Welcome – Thanks for joining us.
ITRC’s Internet-based Training Program

LNAPL Training Part 2:
LNAPL Characterization and Recoverability – Improved Analysis

Do you know where the LNAPL is and can you recover it?

This training is co-sponsored by the US EPA Office of Superfund Remediation and Technology Innovation

Light non-aqueous phase liquids (LNAPLs) are organic liquids such as gasoline, diesel, and other petroleum hydrocarbon products that are immiscible with water and less dense than water. LNAPLs are important because they are present in the subsurface at thousands of remediation sites across the country, and are frequently the focus of assessment and remediation efforts. A sound LNAPL understanding is necessary to effectively characterize and assess LNAPL conditions and potential risks, as well as to evaluate potential remedial technologies or alternatives. Unfortunately, many environmental professionals have a faulty understanding of LNAPL conditions based on outdated paradigms.

The ITRC LNAPLs Team is providing Internet-based training to improve the general understanding of LNAPLs. Better understanding leads to better decision making. Additionally, this training provides a necessary technical foundation to foster effective use of the forthcoming ITRC LNAPLs Team Technical Regulatory Guidance Document: Evaluating LNAPL Remedial Technologies for Achieving Project Goals (to be published in 2009).

This training course is relevant for new and veteran regulators, environmental consultants, and technically-inclined site owners and public stakeholders. The training course is divided into two parts:

**LNAPL Training Part 1:** An Improved Understanding of LNAPL Behavior in the Subsurface - State of Science vs. State of Practice - Part 1 explains how LNAPLs behave in the subsurface and examines what controls their behavior. Part 1 also explains what LNAPL data can tell you about the LNAPL and site conditions. Relevant and practical examples are used to illustrate key concepts.

**LNAPL Training Part 2:** LNAPL Characterization and Recoverability – Improved Analysis - Do you know where the LNAPL is and can you recover it? Part 2 addresses LNAPL characterization and site conceptual model development as well as LNAPL recovery evaluation and remedial considerations. Specifically, Part 2 discusses key LNAPL and site data, when and why those data may be important, and how to get those data. Part 2 also discusses how to evaluate LNAPL recoverability.

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For a state to be a member of ITRC their environmental agency must designate a State Point of Contact. To find out who your State POC is check out the “contacts” section at www.itrcweb.org. Also, click on “membership” to learn how you can become a member of an ITRC Technical Team.
## ITRC Course Topics Planned for 2009 – More information at [www.itrcweb.org](http://www.itrcweb.org)

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<th>Popular courses from 2008</th>
<th>New in 2009</th>
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<td>▶ Enhanced Attenuation of Chlorinated Organics</td>
<td>▶ An Improved Understanding of LNAPL Behavior in the Subsurface</td>
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<tr>
<td>▶ Evaluating, Optimizing, or Ending Post-Closure Care at Landfills</td>
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<td>▶ Survey of Munitions Response Technologies</td>
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More details and schedules are available from [www.itrcweb.org](http://www.itrcweb.org) under “Internet-based Training.”
### LNAPL Basics Part 2: LNAPL Characterization and Remediation

#### Logistical Reminders
- **Phone line audience**
  - Keep phone on mute
  - *6 to mute, *7 to un-mute to ask question during designated periods
  - Do NOT put call on hold
- **Simulcast audience**
  - Use 🔄 at the top of each slide to submit questions
- Course time = 2¼ hours

#### Presentation Overview
- Introduction & Part 1 Summary
- LNAPL Conceptual Site Model
- LNAPL Site Characterization
- Question & Answers
- Hydraulic Recovery Evaluation and Limits
- LNAPL Management Objectives and Goals
- Introduction to LNAPL Remedial Technologies
- Questions & Answers

No associated notes.
Meet the ITRC Instructors

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Pamela Trowbridge is a Licensed Professional Geologist with the Pennsylvania Department of Environmental Protection (PA DEP) in Harrisburg. She has worked for the PA DEP since 1993. She is experienced in regulation, guidance, policy, and procedure development and is working on developing guidance and procedures for addressing separate phase liquids in soils and groundwater. She assists sites under development through the Brownfield Action Team, a process that expedites the permitting process and the Land Recycling cleanup process, and provides technical assistance and input to Departmental permits for these sites. Pamela conducts training seminars of basic program information in the Land Recycling Program to consultants and the regulated community and provides training to DEP staff on new procedures and technical issues. Pamela has been the co-leader for the ITRC LNAPL Team since the team formed in 2007. She earned a bachelor’s degree in earth sciences from Pennsylvania State University in University Park, Pennsylvania in 1992 and is a Licensed Professional Geologist in Pennsylvania.

Derek Tomlinson has over 15 years of diverse experience specializing in development of strategies for managing sites with dense and light non-aqueous phase liquids (DNAPL and LNAPL) and vapor intrusion (VI) concerns. He works for ERM in Exton, Pennsylvania. He is an environmental engineer with graduate training in contaminant hydrogeology including the characterization and remediation of sites contaminated with chlorinated solvents and migration of vapors within the subsurface. Derek has worked at refineries, waste sites, and other industrial facilities under USEPA CERCLA and RCRA programs; state and regional programs in California, Delaware, Georgia, Maryland, New Jersey, Ohio, Pennsylvania, Rhode Island, and West Virginia; and internationally in Australia and Brazil. Technical expertise includes the design, implementation, and operation of a range of in situ remediation technologies within both porous media and fractured bedrock geologic settings. He is active with the ITRC LNAPL team and is a contributing author for the LNAPL technical guidance and training documents currently being developed. He is also active with ASTM and is contributing member that developed standard guides for LNAPL conceptual site models, risk-based remedy selection, and vapor intrusion assessments and mitigation strategies for real estate transactions. Derek earned a bachelor’s degree in Civil Engineering in 1994 and a master’s degree in 1999, both from the University of Waterloo in Waterloo, Ontario, Canada. He is a professional engineer.

Steven Ueland is a Senior Associate with Langan Engineering and Environmental Services, Inc. in Doylestown, Pennsylvania. He started working for Langan in 1993. Steven is a professional engineer with over twenty years of experience focusing on contaminated property characterization for the design and implementation of remediation/closure projects. His expertise includes hydrogeologic assessment and strategic remedial planning for both Light and Dense Non-Aqueous Phase Liquid (NAPL) contamination sites. Steven’s project experience has involved superfund site RI/FS, remedial design and construction oversight, UST closure/remediation, and NAPL assessment, mobility analysis and recovery system design for a large petroleum refinery. He served for two years on the U.S. EPA Region I Technical Assistance Team, where he had direct involvement in emergency response and hazard assessment and clean-up activities for oil spill incidents throughout New England. Steven also has expertise with oil spill contingency planning and regulatory compliance. Steven is currently responsible for a team of scientists and engineers addressing remediation and compliance for private industrial manufacturing sites. Steven is an active presenter at conferences, and has been a member of the ITRC LNAPLs team since its inception in 2007. Steven earned his bachelor’s degree in civil engineering from the University of Vermont in Burlington, Vermont in 1986, and is a registered professional engineer in Pennsylvania and New Hampshire.
LNAPL Training Part 2

- Introduction and Part 1 summary
- LNAPL conceptual site model
- LNAPL site characterization
- Q&A
- Hydraulic recovery evaluation and limits
- LNAPL management objectives and goals
- Introduction to LNAPL remedial technologies
- Q&A

No associated notes.
LNAPL Training Part 2

Introduction and Part 1 summary
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- Q&A

No associated notes.
In our part one training we went over some common mis perceptions of our understanding of how LNAPL behaves in the subsurface. LNAPLs are not distributed as a pancake floating on the water table in the subsurface, but distributes below the water table according to the vertical equilibrium. It’s distributed in multi-phases – air, water and LNAPL. The saturations of LNAPL are not uniform, but controlled by the properties of the soil. Recall that for a specific LNAPL thickness, specific volume includes the recoverable and non-recoverable LNAPL and is greater in a coarse grained soils than in fine grained. As LNAPL saturation increases, so does the relative permeability, in addition the velocity increases.
Part 1 Summary of LNAPL Basics (continued)

- Pressure exerted by LNAPL must exceed the displacement pore entry pressure for LNAPL to enter a water-filled pore
- Measurable LNAPL thickness in a well does not necessarily indicate mobility
- Part 1 - basic principles of LNAPL distribution and mobility
- Part 2 focus - LNAPL assessment, Conceptual Site Model, and recovery evaluation

The pressure exerted by LNAPL must exceed the displacement pore entry pressure for LNAPL to enter a water-filled pore.

Measurable LNAPL thickness in a well does not necessarily indicate mobility. LNAPL plumes generally come to stable configurations over relatively short periods of time.

Part 1 has provided the basic principles for LNAPL distribution and mobility; Part 2 focuses on the LNAPL assessment, LNAPL Conceptual Site Model, and LNAPL recovery evaluation.

The pressure or head exerted by LNAPL has to exceed the displacement pore entry pressure for LNAPL to move into that pore. If the pressure is not there, then it won't move.

We showed you many examples of how the thickness of LNAPL in a well does not correlate to how mobile an LNAPL is in the subsurface. The LNAPL when first released moves quickly then stabilizes in a short period of time.
So what is our purpose of today's training? We’re going to take what we learned in our part one training apply that knowledge to assessing the LNAPL body. What data do we need to characterize our LNAPL plume. What properties of LNAPL in the subsurface can we manipulate to recover LNAPL. Then we’ll discuss remedial goals. How do we fit a remedial technology to our site conditions. What are our endpoints goals and how will you achieve them.
Simplified Subsurface LNAPL Processes

Release Source

Vapor Phase

Vadose Zone

LNAPL

Dissolved Phase

Capillary Fringe

Modified from Huntley and Beckett, 2002

Relative mass distribution percentage – LNAPL, dissolved, vapor, sorbed
Relative distribution percent different and for different LNAPLs
LNAPL phase always contains significantly more mass than the other phases combined
Just briefly, the panel 1 shows the LNAPL body is moving from a recent release. A remedial driver may be to stop the LNAPL from migrating further. Panel 2 shows the LNAPL body is not moving – it's stable. So a remedial driver for this one could be LNAPL removal and source reduction. You're getting at the saturation and chemical properties. Panel 3 shows the LNAPL body is residual and a remedial driver might be the dissolved phase. Based on these three generalized scenarios, today we are going focus on the first two panels – the recovery of LNAPL that is above residual saturation. Specifically through hydraulic means. Late in the presentation we'll introduce technologies which address LNAPL beyond the recoverable portion. Our team is developing a Technical and Regulatory guidance document to assist regulators in making decisions about which technology to choose and which parameter that technology addresses. In addition to this guidance document will be interned based training. So stay tuned for our future training.
Why are we concerned about LNAPL? Well, I had a site in Pennsylvania where a gasoline release went undetected until a neighboring spring house exploded. So on the left of the slide we see some of the main concerns with LNAPL. On the right we see the associated drivers. There is another driver that is a regulatory driver – recover to the maximum extent practicable – as determined by the implementing agency. Well we have 50 states and that many interpretations of maximum extent practicable. Part of our goal of these trainings is to help define what that can be. What can we achieve using good science. Recovery of free product to the maximum extent practicable is merely the first step in a typical remedial action.
The key to understandings sites with LNAPL is to develop a good Conceptual Site Model. The process of evaluating and refining a site conceptual model is iterative. Characterization plays a part in it but so do the objectives and endpoints. As a regulator its challenging to mesh the need to achieve maximum extent practicable with the all the things that drive an LNAPL site cleanup. The sites that have successfully and quickly closed in Pennsylvania are ones where there was a clear understanding of the physics of LNAPL movement and designed a remediation system that worked. They also had a clear understanding of where they wanted to go to meet our regulatory numbers.

Unrealistic expectations of recovery due to incorrect site conceptual model
- Uniform saturations
- Uniform LNAPL distributions

LNAPL Training Part 2

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No associated notes.
What is an LCSM?
A description and interpretation of the physical and chemical state of the LNAPL body and is the site characterization and management link.

Why is an LCSM of value?
Facilitates understanding of the LNAPL conditions, site risks, and how best to remediate.

When is an LCSM adequate?
When the LCSM provides quality of understanding of the LNAPL body and site risks to support necessary decision making and additional information likely would not lead to a different decision. This is an iterative process.

Level of effort?
Scaled to the LNAPL impacts and associated issues that require management
What does a LCSM cover?

- Delineation (horizontal and vertical) – general geometry
- Age and Chemical/Physical Character
- Volume
- Mobility (or Stability) – i.e. fluxes
- Longevity
- Recoverability
- Source / Pathway / Receptors
Ultimately want to understand the sources, pathways and receptors. As shown here we see a release of an underground storage tank and resulting LNAPL body. We have receptors and the risks associated with the LNAPL body could potentially pose emergency concerns such as utility corridors shown as 1, dissolved phase plumes impacting a drinking water well shown as 2, vapor concerns from both the LNAPL body and dissolved phase plumes shown as 3a and 3b, respectively. Other LNAPL risks associated with the LNAPL is the potential mobility from LNAPL within the LNAPL body or observed in wells shown as 4 and 5.

To provide the best management options for the given site, the professional should consider these components.
The complexity and amount of detail necessary within the LCSM increase with the increased complexity of the hydrogeologic and plume conditions and the concern related to potential risks. Simply put the more complex the site conditions are to understand, and the more concern there are with sensitive receptors and other risks, there is more value on a very good LCSM to make the best management decision.

An example of this is shown here graphically from ASTM LSCM guide. But basically put the complexity and level of detail in the LCSM follows can follow a tiered approach. Developing a weight-of-evidence determination for the level of complexity needed in the LCSM.

Factors that affect the complexity are shown in the above figure and in the ASTM guide:

LNAPL Training Part 2

- Introduction and Part 1 summary
- LNAPL conceptual site model
- LNAPL site characterization
  - Q&A
  - Hydraulic recovery evaluation and limits
  - LNAPL management objectives and goals
  - Introduction to LNAPL remedial technologies
  - Q&A

No associated notes.
Typically, when one is building the LCSM we are looking at existing data, as well as collection of new data. This data could be as simple as soil borings, groundwater and other direct / conventional methods, laboratory chemical and physical parameters, as well as other more innovative or "indirect" methods as well. Additionally, there are databases\(^1\) and empirical values for sites available for the professional based on similar site soil types as well.

1. API - Light Non-Aqueous Phase Liquid (LNAPL) Parameters Database Database and Guide for Data Retrieval (see www.api.org/Lnapl)
Example LNAPL Indicators

1. Known LNAPL release
2. Observed LNAPL (for example, in wells or other discharges)
3. Visible LNAPL or other direct indicator in samples
4. Fluorescence response in LNAPL range
5. Near effective solubility or volatility limits in dissolved or vapor phases
6. Dissolved plume persistence and center-of mass stability
7. TPH concentrations in soil or groundwater indicative of LNAPL presence
8. Organic vapor analyzer (OVA) and other field observations
9. Field screening tests positive (for example, paint filter test, dye test, shake test)

Modified from: ASTM E2531 Table 1

From ASTM E2531.
These are some example LNAPL indicators but by no means is this an exhaustive list and not all of these indicators need to be assessed at a given site. Some example indicators are:

1. Known LNAPL release
2. Observed LNAPL (for example, in wells or other discharges)
3. Visible LNAPL or other direct indicator in samples
4. Fluorescence response in LNAPL range
5. Near effective solubility or volatility limits in dissolved or vapor phases
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7. TPH concentrations in soil or groundwater indicative of LNAPL presence
8. Organic vapor analyzer (OVA) and other field observations
9. Field screening tests positive (for example, paint filter test, dye test, shake test)
Considerations for Assessing LNAPL Presence Based on Observation

- Estimates of the source area can be based on observations in wells, boring logs, and other visual observations
  - Uncorrected observations should not be used to estimate the volume or recoverability
- Seasonal fluctuations should be accounted into this assessment
- Locations of seeps along banks or other vertical cuts aid in characterizing LNAPL impacts to surface water bodies

• Estimates of the source area can be based on observations in wells, boring logs, and other visual observations
  • Uncorrected observations should not be used to estimate the volume or recoverability
  • [CASE EXAMPLE] – site by river, top figure is a plot of observed LNAPL thicknesses in wells (i.e., apparent thickness). If one were to use these values/observations one would conclude that the LNAPL “upgradient” is connected to the River. However, as shown in the bottom image, the corrected using API models, observations of LNAPL vertical distributions with some innovative methods, and fingerprinting to discern LNAPL types, the picture is quite different and the LNAPL near the river is of immediate concern and the “upgradient” LNAPL self-contained
• As presented in Part 1, Seasonal fluctuations should be accounted into this assessment
• Locations of seeps along banks or other vertical cuts aid in characterizing LNAPL impacts to surface water bodies ← as shown in the example above.
Existing soil data is typically readily available for most sites. However, most of this more historic data is typically in the form of total petroleum hydrocarbon (TPH) data. One way to estimate what the potential saturation of LNAPL within the subsurface is to use an equation developed by Parker, Waddill and Johnson in 1994, which was also presented in the Natural Attenuation text by Wiedemeier, Rifai, Newell and Wilson in 1999.

$$S_{napl} = \frac{\rho_b \cdot TPH}{\rho_n n (10^6)}$$

- $S_{napl}$ = NAPL saturation (unitless)
- $\rho_b$ = soil bulk density (g/cm³)
- $TPH$ = total petroleum hydrocarbons (mg/kg)
- $\rho_n$ = NAPL density (g/cm³)
- $n$ = porosity

(Parker et al, 1994)

Typically, information exists from the logs as well but may not necessarily be to the detail one would like for a LNAPL assessment.


Existing Groundwater Data

- Dissolved-phase plume maps
  - Characterize source area shape, size and depth
  - Assess if natural attenuation on-going
  - Shrinking/stable groundwater plume

\[ \text{Shrinking GW} = \text{Shrinking LNAPL} \]
\[ \text{Stable GW} = \text{Stable/Shrinking LNAPL} \]
\[ \text{Expanding GW} = \text{Stable/Expanding LNAPL} \]

Space not available for notes.
Existing LNAPL Data

- LNAPL thickness data over time
  - LNAPL saturation limits and vertical extent
  - Characteristics of the source zone
  - Confined or unconfined conditions
  - Lateral stability of LNAPL body

LNAPL thickness data over time
- LNAPL saturation limits and vertical extent
- Characteristics of the source zone, growing as shown in the early times from the Part 1 example
- Lateral stability of LNAPL body, becoming stable as shown in the example.
- Confined or unconfined conditions
  - as will be discussed in the Recoverability example later in this presentation.
Continuous Core/Field Measurements

- Detailed soil boring logs through the zone of LNAPL are key includes
  - Lithology, water content, odor, soil structure, organic vapor meter readings
- Oilphillic dyes and ultraviolet (UV) light can aid assessment for presence of LNAPL
- Laboratory data used to supplement if necessary

Key is detail, detail, detail. Can not have enough detail in logs within the core of the LNAPL body. An example of the detail is shown in this log noting lithology, water content, odor, soil structure, OVA readings and other subtle details. This is aided by use of shaker dyes (shown at bottom) and fluorescent lighting via a black box in the field or laboratory methods discussed later in this presentation. But what is evident is the variability in the saturation of the LNAPL qualitatively in the UV light image on the right. Shown on the left of this image is a white light photo of the soil, where one can see a zone of a sand lens near the top, which corresponds to a high observation of UV light in the core. LNAPLs tend to fluoresce due to the double bonds, the higher the fluorescence response; typically the more LNAPL is present.

Source of shaker image from: http://www.cheiron-resources.com; however, other vendors are available.
As noted, only molecules containing double bonds in the LNAPL phase will fluoresce. But we can use this to aid in understanding where is the LNAPL and qualitatively “how much” is there in the subsurface. Shown on the left is a typical LIF response output. In this example we see a perched zone in orange and a the typical response near the watertable with what we like to call the “shark fin”. Along the left of the figure is the waveform, and this can be used to aid in discerning different LNAPL types if they have been properly tuned/calibrated by the operator. An example of an output that can be generated is zone in the middle center image. A image of the tool is zone on right and this is typically paired with a CPT point at the based of the probe.

Membrane interface probe (MIP) is a semi-quantitative, field-screening device that can detect volatile organic compounds (VOC) in soil and sediment. Useful for indentifying potential source zones in vadose zone. The negative of the tool with respect to LNAPL delineation is that it does not discern between sorbed phase, dissolved phase, or LNAPL.

Shown above is how the probe operates via a heating element that volatilizes the near membrane contaminants, a carrier gas within the probe (typically nitrogen) brings the VOCs to the GC/FID or GC/PID and other probes for measure (shown on bottom right). The probe is advanced via direct push (see top right) and the flights are strong with the gas tubing shown in the top center image.

More information is available at: http://cluin.org/char/technologies/mip.cfm
Other Field Tests

- FLUTe
  - Useful in fractured rock and clays to identify location of LNAPL
  - Flexible color reactive liner that changes color in contact with NAPLs

- Others…

No associated notes.
Laboratory Analysis

- Common laboratory methods
  - Soil, groundwater and vapor concentrations
  - Basic soil properties (e.g., grain size, bulk density, distribution, moisture content)
- Specialized laboratory analysis packages have been developed to support LNAPL evaluations for more complex LCSM
  - Fluid properties
  - Pore fluid saturations and soil properties
  - Soil capillary properties
  - Residual saturation
  - Fingerprinting
- Specialized soil sampling and handling procedures

Laboratory Analysis used to enhance LCSM

  Soil, groundwater and vapor concentrations
  Basic soil properties (e.g., grain size, bulk density, distribution, moisture content)

Specialized lab analysis packages have been developed to support LNAPL evaluations, primarily for modeling of LNAPL volumes and recoverability

  Fluid properties
  Pore fluid saturations and soil properties
  Soil capillary properties (e.g., estimate van Genuchten / Brooks-Corey soil parameters)
  Residual saturation
  Fingerprinting

Specialized soil sampling and handling procedures
Specialized Laboratory Packages for LNAPL Characterization

<table>
<thead>
<tr>
<th>What</th>
<th>When and Why</th>
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<tr>
<td>Fluids Properties Package - LNAPL and Water Pair</td>
<td>• Used for LNAPL recoverability evaluation</td>
</tr>
<tr>
<td>• Dynamic viscosity and fluid density at three temps,</td>
<td>• Empirical data exists and can be used as an estimate</td>
</tr>
<tr>
<td>surface and interfacial tension for each fluid pair (LNAPL/water,</td>
<td>• Consider lab tests for unusual LNAPLs, LNAPL mixtures</td>
</tr>
<tr>
<td>LNAPL/air, and air/water).</td>
<td>• Pre and post-treatment testing to evaluate remedy effectiveness</td>
</tr>
<tr>
<td>• $\rho_o$, $\mu_o$, $\rho_w$, $\mu_w$, $\sigma_{ao}$, $\sigma_{ow}$,</td>
<td>• Used for LNAPL recoverability evaluation</td>
</tr>
<tr>
<td>$\sigma_{aw}$</td>
<td>• Used for LNAPL recoverability evaluation</td>
</tr>
<tr>
<td>Pore Fluid Saturation Package</td>
<td>• Pre and post-treatment testing to evaluate remedy effectiveness</td>
</tr>
<tr>
<td>• Pore fluid saturations (NAPL and water) by Dean-Stark extraction;</td>
<td>• Used for LNAPL recoverability evaluation</td>
</tr>
<tr>
<td>total porosity, air-filled porosity, grain density, dry bulk</td>
<td>• Pre and post-treatment testing to evaluate remedy effectiveness</td>
</tr>
<tr>
<td>density, and moisture content.</td>
<td>• Consider lab tests for unusual LNAPLs, LNAPL mixtures</td>
</tr>
<tr>
<td>• $S_o$, $S_w$, $S_t$, $\Phi$</td>
<td>• Pre and post-treatment testing to evaluate remedy effectiveness</td>
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There are labs that have standardized packages, and with these parameters the professional can use sophisticated models and calculations to better understand the potential recoverability, and what parameters need to be manipulated by the remediation technologies to enhance the physical and chemical parameters to meet the site’s management objectives. For instance, surface tension and viscosity can be manipulated via heating of the subsurface, or through the use of surfactants. The benzene or composition within the gasoline could be removed via air sparging or other like stripping technologies as an example.

Fluid Properties Package:
- $\rho_o$ = specific gravity of oil [typical units g/cm³]
- $\mu_o$ = dynamic viscosity of oil [typical units centipoise, centistokes, Pascal-second]
- $\rho_w$ = specific gravity of water [typical units g/cm³]
- $\mu_w$ = dynamic viscosity of oil [typical units centipoise, centistokes, Pascal-second]
- $\sigma_{ao}$ = surface tension of oil (i.e., interfacial tension of air and oil) [typical units dynes/cm]
- $\sigma_{ow}$ = interfacial tension of oil and water [typical units dynes/cm]
- $\sigma_{aw}$ = surface tension of water (i.e., interfacial tension of air and water) [typical units dynes/cm]

Pore Fluid Saturation Package
- $S_o$ = oil saturation within pore space [%] or normalized to scale of 1.0 of pore space
- $S_w$ = water saturation within pore space [%] or normalized to scale of 1.0 of pore space
- $S_t$ = total saturation
- $\Phi$ = total porosity (measure of void space within total volume) [dimensionless]
- bulk soil density [typical units g/cm³]
- soil grain density [typical units g/cm³]

Details about test methods are available in these notes and from API 4711 and API 4760, at www.api.org/lnapl, we unfortunately do not have the time in this training to go into the details of the methods; however, future trainings are planned to cover this topic in greater detail, as well as the upcoming technical guidance document.

**Methods for Determining Inputs to Environmental Petroleum Hydrocarbon Mobility and Recovery Models, API Publication 4711, July 2001**

**LNAPL Distribution and Recovery Model (LDRM), API Publication 4760, January 2007**
Specialized Laboratory Packages for LNAPL Characterization (continued)

<table>
<thead>
<tr>
<th>Capillarity Package: Air/Water Drainage</th>
<th>What</th>
<th>When and Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Air/Water Drainage Capillary Pressure Curve (air displacing water) with Air Permeability and Hydraulic Conductivity: includes fluid production vs. capillary pressure, total porosity, dry bulk density.</td>
<td>• Used for LNAPL recoverability evaluation</td>
<td>• Provides data needed to estimate van Genuchten, and Brooks-Corey water retention curve (calculated from data)</td>
</tr>
<tr>
<td>• Sw, φ, Kw, (M, α), (λ, P_d)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LNAPL Residual Saturation</th>
<th>What</th>
<th>When and Why</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Centrifuge and/or water drive</td>
<td>• Used for LNAPL recoverability evaluation</td>
<td>• Define effectiveness limits of dual and multi-phase extraction</td>
</tr>
<tr>
<td>• S_or</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Capillarity Package: Air/Water Drainage
• Sw = Irreducible water saturation
• φ = porosity
• Kw = hydraulic conductivity of water
• Water retention curve models
  • Van Genuchten soil parameters:
    • M = van Genuchten fitting parameter [dimensionless]
    • α = van Genuchten fitting parameter [L²/F]
  • Brooks-Corey soil parameters: λ, P_d
    • λ = lambda [dimensionless]
    • P_d = displacement pressure [F/L²]

LNAPL Residual Saturation
• S_or = Irreducible oil saturation

van Genuchten References:

Brooks-Corey References:

Comparing/Converting Between Both Models

Additional information regarding parameters:
Methods for Determining Inputs to Environmental Petroleum Hydrocarbon Mobility and Recovery Models, API Publication 4711, July 2001
LNAPL Distribution and Recovery Model (LDRM), API Publication 4760, January 2007
Define data needs based on assessment objectives

Laboratory packages may not include everything required and may include data not required

LNAPL parameters may be estimated

- Published “default” or “average” parameters published for soil textural class determined from lithology and grain size distribution (e.g., API Interactive LNAPL Guide)
- Empirical databases useful through comparison of basic site soil properties (e.g., API Parameter Database)

Shown on this figure is an example of a Grain Size distribution (left), and a water retention curve (right)

References at www.api.org/lnapl:

- **LNAPL Distribution and Recovery Model (LDRM)**
  API Publication 4760
  January 2007

- **API Interactive LNAPL Guide Version 2.0**
  August 2004
Why Not Just Use Estimated Values?

- Estimated values versus laboratory measurements
  - Consider accuracy versus cost
  - Is reduction in uncertainty likely to impact management decision?
  - Not all information is needed for every site

- Typical process for characterization
  - Use estimated values and existing data first
  - Conduct sensitivity analysis
  - Site-specific analyses
    - Tiered data collection
    - More useful at complex sites based on geology, composition, risk, receptors

No associated notes.
Summary of LCSM and LNAPL Characterization

- LCSM helps to understand LNAPL site conditions, risks, if/why a remedy is needed and supports management decisions
- Site characterization methods and comprehensiveness are a function of the complexity of the LNAPL site conditions
- LNAPL distribution is not as simple as we thought
  - Not distributed as a pancake
  - Vertical equilibrium
  - LNAPL saturation is not uniform

No associated notes.
As was mentioned earlier, the LCSM is a site characterization and management link. Ultimately a good LCSM will support the identification of appropriate objectives and setting relevant goals for the site, which will aid in the management options for the site.
LNAPL Training Part 2

- Introduction and Part 1 summary
- LNAPL conceptual site model
- LNAPL site characterization
- Q&A
  - Hydraulic recovery evaluation and limits
  - LNAPL management objectives and goals
  - Introduction to LNAPL remedial technologies
- Q&A

Building on the concepts presented in the Part 1 training, this section will continue to build out the LNAPL Conceptual Site Model with the hydraulic recovery evaluation.
LNAPL Training Part 2

- Introduction and Part 1 summary
- LNAPL conceptual site model
- LNAPL site characterization
- Q&A

Hydraulic recovery evaluation and limits
- LNAPL management objectives and goals
- Introduction to LNAPL remedial technologies
- Q&A

Building on the concepts presented in the Part 1 training, this section will continue to build out the LNAPL Conceptual Site Model with the hydraulic recovery evaluation.
Focus of talk and the hydraulic recovery evaluation is on the LNAPL body itself – represented here by numbers 4 and 5.

Both of these address the non-risk-based concerns of potential mobility and the aesthetic or regulatory concerns of LNAPL presence in a well.

Primary concern of both regulators and stakeholders….is the LNAPL moving?

Also represents one of the biggest misperceptions, that if there is LNAPL in a well, it is mobile and migrating and similarly recoverable.

Recoverability evaluation very important step in getting all parties on the same page with respect to understanding the LNAPL body and how to approach its remediation.
So how much LNAPL is potentially recoverable?

Illustrate this using the theoretical saturation profile.

The potentially mobile and therefore recoverable LNAPL is that amount that exists above the residual saturation.

Residual saturation is illustrated as two values - for both above and below the water saturated zone.
Objectives of Recovery Predictions

- Design of efficient (realistic) free-product recovery systems
- Provide estimates of recovery performance
- Provide estimates of recovery time
- Provide a means of establishing practical goals

The objectives of recovery predictions are to design efficient free product recovery systems using trenches, skimmer wells and single and dual-pump wells, to provide estimates of recovery performance, to provide estimates of recovery time, and to provide a means of establishing practical endpoints. Over the next few slides, recovery predictions using analytical models will be described, so the relationship between the soil and fluid properties and the understanding developed earlier becomes clear.

Based on the complexities of LNAPL occurrence and behavior, and the misconceptions, LNAPL volumes and recovery are typically over-estimated.

Important point to remember, however, is that LNAPL recovery is limited and finite. As you recover the LNAPL, its saturation is being decreased, and therefore, its mobility and recoverability is diminishing.
Methods to Estimate Potential Recoverability

- Weight of evidence
- Field methods
  - Baildown tests
  - Pilot test technologies
- Desktop methods
  - Extrapolate existing system performance
  - Predictive models

Several ways to assess recoverability
The weight of evidence approach can be very useful for evaluating mobility.

This topic is discussed in relatively new documents from the Massachusetts Licensed Site Professionals, as well as a recent guidance document from the Wisconsin Department of Commerce and Natural Resources.

Wisconsin Department of Commerce & Wisconsin Department of Natural Resources Assessment Guidance for Sites with Residual Weathered Product (PUB-RR-787):  

Massachusetts Licensed Site Professionals LNAPLs and the Massachusetts Contingency Plan Part I:  

Massachusetts Licensed Site Professionals LNAPLs and the Massachusetts Contingency Plan Part II:  
http://www.lspa.org/download/whitepapers/LSPALNAPLPartII.pdf

A spill of heavier oil such as No. 6 fuel is a simple example, where we know that this material is not mobile under typical subsurface temperatures.

A known release date or volume are also very useful indicators for potential recoverability, as it is generally well understood that LNAPL spills spread out relatively quickly, and reach of point of stability within a short period of time.

Plume stability can demonstrated fairly easily using historic monitoring data that has been collected consistently over time.
An LNAPL baildown test is performed and analyzed very similarly to a water baildown test but with some important differences. First, instead of the water being evacuated from the well, only the LNAPL is removed – in practice this is hard to do. We often try to do it with a vacuum truck rather than a bailer. Instead of only monitoring the water-air interface, both the water-LNAPL and LNAPL-air interfaces need to be monitored versus time. The figure shows a plot of such data.

There are two methods for analyzing the data. The first is that of Lundy and Zimmerman, and the second is that of Huntley. We typically use both and compare them to theory.

There are practical limitations to the test. First, there needs to be enough LNAPL in the well to measure and determine a change in thickness of LNAPL flow into the well. Second, the conductivity of the LNAPL needs to be great enough that the LNAPL flows back into the well. Thus, for high viscosity liquids (about 10 centipoise or higher) or low permeability soils, several days may be required for the LNAPL to flow into the well which could be a problem if the potentiometric surface also changes.

Similar to a typical slug test for determining soil hydraulic properties

Baildown test involves rapidly removing LNAPL from the well while minimizing recovery or disturbance of the groundwater.

Although this is a short term test and quite simple, it can provide valuable information.
The baildown test can then be used to calculate the oil transmissivity.

This solution has been described by David Huntley at San Diego State University.

The calculation of T from baildown tests is based on modifications of the familiar slug test solutions provided by Bower and Rice and Cooper-Jacobs, correcting for LNAPL fluid properties and multiple fluid phases in the system.

Very useful way to quantify LNAPL mobility.

Pilot tests provide some of the most valuable information regarding potential LNAPL recoverability, particularly for simpler sites where more complex modeling may not be warranted.

Similar to baildown tests, they can be used to quantify important parameters such as T.

Slide shows real data from a site with multiple varying product bodies over a fairly large area.

The bar chart summarizes the total volume of LNAPL recovered from each of several wells over a 48-hour skimming pilot test conducted in each well.

Total recovered volumes ranged from less than 10 gallons to over 250 gallons.

It must be noted that the total recovered volumes from the wells does not correlate with the initial product thickness in the wells.
The zone of highest LNAPL saturation has the highest LNAPL conductivity.

Low LNAPL saturation results in low LNAPL conductivity.

Hydraulic recovery rate is proportional to transmissivity for a given technology.

Well thickness does not dictate relative recoverability.

\[ T_o = K_o \cdot b_o \]

The graphic at the right shows both a soil core and a monitoring well under ultraviolet light.

The LNAPL conditions in the soil and well fluoresce.

The typical LNAPL saturation profile illustrates saturation over the vertical interval.

Highest LNAPL saturation has highest conductivity.

Low saturation = low conductivity

Hydraulic recovery is proportional to \( T \), and is not indicated accurately by LNAPL well thickness.
These next two slides provide an example using real site data.

Baildown test, but only shows recovered (rebounded) LNAPL thickness.

This first graph illustrates the results of baildown tests on three wells, each with a different initial LNAPL thickness.

These test results were used to calculate transmissivity for each well.
## LNAPL Transmissivities and Thicknesses (in a Well)

### Key Points:
- LNAPL thickness is a poor indicator of LNAPL recoverability → thickness is too dependant on soil type, heterogeneity, water levels, LNAPL occurrence (confined, perched, unconfined), etc.
- Transmissivity (via baildown tests, pilot test, or existing recovery data) is a more direct measure of LNAPL recoverability that factors in soil type heterogeneity and water levels.

(Atlantic Richfield Corporation, 2008)

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<table>
<thead>
<tr>
<th>Location</th>
<th>Approximate Gauged Thickness (ft)</th>
<th>Recovery Rate Based on Baildown Test Data</th>
<th>LNAPL Transmissivity (ft²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMR/200-D</td>
<td>15</td>
<td>40 (LNAPL Skimming (GPD))</td>
<td>115 (1 GPM - Water Enhanced Recovery (GPD))</td>
</tr>
<tr>
<td>AMR/185-6</td>
<td>30</td>
<td>0.4 (LNAPL Skimming (GPD))</td>
<td>0.7 (1 GPM - Water Enhanced Recovery (GPD))</td>
</tr>
<tr>
<td>AMR/606-D</td>
<td>34</td>
<td>2 (LNAPL Skimming (GPD))</td>
<td>5.7 (1 GPM - Water Enhanced Recovery (GPD))</td>
</tr>
</tbody>
</table>

This slide shows a comparison of the data for the three wells tested on the previous slide.

This table provides transmissivity and recovery calculations for the wells on the previous slide. Note the well with the greatest LNAPL thickness (34 ft) recovers much more slowly and has lower LNAPL recovery rates than the well with 15 ft of LNAPL thickness.

The well with the least thickness resulted in the best recovery rate; and the wells with much higher thicknesses resulted in much lower recovery.

The transmissivity values correlated well with the recovery rates.
The next several slides present desktop methods to assess recoverability.

The first slide presents the decline curve analysis. This is a great way to extrapolate existing system performance data to predict total recoverability.

For mature and efficient recovery systems operated in a consistent mode – the declining recovery data will fit a straight line.

Extrapolation of the straight line to some practical recovery rate provides an estimate of total recoverable LNAPL.
This slide provides a real life example.

The blue bars indicate daily recovery.

The cumulative recovery curve, shown in red, illustrates the typical asymptotic curve where continued system operation is having little benefit adding to the total cumulative recovery of approximately 3,700 gallons.
This slide is showing the same site data as the previous slide, plotted using the decline curve.

The best fit line through the data, extrapolated to the x-axis or zero recovery rate, indicates the total maximum recoverable volume.

In this case, the extrapolation is very short as the system had already reached its practical limit, again at a total recovery of around 3,700 gallons.
Desktop Methods
Predictive Models for LNAPL Recovery

- **Analytical models** (e.g., API LNAPL Distribution and Recovery Model (LDRM), and API Interactive LNAPL Guide)
  - 1-D analytical
  - Relatively easy to use and inexpensive
  - Good estimates (if properly applied)
  - API LNAPL parameters database

- **Numerical models** (e.g., ARMOS, BIOSLURP, MAGNAS3, MARS, MOTRANS, MOVER)
  - 2-D, 3-D; consider need!
  - Can be headaches and expensive
  - May be, but not necessarily, more accurate

Links to these API resources are provided in the end of this training.

American Petroleum Institute Light Non-Aqueous Phase Liquid Resource Center:
Predictive Models for LNAPL Recovery

- Models typically are based on vertical equilibrium (VEQ) model and utilize in well LNAPL thicknesses
- If there is recovery or transmissivity measurement data, can try to “calibrate” model to match recoveries
- Modeling may be appropriate on more complex sites, may be useful as what-if predictor to evaluate different scenarios
- Additional site specific data generally required as complexity of model increases

It is important to remember the underlying assumptions behind these model solutions.

As you learned in the Part 1 training, these are typically based on the vertical equilibrium (VEQ) model and utilize in well LNAPL thickness for an unconfined aquifer.

These models are typically appropriate for more complex sites and can be very useful to predict and help assess different recovery scenarios.
Using single layer API model.

This slide shows an example of a good model prediction of actual system recovery.

During system operation, it was found that nearby pumping conditions by others were varying substantially and therefore, affected the accuracy of the model predictions.
Using LDRM 3-layer model.

This slide illustrates the results of updated site modeling performed using a three layer model and additional years of recovery.

As shown by the updated orange model prediction, the three layer model was more representative and better matched the actual recovery system performance.
What is the uncertainty in the predictive models?

- Vertical equilibrium?
- Hydrogeologic properties
- Spatial and vertical heterogeneity
  - Geologic
  - Texture/capillary properties
  - Fluid properties
- Residual saturation
- Radii of capture and influence
- Ideal versus real wells

**Key Point:** Many of these lead to overestimating volume and recovery rate, and underestimating time of recovery

The user must assess the uncertainty behind the modeled solutions.

Even when done very carefully, models should be considered approximations.
Case Study: Recoverability Analysis Overview

- Closed refinery RCRA site
  - 250 acres underlain by hydrocarbons
- 180 acres of LNAPL with potential to migrate (evaluate with modeling)
- Remedy decision: LNAPL recovery is required
  - Where LNAPL with the potential to migrate exists within 300 ft of downgradient boundary
  - Where LNAPL is a source of benzene to groundwater
- Hydraulic conductivities 240-350 feet/day
- DTW 8-12 feet
- Gasoline, diesel, lube oil, and composite
- Currently, 300,000 gallons per year of recovery

Case 4 is the development of a recovery plan for LNAPL at a closed refinery that has reuse potential. It is a RCRA site of 250 acres underlain by LNAPL some of which has a very low conductivity and some of it is at residual saturation. There are about 180 acres of LNAPL that may have the potential to migrate.

The question was how to define “potential to migrate”.

The Remedy Decision for the site is that LNAPL recovery is required when: LNAPL with the potential to migrate exists within 300 ft of downgradient boundary – the question is how to define “potential to migrate”. This will be explored using our new understanding. The other Remedy Decision is when LNAPL is a source of benzene to groundwater; this will not be explored here because the subject is beyond this training.
This figure depicts the areas that were suspected of containing LNAPL that had an ability to migrate. The different colors (yellowish and pinkish) are from different investigations and don’t mean anything for this training. The receptor is the North Platte River.

Figure shows the site area initially suspected of having LNAPL with the potential to migrate.
Case Study: Data and Model Comparisons

- Correlate LIF, capillary data, and saturation with API spreadsheets
- Make saturation and conductivity predictions and validate versus field data

The analysis method used here was performed by Brubaker and others, and involved developing a corrected LNAPL saturation profile with depth by correlating saturation data from LIF/ROST, with saturation measurements from soil borings across the site.

This profile was then correlated with saturation curves calculated using the API spreadsheet. This data is shown in the figure on the left.

The saturation data was then used to make conductivity predictions vs. depth that were then validated with baildown tests.

The right figure shows the agreement that can be expected between calculated and baildown test-determined conductivities.

Scatter in data is due primarily to the varying distance between tested wells and the corresponding borings used for the calculated conductivities, however, overall the graph illustrates reasonable predictions.
Case Study: LNAPL Transmissivity Distribution

Blue = >10^{-2} \text{ cm}^2/\text{sec} (2.5 \text{ acres})
Teal = >10^{-3} \text{ cm}^2/\text{sec} (23 \text{ acres})
Grey = >10^{-4} \text{ cm}^2/\text{sec} (82 \text{ acres})
Brown = >10^{-5} \text{ cm}^2/\text{sec} (179 \text{ acres})

This map was generated to illustrate the distribution of LNAPL transmissivities calculated using the API spreadsheet.

Substantial area, approximately 179 acres, is represented by the low transmissivity values.
Case Study: Summary of Results

- LNAPL recovery will only be implemented within areas that contain benzene impacted LNAPL at an initial transmissivity greater than $10^{-4}$ cm$^2$/sec

- Approximately 46 acres (180 acres previously)

In regulatory negotiation and incorporating the potential reuse of the site, the LNAPL recovery was only to be implemented within areas that contain benzene impacted LNAPL at an initial conductivity greater than $10^{-4}$ cm$^2$/sec. This corresponds to 0.15 ft thickness with a gasoline type product and is approximately 46 acres whereas approximately 180 acres were previously thought to require recovery. This saves a substantial amount of resources for other beneficial uses.
LNAPL Recoverability Summary

- Transmissivity
  - Most universal (site and condition independent)
  - Estimated with recovery data or field testing on monitoring wells
  - Consistent across soil types (the transmissivity accounts for it)
  - Consistent between recovery technologies
  - Consistent between confined, unconfined or perched conditions
- Transmissivity provides a consistent measure of recoverability and impacts across different LNAPL plumes within one site or across multiple sites
- If LNAPL transmissivity high, recoverability is high

No associated notes.
LNAPL Recoverability Summary

- LNAPL thickness
  - Inconsistent between hydraulic scenarios (unconfined, confined, etc)
  - Inconsistent between soil types
- LNAPL recovery rate (presupposes have a recovery system, and a good one)
  - More robust metric than LNAPL thickness
  - Need recovery system or pilot test data
  - Operational variability and technology differences make it difficult to use across technologies and/or sites
  - Decline curve analysis very useful for long term predictions

The other typical metric used is LNAPL recovery rate. Recovery rate is a more robust metric than apparent LNAPL thickness. However due to a number of variables such as operational issues, potential confining conditions, and fluctuating water tables, recovery systems typically exhibit variability with regards to LNAPL recovery. This point will be illustrated in the example we’ll go over.

LNAPL thickness is a poor indicator for recoverability, and in fact can be quite misleading.

By comparison, LNAPL transmissivity as a remediation metric factors out these variables, resulting in a metric that is dependent primarily on the relative level of free-phase LNAPL impacts.
illustrated in this modeled example, our monitoring well post-hydraulic recovery is shown without any LNAPL thickness.

It must be noted that this is not always the case, and that well thicknesses can occur following a practical end point to hydraulic recovery.
Important to understand potential risks associated with residual LNAPL left behind following recovery.

As illustrated in the figure on the right, removal of all recoverable LNAPL does not reduce the dissolved benzene concentration.
Will mass recovery of LNAPL abate the risks and concerns associated with the LNAPL?

And what are the appropriate remediation objectives for LNAPL?
LNAPL Training Part 2

- Introduction and Part 1 summary
- LNAPL conceptual site model
- LNAPL site characterization
- Q&A
- Hydraulic recovery evaluation and limits
- LNAPL management objectives and goals
- Introduction to LNAPL remedial technologies
- Q&A

No associated notes.
Now that you've characterized the site, developed a LNAPL conceptual site model, and evaluated the recoverability, we want to set some objectives. Our goal may be to meet a state standard in soil and to return groundwater to acceptable use. To reach this goal, we would need to excavate all LNAPL contaminated soils. Knowing where you're heading, helps you plan an approach. As a state regulator I have seen many remediators spending large amounts of money on a site without an end goal in mind. They didn’t understand the site from the start and didn’t have a goal in mind when they started.

What types of goals may be important? Compliance with existing regulations and rules, achieving beneficial land use (intermediate and long-term), reducing risk by managing exposures, returning aquifers to maximum beneficial use, non-risk goals (aesthetic issues)
The Importance of Establishing a Long-term Vision

- Gets stakeholders on the same page
- Begin to flesh-out what is achievable
- Sets the stage for discussing objectives and goals
- Long-term vision may be revised if goals are later found not achievable
- A long-term vision can be developed for operating or inactive sites

Establishing the goal early on saves time, money and resources. It helps get all the stakeholders on board with the project. Sets the stage for a meaningful conversation with the site owner, regulator and consultants. Depending on site conditions through time, your goals may change. A great resource to use is the document from the Federal Environmental Protection Agency (EPA) "A Decision-Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquids (LNAPL)" A link to the document in at the end of our presentation.

State/Federal Regulatory:
- Evaluate workplans and recommend remedial/monitoring strategies
- Sound and consistent decision making

Consultants:
- Better understanding/predictions recovery, system design

Industry/Owners:
- Understand when/why action warranted
- Collaboration between public and private stakeholders

Stakeholders:
- Better understand risk and non-risk based cleanup objectives and differing land use goals with LNAPL issues.

Anyone who needs basic information about the behavior of LNAPL in the subsurface.
**LNAPL Remediation Objectives**

- Risk-based objectives
  - Reduce risk-level or hazard
  - Exposure pathway/LNAPL specific
- Non-risk objectives (examples)
  - Reduce LNAPL flux
  - Reduce source longevity
  - Reduce LNAPL mass or well thickness
  - Reduce LNAPL transmissivity
  - Abate LNAPL mobility
  - Corporate policy – liability/risk tolerance
- Regulatory driver: “recover to maximum extent practicable”
  - Different states have different interpretation

- Potentially a different remedial strategy to target LNAPL saturation versus LNAPL composition drivers

- Evaluate whether applicable objective(s) are best addressed by reducing LNAPL saturation or by modifying the LNAPL composition

By addressing the other, Maximum Extent Practicable (MEP) takes a back seat, but still adequately addressed. Site Characterization → good LCSM → gives good reasoning as to what/how needs to be recovered, and thus inherently addresses the MEP criterion

An issue at thousands of site
Perceived as significant environmental threat
Technical and regulatory complexity
Typically no clear policy/regulation framework for decision making
RCRA, HSWA, CERCLA, …LNAPL not specifically addressed
UST 40 CFR 280.64 (1988): “…remove free product to the maximum extent practicable as determined by the implementing agency…”

Many developed/determined prior to current State of Knowledge
Federal Statute, State Statute/Regulation, Policy, Guidance Document Ranges from...

Remove all detectable levels of LNPL at all sites ,
Defined measurable amount (.01’-1/8”),
Risk based/Site Specific
No clear requirement

Multiple policies within same State - Project Manager to Project Manager

Unresolved LNAPL issues hold up site closure
Unending LNAPL management costs can dominate the limited resources
Goals Provide the Measure of Performance

- Goals should provide metrics to measure achievement of specific LNAPL management/remediation goals.
- Goals are highly site and project-specific
- Goals quantify the point at which active systems can be shut down
- Goals can be phased or tiered

An example here might be you have an LNAPL release, your LNAPL is mobile and migrating to a drinking water well. Our endpoint is no LNAPL in the drinking water well. We install recovery wells in the proper locations – because we’ve done a good characterization and have our LNAPL site conceptual model developed. We understand the LNAPL body is hydraulically recoverable and have installed a system to remove it.
Recovery versus Control-Based Goals

Considering residual LNAPL complications, what is the applicability of control-based goals?

- Acceptable for only specific objectives or site conditions?
  - Certain or all risk-based objectives?
  - Certain or all non-risk objectives?
- Only if no effective way to further recovery and risks remain?
- Anytime controls be can reliably applied?
- Consistent with planned use

Consider if and when control-based endpoints are potentially acceptable as a concept. As they “design” an LNAPL management strategy as a program or for a site, they should realize control-based endpoints may also have a place at the table: after LNAPL recovery, in conjunction with LNAPL recovery, or in lieu of LNAPL recovery, depending on the situation/concerns.

Engineering controls: e.g., vapor controls
Institutional controls and long term stewardship: e.g., restrictive covenant

As we’ve learned from our Part 1 training, the residual saturation of LNAPL at a site if difficult to remove. So if we’ve hit a recovery endpoint, we now need to look to another endpoint. The remediator now needs to choose how to address the residual phase. In many situations, the residual can be managed through a long term control. This can be an engineered control such as periodic product removal. Or it can be an institutional control such as a restriction on the use of groundwater at the property. These may not be protective enough or other risks remain. I had a site where the was residual LNAPAL, but no dissolved phase plume. Groundwater was not used in this city, there are ordinances in place and also environmental covenants on the deed. This property is under redevelopment. Now there is an issue with infiltrating the storm water through the LNAPL area. They are going to have to come up with an alternate plan for the stormwater. Yes, they met a regulatory endpoint, but it has now become an issue for redevelopment.
Pioneering: Examples of Setting Objectives and Goals

- A Decision-Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquids (LNAPL), USEPA OSWER 542-R-04-011
- Risk-Based NAPL Management, TCEQ RG-366/TRRP-32


Here are some documents that you can reference.
LNAPL Training Part 2

- Introduction and Part 1 summary
- LNAPL conceptual site model
- LNAPL site characterization
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- Q&A

No associated notes.
Choosing a Remedial Technology

You now have an understanding of your site, you know what is recoverable (hydraulically) and you have goals and objectives in mind.

What physical parameters will a remedial technology manipulate?
- Composition
- Saturation

No associated notes.
LNAPL Composition

- LNAPL composition is modified by increasing rates of volatilization and dissolution from the LNAPL body – phase change from liquid to vapor phase or liquid to dissolved phase.

- Example technologies
  - In-situ chemical oxidation
  - Soil vapor extraction, or in combination:
    - Air sparging
    - Heating
    - Steam injection

For example, remediation by chemical oxidation involves the injection of strong oxidants such as hydrogen peroxide, ozone gas, potassium permanganate or persulfates to break down compounds dissolved from the LNAPL via direct reactions or by providing the natural bio-organisms more oxygen to break down the dissolved-phase compounds via bio-chemical processes. The increased the dissolved-phase loss rate, reduces dissolved-phase concentrations which increases the concentration gradient between the LNAPL and the groundwater, resulting in a higher rate of dissolution of soluble compounds out of the LNAPL, changing its composition to a less soluble LNAPL.

Vapor technologies, increase the vapor gradient between the LNAPL and the native environment, increase the rate of volatilization out of the LNAPL and changing the LNAPL composition to a low volatile content. These technologies may leave LNAPL in place, but can reduce or eliminate other pathway concerns such as explosive vapor accumulations, inhalation of toxic vapors, or ingestion of dissolved compounds, which may be the effective endpoint for the site/LNAPL recovery.

Steam injection, increases the volatility, changing the composition by reducing the composition of the volatile fraction of the LNAPL composition.
LNAPL Saturation

- Reduce LNAPL saturation by bulk LNAPL mass removal via excavation or fluid flow recovery
- LNAPL fluid factors to manipulate
  - LNAPL gradient – skimming, hydraulic recovery, water flood, high vacuum extraction
  - LNAPL viscosity – heating, hot water flood
  - Interfacial tension – surfactant/co-solvent flushing
  - Wettability – surfactant/co-solvent flushing

It takes a fluid gradient (pressure) for LNAPL to move into or out of pores – displacement entry head. When moving in or out of pores, an LNAPL droplet may encounter pore throats that are smaller than the droplet size. Sufficient pressure must be exerted to deform the droplet in order for it to move through the pore throat.

LNAPL skimming directly creates an LNAPL gradient, inducing LNAPL fluid flow. Hydraulic recovery methods, change the hydraulic gradient of the groundwater which can indirectly increase the LNAPL gradient.

Steam injection, for example, creates pressure gradients as first cold water is pushed in front of the steam as it spreads from the injection site to across the LNAPL body. The cold water pressure is followed by hot water advancing in front of the steam front which increases pressure and reduces viscosity. Finally, steam further decreases viscosity, but as stated earlier, it also increase volatility. So it not only decreases saturation by increasing bulk LNAPL fluid recovery, but can modifies the composition of the LNAPL.

Low viscosity fluids flow more readily than higher viscosity fluids. Heating LNAPL reduces LNAPL viscosity.

LNAPL flow can be enhanced by lower the interfacial tension and wetting contact angles between pore water and LNAPL. LNAPL interfacial tension and wetting contact angles can be reduced by surfactants and co-solvents.
LNAPL Saturation – Pore Entry Pressure

LNAPL needs to displace existing fluids to enter a pore

- Heating technologies reduce the viscosity of the LNAPL, therefore you need less pressure to move the LNAPL through the water wet pores
- Hydraulic pumping can too, but LNAPL may still be trapped and can’t be removed via hydraulic methods

Displacement head for LNAPL-water system, the LNAPL head required to displace water from water-filled pores

Easier for LNAPL to displace air (vadose zone) than water (saturated zone)
Hard for LNAPL to displace water from finer-grained pores

It takes pressure for LNAPL to move into or out of pores. To move in or out of these pores, a droplet may encounter pore throats that are smaller than the droplet size. Sufficient pressure must be exerted to deform the droplet in order for it to move through the pore throat. The situation is illustrated in this slide.

- In the upper figure, the pressure gradient is too low to deform the LNAPL droplet and allow it to move through the pore throat. In the lower figure, the pressure is sufficient to deform the droplet and make it mobile. In this scenario, the LNAPL is recoverable.

- Difficulty in overcoming the pressure gradient is the reason why LNAPL fills the large pores first in a water-wet soil. It is also why some LNAPL is trapped in the pores during recovery and cannot be removed using hydraulic recovery methods, such as pump-and-treat.
LNAPL Saturation – Capillary Pressure

- Capillary pressure highest at LNAPL-air interface and zero at Water-LNAPL interface
- Higher the capillary pressure, the higher the LNAPL saturation
- Surfactants help break the interfacial tension that is responsible for capillary rise.

In porous media, the smallest pores will take in the water first and hold it the tightest. It takes significant pressure to get the water out of the smallest pores. This attribute is why coarse sands and gravels have a relatively small capillary fringe, while silts and clay have a large capillary fringe (and hence, stay moist). Because of the smaller pore sizes, silts and clays hold water more tightly and exhibit a higher capillary pressure than sands.

Surfactants reduce interfacial tension and allow residual LNAPL to escape from the small pores and flow to a capture zone. Then the LNAPL is in solution and can be easily pumped out. Co-solvents do the same thing.
LNAPL Saturation – Viscosity

- Viscosity of LNAPL is measured when evaluating mobility
- Distinct differences between different petroleum products
- Mixtures of different products at sites
- Weathering that occurs over time, which may change viscosity
- Heating up the LNAPL body reduces the viscosity; therefore, the interfacial tension holding the LNAPL in place – moves easier to a recovery well

LNAPL conductivity is inversely proportional to its viscosity
Heat or steam reduces LNAPL viscosity and increases its volatilization
Each one of these blocks represents a place where the remediator can plan their attack. The remediator has many choices to make about how to approach the problem. As a regulator we need to make sure that whatever remedy or combination of remedies successfully control the site risks now and into the future.

Key Point: Remedial options include all remedies which control the site risks (i.e., site exposures).
There are natural processes that begin when the LNAPL is released into the environment. These processes occur regardless of any remediation being applied. ITRC LNAPL team has a technology overview document available you can review that goes into detail on this process and how to predict the mass lost due to the process.

Because residual hydrocarbons are both tightly bound and discontinuous in pore spaces, they are essentially immobile and, therefore, not amenable to collection by standard free product recovery methods. However, the residual phase often represents a potential long-term source for continued groundwater contamination. Although some portion of the residual mass will be slowly diminished (i.e., will naturally attenuate) over time as the result of dissolution, volatilization, and biodegradation, more aggressive remedial action may be required to mitigate this source within a reasonable amount of time.
Relate endpoints to technology capabilities

Barrier wall / slurry wall / sheet piling
Air sparging – injecting air / ozone to strip out vapors and to add oxygen for natural attenuation
Soil vapor extraction (SVE) – capturing soil vapor

Dual phase pulling down the water table with one pump and then pumping the LNAPL out with another one
Total fluids – one pump getting both water and LNAPL
Multiphase – pumping out air, water and LNAPL – using vacuum system most common

Water flooding – Increase the hydraulic gradient to force the LNAPL to the recovery well
In-situ chem/ox – inject a chemical oxidizer (peroxide/persulfate. Permangenate/ozone) to react with the LNAPL body
Radio heating – using radio waves lower temperature than electrical resistance
Co-solvent – use a chemical to increase the solubility of the LNAPL to get it moving

Visit www.itrcweb.org for more information on some of these technologies.
LNAPLs Training Part 2 Summary

- LNAPLs more complex than thought – apply the LCSM concept
- LNAPL characterization should be commensurate with the LNAPL site complexity and risks
- LNAPL fluid recovery addresses mobility – recovery potential is limited – LNAPL concerns saturation or composition driven?
- Consider matching LNAPL concerns with remediation objectives

No associated notes.
Thank You for Participating

Links to additional resources at:
• http://www.cluin.org/conf/itrc/LNAPLcr/resource.cfm

Question and Answer Break

Links to additional resources:
http://www.cluin.org/conf/itrc/LNAPLcr/resource.cfm

Your feedback is important – please fill out the form at:
http://www.cluin.org/conf/itrc/LNAPLcr/

The benefits that ITRC offers to state regulators and technology developers, vendors, and consultants include:
✓ Helping regulators build their knowledge base and raise their confidence about new environmental technologies
✓ Helping regulators save time and money when evaluating environmental technologies
✓ Guiding technology developers in the collection of performance data to satisfy the requirements of multiple states
✓ Helping technology vendors avoid the time and expense of conducting duplicative and costly demonstrations
✓ Providing a reliable network among members of the environmental community to focus on innovative environmental technologies

How you can get involved with ITRC:
✓ Join an ITRC Team – with just 10% of your time you can have a positive impact on the regulatory process and acceptance of innovative technologies and approaches
✓ Sponsor ITRC’s technical team and other activities
✓ Use ITRC products and attend training courses
✓ Submit proposals for new technical teams and projects