; June 2000.
http://www.api.org/~/media/Files/EHS/Clean_Water/Bulletins/09_Bull.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.);* 2016.
http://www.api.org/environment-health-and-safety/clean-water/ground-water/lnapl\

American Society for Testing and Materials (ASTM International)

ASTM E2531 – 06: *Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface;* 2014.
http://www.astm.org/Standards/E2531.htm

ASTM E2856-13: Standard Guide for Estimation of LNAPL Transmissivity; 2013.
http://www.astm.org/Standards/E2856.htm

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

Estimating LNAPL Transmissivity: A Guide to Using ASTM Standard Guide E2856; 2015.
http://www.astm.org/TRAIN/filtrexx40.cgi?+-P+ID+193+traindetail.frm

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, Volume 25, no.1, pages 100–112, Winter 2005 .

Johnston, C., Adamski, M., *Relationship Between Initial and Residual LNAPL Saturation for Different Soil Types*; Petroleum Hydrocarbons and Organics Chemicals in Ground Water Conference, Costa Mesa, CA, August 18-19, 2005.
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"; 2016.
http://www.napl-ansr.com

Hawthorne, Michael, Kirkman, A., *LCSM Tools: Conversion of TPH in Soil to NAPL Saturation*; Applied NAPL Science Review; Volume 2, Issue 1; January 2012.
http://www.h2altd.com/wp-content/uploads/2012/02/ANSR-v2i1.pdf

British Columbia Ministry of Environment (with Golder Associates)

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

APPENDIX I
DEFINITIONS OF KEY TERMS

DEFINITIONS OF KEY TERMS

Key terms in this document that are defined in the MCP (at 310 CMR 40.0006):

Conceptual Site Model (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.

Non-stable NAPL means 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.

NAPL with Micro-scale Mobility means a NAPL with a footprint that is not expanding, but which is visibly 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.

Source of OHM Contamination means:

(a) a point of discharge of OHM into the environment that may include, without limitation:

1. leaking storage tanks, vessels, drums and other containers;
2. dry wells or wastewater disposal systems that are not in compliance with regulations governing discharges from those systems; or

(b) waste deposits, sludges, or impacted soil, sediment, or bedrock at or near a point of discharge or deposit of OHM into the environment containing sorbed OHM or NAPL that is contaminating surrounding environmental media via dissolution or volatilization processes;

except that the downgradient leading edge of a plume of oil and/or hazardous material dissolved in and migrating with groundwater or as vapor-phase shall not, in and of itself, be considered a Source of OHM Contamination.

Vadose Zone means the unsaturated zone below the ground surface and above the water table.

Key terms in this document that appear in capital letters that are not defined in the MCP:

Fluid Flow in Porous Media (FFPM) means the science based primarily on Darcy's Law that describes the fate and transport of liquid (and gas) moving through subsurface porous geologic formations.

Line of Evidence means, in the context of this document, a set of data or observations related to LNAPL that indicate characteristics or approximate degrees of LNAPL behavior in the subsurface environment.

LNAPL Conceptual Site Model (LCSM) means the Conceptual Site Model for sites at which LNAPL is or may be present which includes the body of fundamental scientific principles describing the behavior of Fluid Flow in Porous Media necessary to assess LNAPL in subsurface strata.

LNAPL Saturation (S_o) means the fraction or percentage of pore space occupied by LNAPL.

LNAPL Transmissivity (T_n) is a hydrogeologic measure of how much and how quickly LNAPL can flow through soil, typically expressed in units of ft^2/day. This metric is often used as an indicator of LNAPL "recoverability."

Residual LNAPL Concentration (C_{res}) means the concentration-based equivalent to Residual LNAPL Saturation (often expressed as milligrams (mg) of LNAPL per kilogram (kg) of soil).

Residual LNAPL Saturation (S_{or}) means the fraction or percentage of pore space occupied by LNAPL below which LNAPL will not migrate due to convection or gravity.

Saturated Zone means the zone below ground where the pore spaces are filled with groundwater.

Simplified Approach is the voluntary approach described in Section 5 of this document, that absent unusual site-specific factors and pertaining only to spills of petroleum-based oil and waste oil, the Simplified Approach can be used in its entirety to satisfy MCP performance standards to assess and address LNAPL mobility and recoverability.

Smear Zone means the subsurface vertical interval containing some amount of LNAPL extending from the bottom of the LNAPL-impacted zone to the highest water table elevation in the impacted area after release of the LNAPL.

Soil Saturation Limit (C_{sat}) means the contaminant concentration in soil at which the absorptive and adsorptive limits of the soil, the solubility limits of the soil pore water, and the saturation of the soil pore air have been reached. Above this concentration, the contaminant will be present in a nonaqueous phase.

APPENDIX II
LNAPL SCREENING CHECKLIST & LINES OF EVIDENCE MATRIX

LNAPL SCREENING CHECKLIST

Possible presence of LNAPL based on:

___Visual/olfactory?   ___TPH Concentration?   ___Site history?

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 not affected by significant rain event?
  Well completion/screen through entire Smear Zone into GW table?
  Well diameter(s):________

- ☐ 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?

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

- ☐ Has LNAPL been "removed if and to the extent feasible?"
  Based on what Line(s) of Evidence?
  Volume removed _____ over ______days/months

- ☐ Is an AUL Required related to LNAPL with Micro-scale Mobility (1/2 inch or greater remaining in excavation, boring, or monitoring well)?

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

LINES OF EVIDENCE MATRIX

LINES OF EVIDENCE	MCP PERMANENT AND TEMPORARY SOLUTION REQUIREMENTS AND RELATED CITATIONS			
	LNAPL presence & characterization using CSM 310 CMR 40.0006, 310 CMR 40.0191(2)(b) 310 CMR 40.0483(1)5. 310 CMR 40.0835(4)(f) 310 CMR 40.1003(7)	**Non-stable LNAPL (or macro-scale mobility)** 310 CMR 40.0006 310 CMR 40.1003(7)(a) & (b)	**LNAPL Removal "if and to the extent feasible"** 310 CMR 40.1003(7)(a) & (b) 310 CMR 40.0860	**LNAPL Micro-scale Mobility and AULs** 310 CMR 40.0006, 310 CMR 40.1003(7)(a) & (b) 310 CMR 40.0860 310 CMR 40.1012(2)
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

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

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

APPENDIX III

**Hyperlink to the UNDERGROUND STORAGE TANK
PETROLEUM PRODUCT CLEANUP FUND (M.G.L. CHAPTER 21J)
503 CODE OF MASSACHUSETTS REGULATIONS 2.00
APPENDIX 3 - REIMBURSEMENT FEE SCHEDULE & GUIDELINES**

http://www.mass.gov/dor/docs/dor/ust/regulations/appendix3new.pdf