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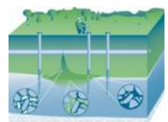
Welcome – Thanks for joining us.
ITRC's Internet-based Training Program

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

Sponsored by: Interstate Technology and Regulatory Council (www.itrcweb.org)
Hosted by: US EPA Clean Up Information Network (www.cluin.org)

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 Unfortunately, many environmental professionals have a faulty understanding of LNAPL conditions based on outdated paradigms.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 three 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.

LNAPL Training Part 3: Evaluating LNAPL Remedial Technologies for Achieving Project Goals - uses the LNAPL conceptual site model (LCSM) approach to identify the LNAPL concerns or risks and set proper LNAPL remedial objectives and technology-specific remediation goals and performance metrics. The training course also provides an overview of the LNAPL remedial technology selection framework. The framework uses a series of tools to screen the seventeen remedial technologies based on site and LNAPL conditions and other important factors.

ITRC (Interstate Technology and Regulatory Council) www.itrcweb.org

Training Co-Sponsored by: US EPA Technology Innovation and Field Services Division (TIFSD) (www.clu-in.org)

ITRC Training Program: training@itrcweb.org; Phone: 402-201-2419

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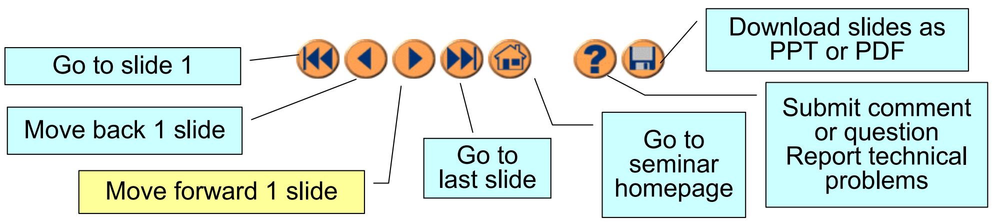
Housekeeping

- Course time is 2¼ hours
- Question & Answer breaks
  - Phone - unmute *6 to ask question out loud
  - Simulcast - ? icon at top to type in a question
- Turn off any pop-up blockers
- Move through slides
  - Arrow icons at top of screen
  - List of slides on left
- Feedback form available from last slide – **please** complete before leaving
- This event is being recorded



Although I'm sure that some of you are familiar with these rules from previous CLU-IN events, let's run through them quickly for our new participants.

We have started the seminar with all phone lines muted to prevent background noise. Please keep your phone lines muted during the seminar to minimize disruption and background noise. During the question and answer break, press *6 to unmute your lines to ask a question (note: *6 to mute again). Also, please do NOT put this call on hold as this may bring unwanted background music over the lines and interrupt the seminar.

You should note that throughout the seminar, we will ask for your feedback. You do not need to wait for Q&A breaks to ask questions or provide comments using the ? icon. To submit comments/questions and report technical problems, please use the ? icon at the top of your screen. You can move forward/backward in the slides by using the single arrow buttons (left moves back 1 slide, right moves advances 1 slide). The double arrowed buttons will take you to 1st and last slides respectively. You may also advance to any slide using the numbered links that appear on the left side of your screen. The button with a house icon will take you back to main seminar page which displays our presentation overview, instructor bios, links to the slides and additional resources. Lastly, the button with a computer disc can be used to download and save today's presentation slides.

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ITRC (www.itrcweb.org) – Shaping the Future of Regulatory Acceptance

- Host organization
- Network
  - State regulators
    - All 50 states, PR, DC
  - Federal partners

    DOE DOD EPA
  - ITRC Industry Affiliates Program
  - Academia
  - Community stakeholders
- Wide variety of topics
  - Technologies
  - Approaches
  - Contaminants
  - Sites
- Products
  - Technical and regulatory guidance documents
  - Internet-based and classroom training

The Interstate Technology and Regulatory Council (ITRC) is a state-led coalition of regulators, industry experts, citizen stakeholders, academia and federal partners that work to achieve regulatory acceptance of environmental technologies and innovative approaches. ITRC consists of all 50 states (and Puerto Rico and the District of Columbia) that work to break down barriers and reduce compliance costs, making it easier to use new technologies and helping states maximize resources. ITRC brings together a diverse mix of environmental experts and stakeholders from both the public and private sectors to broaden and deepen technical knowledge and advance the regulatory acceptance of environmental technologies. Together, we're building the environmental community's ability to expedite quality decision making while protecting human health and the environment. With our network of organizations and individuals throughout the environmental community, ITRC is a unique catalyst for dialogue between regulators and the regulated community.

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.

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ITRC Course Topics Planned for 2012 – More information at www.itrcweb.org

Popular courses from 2011

- Bioavailability Considerations for Contaminated Sediment Sites
- Biofuels: Release Prevention, Environmental Behavior, and Remediation
- Decision Framework for Applying Attenuation Processes to Metals and Radionuclides
- Development of Performance Specifications for Solidification/Stabilization
- LNAPL 1: An Improved Understanding of LNAPL Behavior in the Subsurface
- LNAPL 2: LNAPL Characterization and Recoverability - Improved Analysis
- LNAPL 3: Evaluating LNAPL Remedial Technologies for Achieving Project Goals
- Mine Waste Treatment Technology Selection
- Phytotechnologies
- Permeable Reactive Barrier (PRB): Technology Update
- Project Risk Management for Site Remediation
- Use and Measurement of Mass Flux and Mass Discharge
- Use of Risk Assessment in Management of Contaminated Sites

New in 2012

- Green & Sustainable Remediation
- Incremental Sampling Methodology
- Integrated DNAPL Site Strategy

2-Day Classroom Training:

- **Light Nonaqueous-Phase Liquids (LNAPLs): Science, Management, and Technology**

October 16-17, 2012 in Novi, Michigan (Detroit Area)

More details and schedules are available from www.itrcweb.org.

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Meet the ITRC Instructors

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Lily Barkau is an Environmental Project Manager with the Hazardous Waste Permitting and Corrective Action section of the State of Wyoming – Department of Environmental Quality (WY DEQ) in Cheyenne. She has worked at the WY DEQ since 2006. She reviews complex permit applications for technical adequacy; evaluates complicated environmental monitoring systems and data, determining whether releases of contaminants to the environment have occurred; reviews complicated site investigation work plans and reports; and takes actions to address releases to the environment. Previously, she worked for 5 years as a geologist/project manager at Earth Tech in Englewood, Colorado and has worked as a geologist for ThermoRetec, Tetra Tech EMI, and Barkau Engineering. She has been a member of the ITRC LNAPL team since the team started in 2007. Lily earned a bachelor's degree in geology from Wichita State University in Wichita, Kansas in 1998 and a master's degree in Environmental Science & Engineering from Colorado School of Mines in Golden, Colorado in 2004.

Mark R. Adamski, PG is a Technical Specialist with BP America in Houston. Texas where he supports projects both in the US and globally. He has worked for BP America since 1993. In his position, he directs both BP and American Petroleum Institute (API) research in the occurrence and behavior of LNAPL in the subsurface. He has conducted site assessments, analyzed, and modeled LNAPL distribution and recovery at BP sites worldwide. As a result of this experience, he has presented at conferences, seminars, and workshops internationally since 2000. He has been involved with the development of landmark regulatory LNAPL guidance documents developed by the State of Texas, ITRC, and the US EPA. His primary areas of current LNAPL study are site characterization techniques, residual saturation, plume migration, and recovery techniques. Mark has worked in modeling fluid migration in porous media throughout his career with BP. Mark has been an ITRC LNAPL team member since 2007. He earned a bachelor’s degree in Geological Engineering from the University of Arizona in Tucson, Arizona in 1987 and a master’s degree in Hydrogeology from Texas A&M University College Station, Texas in 1993. Mark is a registered professional geologist in Texas.

Ian Hers is a Senior Associate Engineer with Golder Associates located in Vancouver, British Columbia. He has 20 years professional experience in environmental site assessment, human health risk assessment and remediation of contaminated lands. Ian is a technical specialist in the area of LNAPL and DNAPL source characterization, monitored natural attenuation and source zone depletion, vapor intrusion, and vapor-phase in situ remediation technologies, and directs or advices on projects for Golder at petroleum-impacted sites throughout North America. He has developed guidance on LNAPL assessment and mobility for the BC Science Advisory Board for Contaminated Sites (SABCS) and the BC Ministry of Environment. Ian joined the ITRC LNAPL team in March 2008. Ian earned a doctoral degree in Civil Engineering from University of British Columbia in Vancouver, BC. He is on the Board of Directors of the SABCS, is a Contaminated Sites Approved Professional in BC, and is a sessional lecturer at the University of British Columbia.

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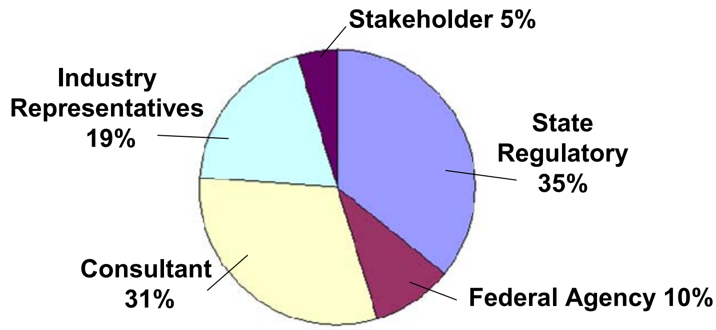
ITRC LNAPL Team

- ITRC LNAPL Team formed in July 2007
- Collaborative effort involving State and Federal Regulators, Consultants, Industry Representatives, and Stakeholders



No associated notes.

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ITRC LNAPL Team Approach

- Develop a basics training
  - Internet-based training – Part 1
  - Internet-based training – Part 2
- Develop a Technical Regulatory document
- Develop a Technical Regulatory document training
  - Internet-based training – Part 3
- Develop classroom training

No associated notes.

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Why an LNAPL Team and this LNAPL Basics Training?

- LNAPL is present at thousands of sites
- Perceived as significant environmental threat
- Technical and regulatory complexity
- 2008 ITRC LNAPLs Team State Survey – training request
- Better understanding facilitates better decision making
- Keep in mind, addressing LNAPL is not the entire part of remediating a site

No associated notes.

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Basics Training: Two Part Approach

- Part 1: Understanding LNAPL Behavior
  - Overview of factors that control LNAPL distribution and behavior in the subsurface
  - Sites with LNAPL saturation > residual saturation (When LNAPL *Saturation* in the ground exceeds LNAPL *Residual Saturation*)

No associated notes.

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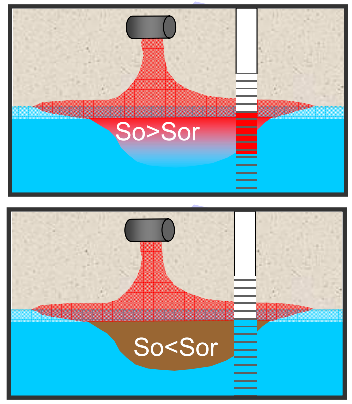
Saturation versus Residual Saturation

When LNAPL *Saturation* in the ground exceeds LNAPL *Residual Saturation*

LNAPL Saturation (So)

Fraction of pore space occupied by LNAPL



Residual LNAPL Saturation (Sor)

Fraction of pore space occupied by LNAPL that cannot be mobilized under an applied gradient

When So < Sor, non-multiphase flow fate-and-transport decision frameworks (dissolved phase or vapor phase) work well (e.g., RBCA)

No associated notes.

12

Basics Training: Two Part Approach

- Part 2: LNAPL Characterization and Recoverability
  - LNAPL Conceptual Site Model (LCSM)
  - Site and LNAPL factors that influence LNAPL recovery
  - Hydraulic recovery evaluation
  - Objectives and goals
  - Remedial technologies
- Be sure to register for and attend Part 2!

No associated notes.

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Training Associated with Technical and Regulatory Guidance Document

- Part 3: ITRC Technical and Regulatory Guidance: Evaluating LNAPL Remedial Technologies for Achieving Project Goals
  - Based on the LNAPLs Team Technical Regulatory Document
    - LNAPL remedial decision making
    - LNAPL remedial technologies
    - LNAPL remedial technology screening and evaluation
    - Data requirements
    - Case studies

No associated notes.

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ITRC 2-day Classroom Training

- 2010 and early 2011 – developed training
- 2011 on – plan to offer classes in locations across the country
  - October 16-17, 2012 in Novi, Michigan (Detroit Area)
  - Coming soon: more information about 2013 dates and locations

More information and registration at www.itrcweb.org under "Training"

No associated notes.

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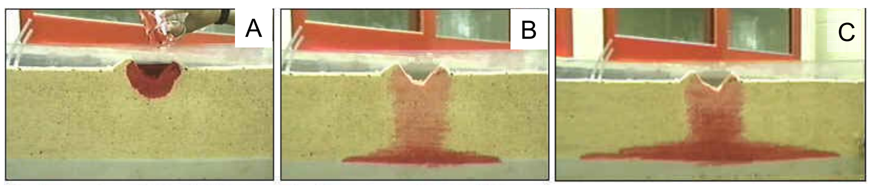
Section 1: LNAPL Definitions and Concerns about LNAPL

- Section 1: LNAPL definitions and concerns about LNAPL
- Section 2: How LNAPL enters soil and aquifers
- Section 3: How LNAPL distributes vertically
- Section 4: How LNAPL moves



Modified from Schwille, 1988

No associated notes.

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Some Real Basics First – What Is LNAPL?

- NAPL = Non-Aqueous Phase Liquid
  - Contaminants that remain undiluted as the original bulk liquid in the subsurface
  - Do not mix with water and remain separate phase
  - e.g., chlorinated solvents and petroleum hydrocarbon products
- LNAPL = NAPL that is less dense than water
  - e.g., gasoline, diesel, jet fuel, crude oil
- DNAPL = NAPL that is more dense than water
  - e.g., chlorinated solvents
  - Not addressed in this course…see ITRC's information on DNAPL's
    - Surfactant/Cosolvent Flushing of Source Zones, DNAPL Performance Assessment, In Situ Bioremediation of Chlorinated Ethene

No associated notes.

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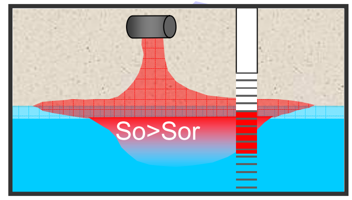
Saturation versus Residual Saturation

When LNAPL *Saturation* in the ground exceeds LNAPL *Residual Saturation*

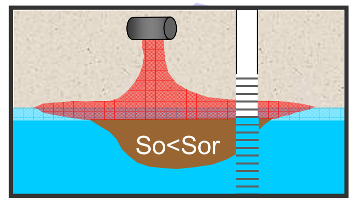
LNAPL Saturation (So)

Fraction of pore space occupied by LNAPL



Residual LNAPL Saturation (Sor)

Fraction of pore space occupied by LNAPL that cannot be mobilized under an applied gradient



When So < Sor, non-multiphase flow fate-and-transport decision frameworks (dissolved phase or vapor phase) work well (e.g., RBCA)

No associated notes.

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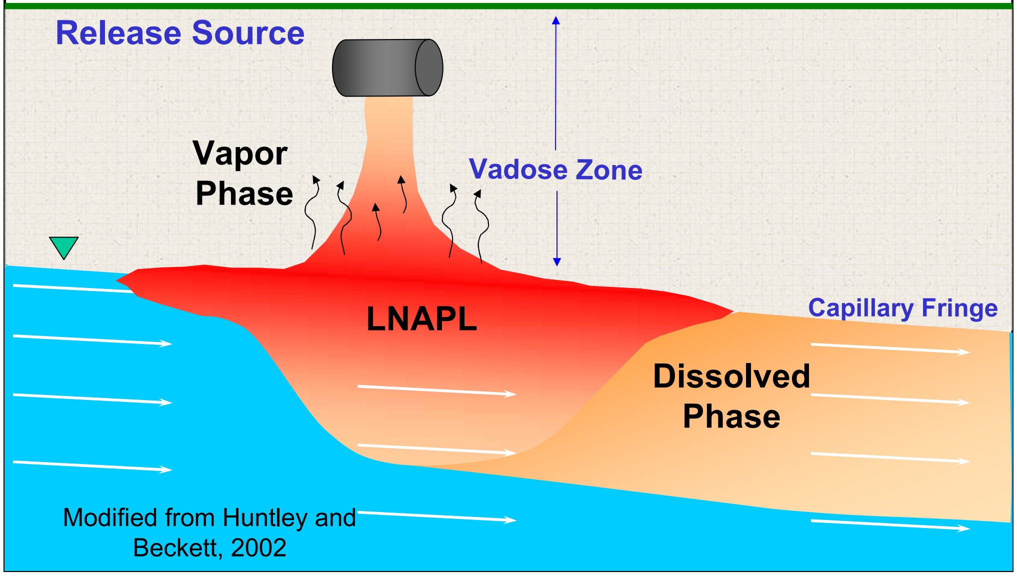
Simplified Conceptual Model for LNAPL Release to the Subsurface and Migration



No associated notes.

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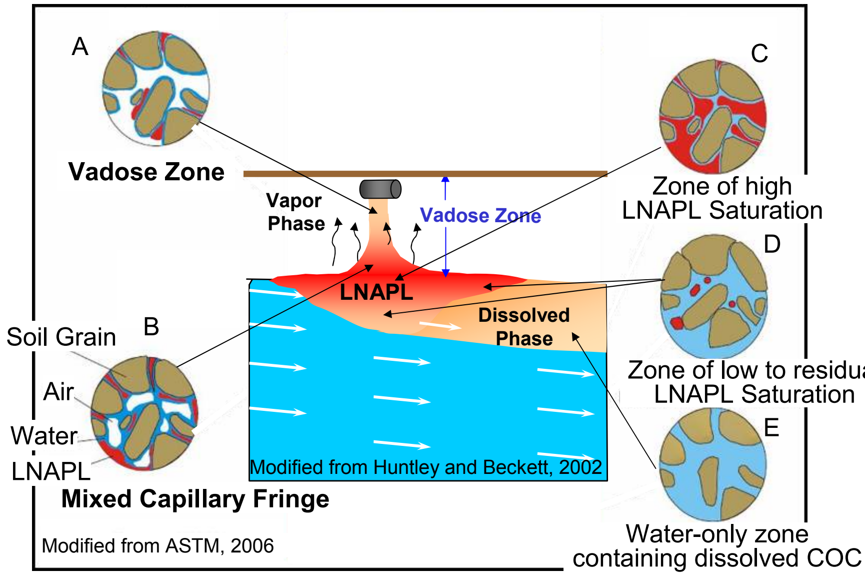
Pore Scale LNAPL Distribution



No associated notes.

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Why be Concerned about LNAPL?

Should evaluate LNAPL from three perspectives:
what, **how much,** and **where?**

- LNAPL composition (what)
  - Explosive hazards
  - Dissolved-phase concentration
  - Vapor-phase concentration
    - (see ITRC Vapor Intrusion Guide)
  - Soil direct contact or ingestion
- LNAPL saturation (how much)
  - Mobility (problem moves to new area and create a risk)
  - Seepage to surface water
  - Longevity of dissolved phase and vapor phase plumes
  - Aesthetic
- LNAPL location (where) addressed in Part 2

No associated notes.

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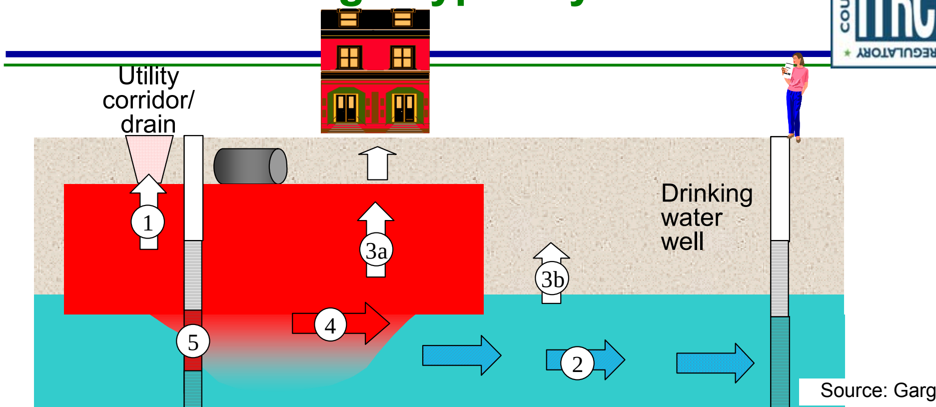
What Do the Regs Typically Address?



LNAPL emergency issues when LNAPL in the ground	LNAPL considerations when LNAPL in the ground (evaluated using standard regulations)	Additional LNAPL considerations when LNAPL in wells (not evaluated using standard regulations)
(1) Vapor accumulation in confined spaces causing explosive conditions ***Not shown*** - Direct LNAPL migration to surface water ***Not shown*** - Direct LNAPL migration to underground spaces	(2) Groundwater (dissolved phase) (3a) LNAPL to vapor (3b) Groundwater to vapor ***Not shown -*** Direct skin contact	(4) LNAPL potential mobility (offsite migration, e.g. to surface water, under houses) (5) LNAPL in well (aesthetic, reputation, regulatory)

LNAPL Composition	LNAPL Saturation

No associated notes.

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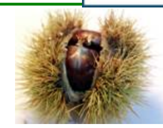
LNAPL in a Regulatory Nut Shell



- 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 LNAPL 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

No associated notes.

Common (mis) Perceptions about LNAPL

- LNAPL enters the pores just as easily as groundwater
- You can recover all LNAPL
- All the pores in an LNAPL plume are filled with LNAPL
- LNAPL floats on the water table or capillary fringe like a pancake and doesn’t penetrate below the water table
- Thickness in the well is exaggerated by a factor or 4, 10, 12, etc.
- LNAPL thickness in a well is always equal to the formation thickness
- If you see LNAPL in a well it is mobile and migrating
- LNAPL plumes spread due to groundwater flow
- LNAPL plumes continue to move over very long time scales

No associated notes.

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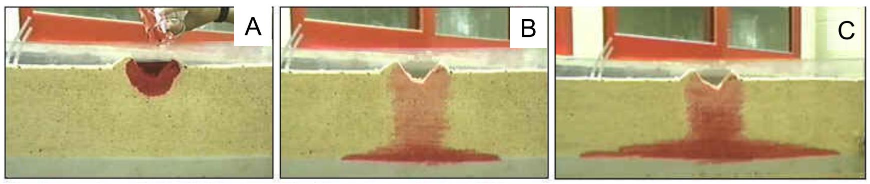
Section 2 : How LNAPL Enters Soil and Aquifers

- Section 1: LNAPL definitions and concerns about LNAPL
- Section 2: How LNAPL enters soil and aquifers
- Section 3: How LNAPL distributes vertically
- Section 4: How LNAPL moves



Modified from Schwille, 1988

Slide 24

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Common (mis) Perceptions about LNAPL

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Slide 25

Misconception because common assumption is LNAPL pore entry is analogous to that of water. LNAPL and groundwater are generally similar but there are some differences/considerations that should be accounted for during multi-phase flow:, e.g., relative permeability and pore entry pressure. These are discussed later in this presentation.

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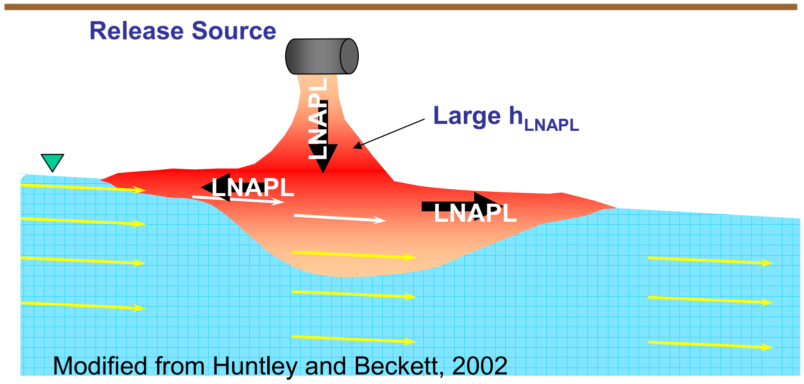
LNAPL Plume Spreading



- LNAPL must displace existing fluids (air, water) filling a soil pore to enter a pore
- It is easier for LNAPL to displace air than water

Slide 26

The LNAPL must displace fluids existing in the pores to enter the soil pore

LNAPL needs to displace air from vadose-zone pores and water from saturated-zone pores

LNAPL distributes itself vertically at and under the water table and also spreads laterally

Both aspects – vertical distribution and lateral migration – are discussed in this presentation

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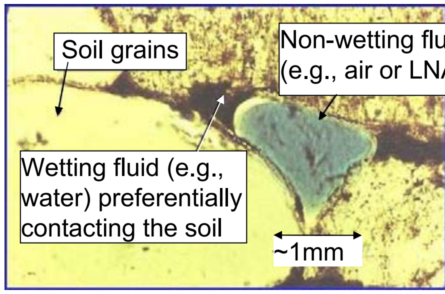
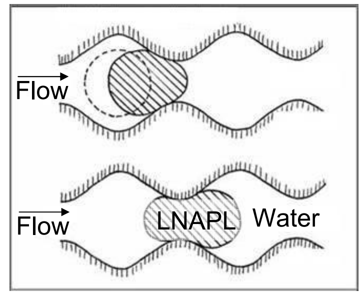
"Resistance" to Movement of LNAPL into and Out of Water-saturated Soil Pores



For water wet media



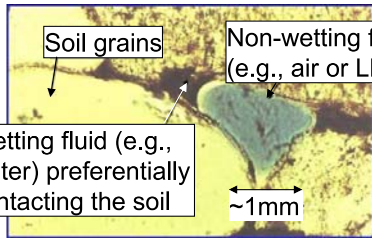
- LNAPL will only move into water-wet pores when entry pressure (resistance) is overcome
  - To distribute vertically and to migrate laterally

Slide 27

It takes pressure for LNAPL to move into or out of pores. LNAPL 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.

In the upper right 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.

How is a Water-Filled Pore Resistant to LNAPL Entry?



Displacement head for LNAPL entry into water-filled pores

$$h_{Nc} = \frac{2\sigma \cos\phi}{r(\rho_W - \rho_o)g}$$

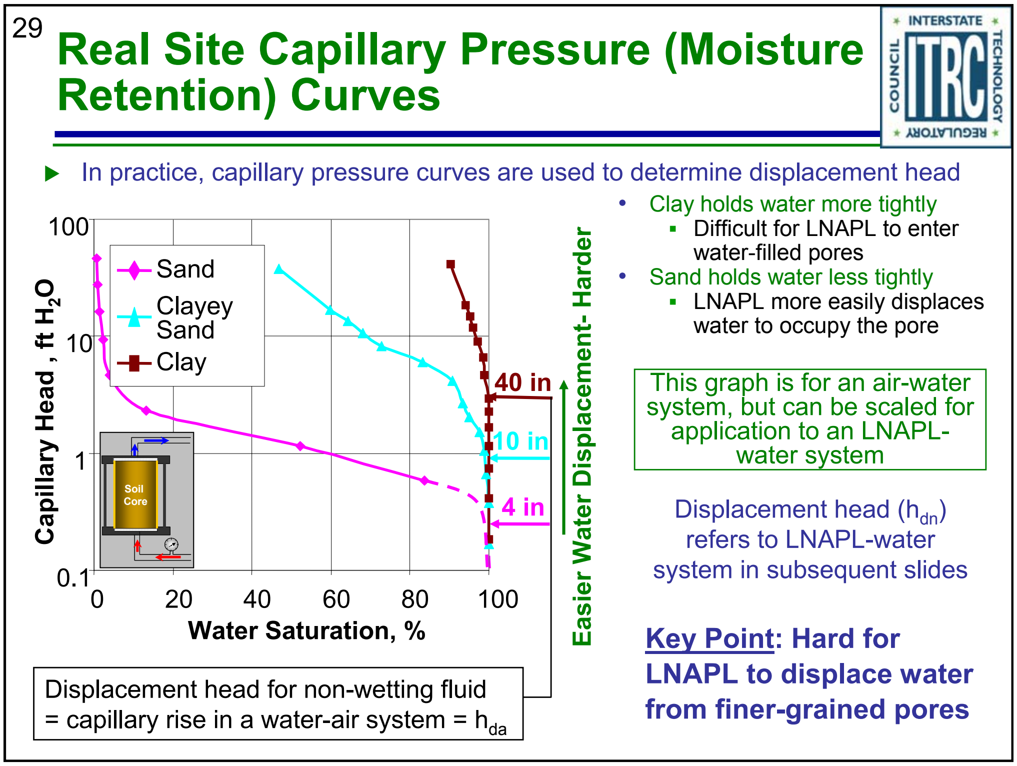
h_{Nc} = displacement head for LNAPL-water system, the LNAPL head required to displace water from water-filled pores

Parameter	Parameter trend	h_{Nc}	LNAPL potential to enter water-filled pore
Water/LNAPL interfacial tension (σ)	↑	↑	↓
Wettability (wetting fluid contact angle) Cos Φ	↑	↑	↓
Pore size (r)	↑	↓	↑
LNAPL density (ρ_o)	↑	↑	↓

Key Point: Higher h_{Nc} means its harder for LNAPL to displace water from pores

Slide 28

Slide has force balance equation for a capillary tube. Parameters and effect is shown in table.



Slide 29

In practice, capillary pressure curves are used to determine displacement head. It is a lab measurement where a non-wetting fluid is used to displace a wetting fluid (water) from a soil core.

The results can be scaled or adjusted for any pair of fluids based on fluid properties. There are databases and software available (e.g., API) that have the necessary parameters to develop these curves.

Pore entry pressure for air had is also equal to the height of capillary fringe in an air-water system

hd is conceptually same as hNC but based on a field measurement for a soil type and air and water

30

How Displacement Head Affects Lateral Migration and Vertical Distribution

- Displacement head affects both the vertical distribution and the lateral migration of LNAPL
- Can explain why LNAPL bodies stabilize over time
- LNAPL needs to displace existing fluids to enter a pore
  - Easier for LNAPL to displace air (vadose zone) than water (saturated zone)

Slide 30

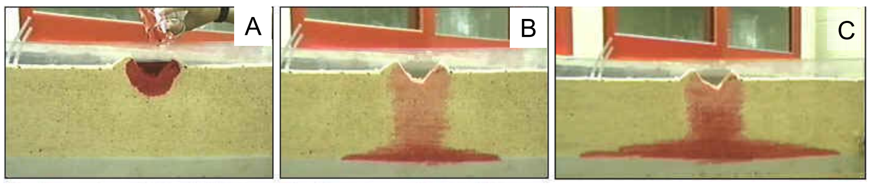
Displacement head is relevant because LNAPL needs to get into the pores in the first place to distribute vertically or migrate laterally.

Easier to cleanup spilt oil with a dry sponge versus a wet sponge – example of displacing air versus water by LNAPL.

Summary of section – nonwetting fluids have a pore entry pressure.

Section 3 : How LNAPL Distributes Vertically

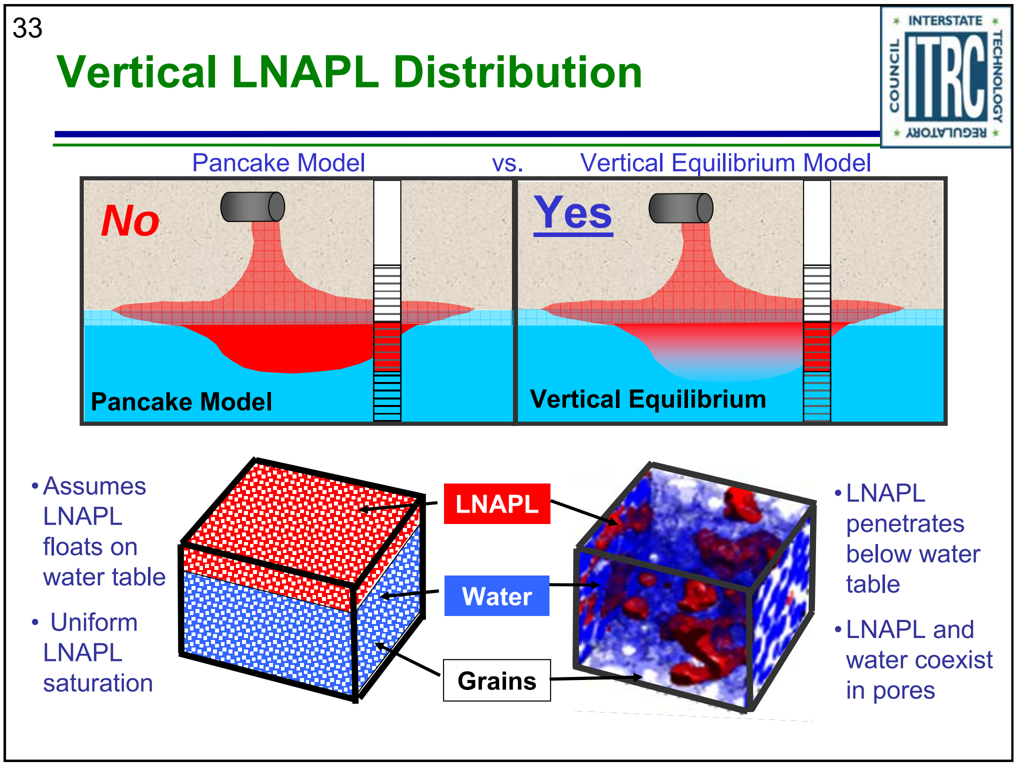
- Section 1: LNAPL definitions and concerns about LNAPL
- Section 2: How LNAPL enters soil and aquifers
- Section 3: How LNAPL distributes vertically
- Section 4: How LNAPL moves



Modified from Schwille, 1988

Common (mis) Perceptions about LNAPL

- LNAPL enters the pores just as easily as groundwater
- You can recover all LNAPL
- All the pores in an LNAPL plume are filled with LNAPL
- LNAPL floats on the water table or capillary fringe like a pancake and doesn’t penetrate below the water table
- Thickness in the well is exaggerated by a factor or 4, 10, 12, etc.
- LNAPL thickness in a well is always equal to the formation thickness
- If you see LNAPL in a well it is mobile and migrating
- LNAPL plumes spread due to groundwater flow
- LNAPL plumes continue to move over very long time scales



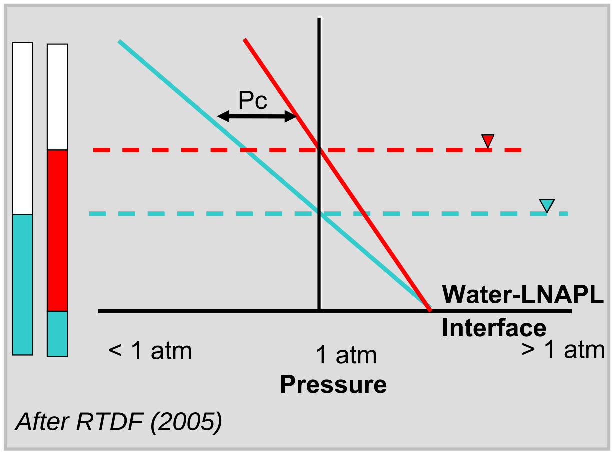
Slide 33

Left: Old model is the pancake model. All pores are filled with LNAPL.

Right: Reality. LNAPL and water coexist in the pore space and the and the relative saturations of water and LNAPL varies with depth. The pressure is varies with depth and thus there is a different saturation of LNAPL at each point vertically.

34

Saturation Distribution is Determined by Capillary Pressure - 1



Pc = non wetting pressure – wetting phase pressure

Key Point: Capillary pressure highest at LNAPL-air interface and zero at water-LNAPL interface

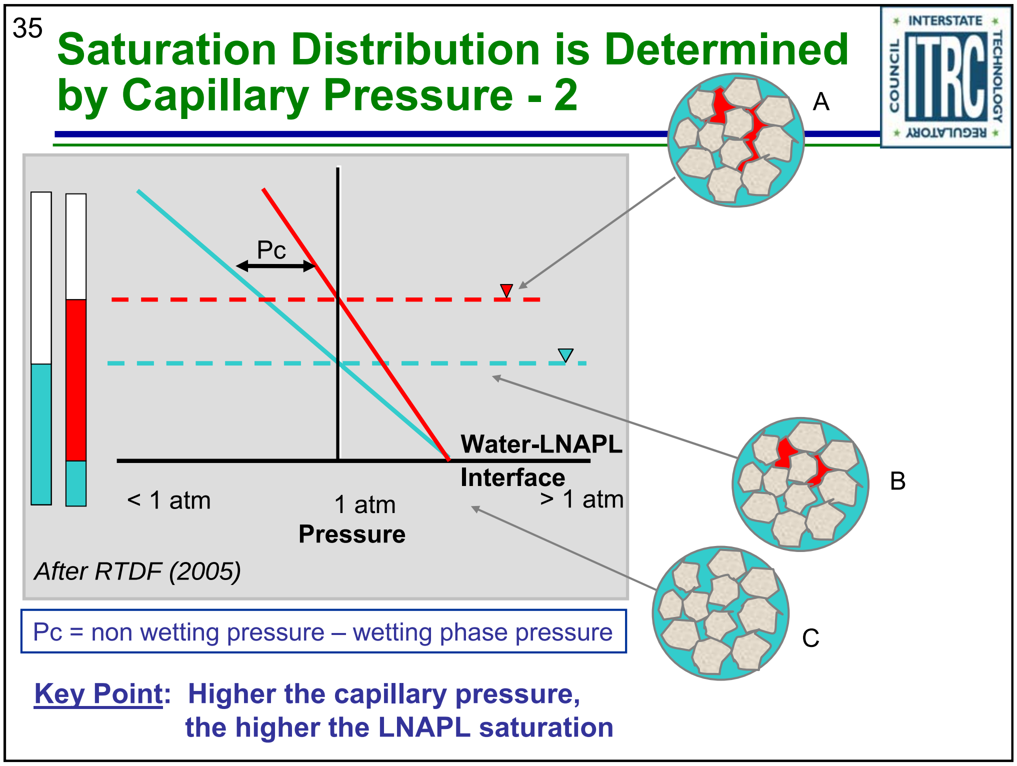
Slide 34

Blue Inclined Line: Water pressure line. 1 atm at the water table. Wetting Fluid.

Red Inclined Line: LNAPL pressure line. 1 atm at the LNAPL table. Non wetting fluid

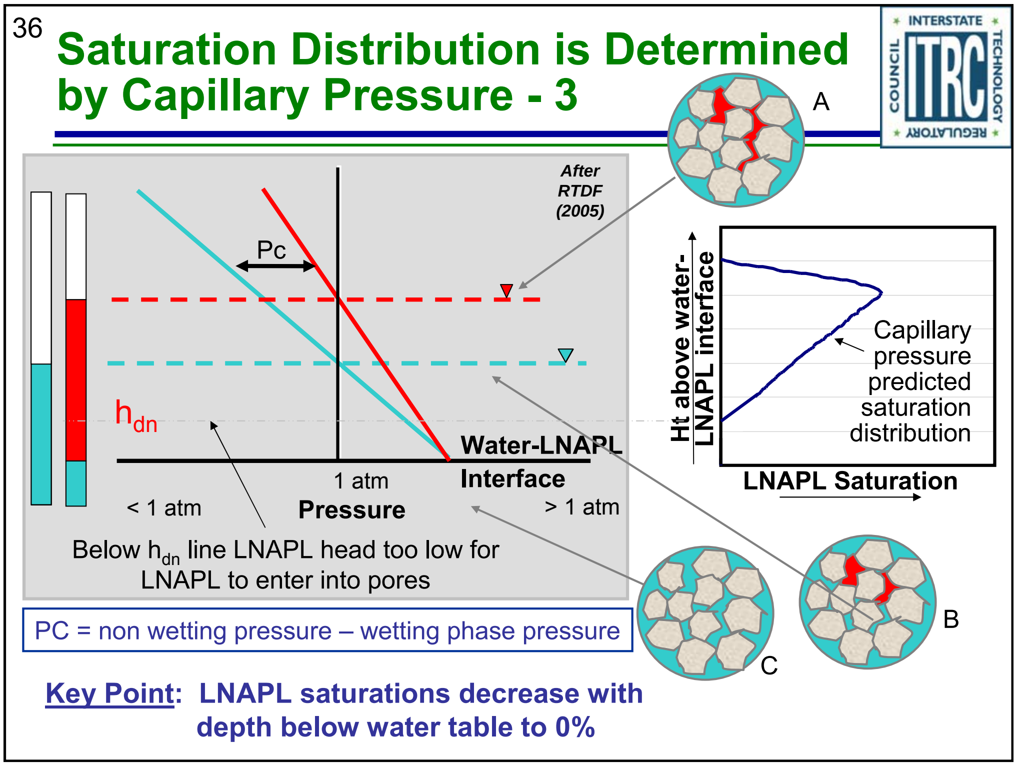
Capillary pressure is defined as the difference between the pressures of the nonwetting (i,.e. LNAPL) and the wetting fluid (I.e., water).

Capillary pressure is maximum at the top of the LNAPL and zero at the bottom of the LNAPL column.



Slide 35

The 3 panes have different amount of LNAPL because of different capillary pressures at each point. Maximum LNAPL is where capillary pressure was highest in the previous slide.



Slide 36

The actual shape of the sharkfin is arrived at by using the (I) capillary pressure curve (refer to slide 30) and (ii) the pressure distribution (the distance between the blue and the red lines above).

There are several tools that can generate these curves, e.g., API Interactive Guide and the API LDRM

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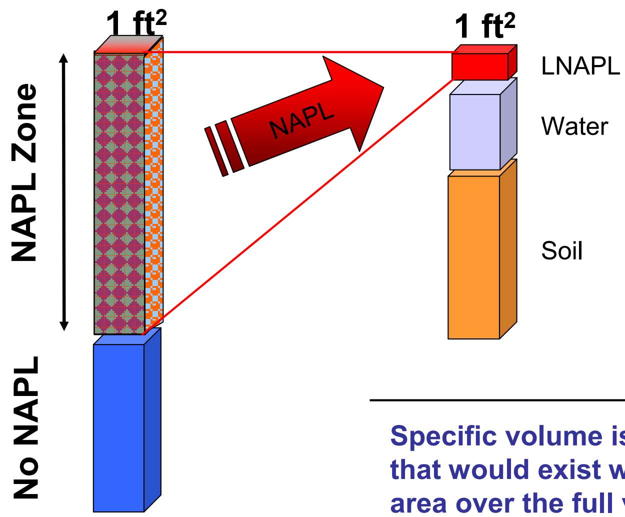
Definition of Specific Volume

Schematic Boring | **What is in the soil column?**



Specific volume is the volume of LNAPL that would exist within a boring 1 ft^2 in area over the full vertical interval of LNAPL presence (units = volume/area)

Slide 37

Specific volume: volume of LNAPL per unit area of land

Integrate all LNAPL impacts observed vertically in a core = area under the sharkfin*porosity

Volume includes total LNAPL (both recoverable and non-recoverable)

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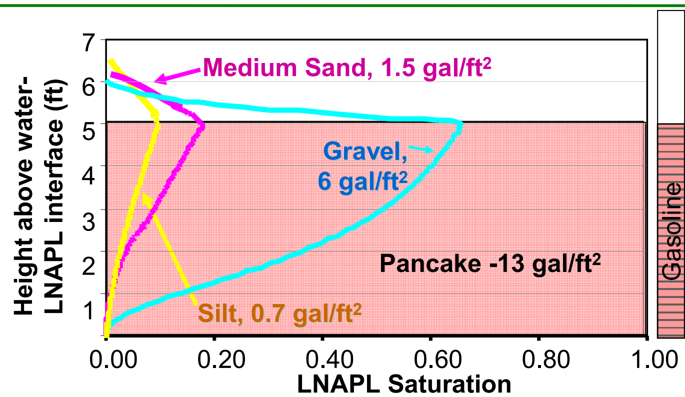
Grain Size Effects on LNAPL Saturation Distributions (Vertical Equilibrium Model)



Key Point: Volumes based on pancake model (uniform saturations) are over estimated!

For a given LNAPL thickness, LNAPL saturations and volumes are different for different soil types (greater for coarser-grained soils)

Slide 38

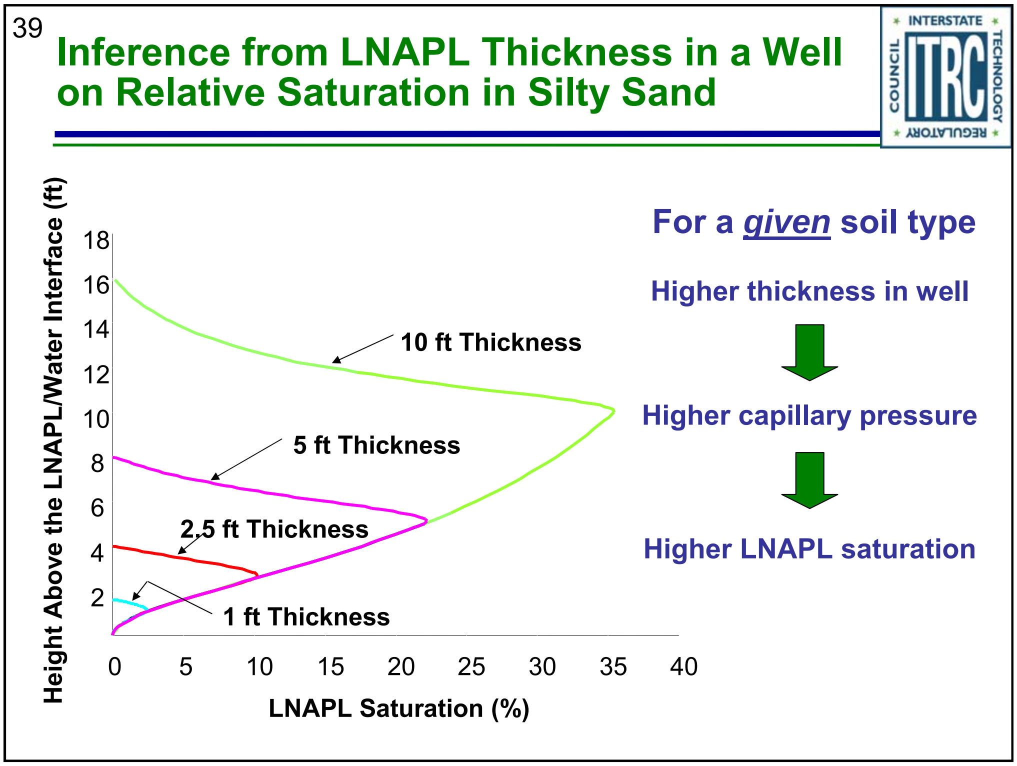
Graph shows volume estimates for different soil types for a given LNAPL thickness in the well.

Volume of gasoline via pancake = LNAPL thickness in well x porosity

Volume of gasoline = area under the curve x porosity

Pancake over-predicts volume and the over-prediction gets more and more significant as grain size becomes smaller.

LNAPL thickness is same for all cases →capillary pressure distribution is same, but pore sizes are different. Therefore, different sharkfins for different soils even though well thickness is the same.



Slide 39

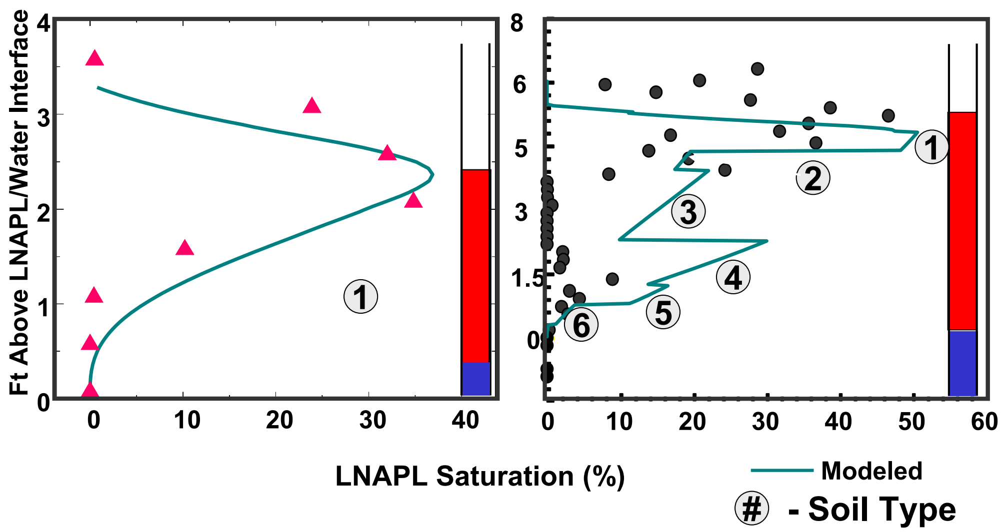
This slide illustrates that LNAPL (diesel fuel) saturation distributions vary in silty sand with differing LNAPL thicknesses measured in monitoring wells. We can see that for a 10-ft thickness of diesel fuel in a monitoring well, the maximum saturation in silty sand is predicted to be about 36%. If the diesel fuels thickness were 1 foot, the maximum saturation would be predicted to be less than 5%.

In summary, if we have capillary pressure curves and homogeneous media and know the LNAPL thicknesses measured in monitoring wells and the fluid properties, we can estimate the saturations of LNAPL in media of various grain sizes.

If keep adding LNAPL mass, the saturation will reach a maximum (<<100%, 1 - irreducible water saturation), above which volume will increase, but the saturations will remain constant at that maximum.

40

Measured and Modeled Equilibrium LNAPL Saturations



Beckett and Lundegard (1997) , Huntley et al. (1994)

Slide 40

Symbols are data. Lines are calculations.

Left panel has homogeneous soil. Right panel has 6 soil types.

Model predictions have a good match for the homogeneous soil. Reasonable match for the heterogeneous case.

Important to know geology and other factors like water table fluctuations if calculating profile.

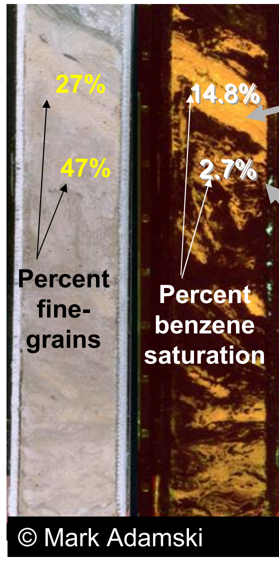
Key point: LNAPL Saturation is never 1 and varies.

41

LNAPL Saturations Are Not Uniform

- LNAPL preferentially enters larger pores (easier to move water out of the pore)
- Maximum LNAPL saturations typically low (5-30%) in sands (can be higher at new release or constant release)
- Saturations even lower for finer-grained sediments

Plain light



UV light

Higher LNAPL saturation in coarser-grained soil

Lower LNAPL saturation in finer-grained soil

Fluoresced benzene in soil core

Slide 41

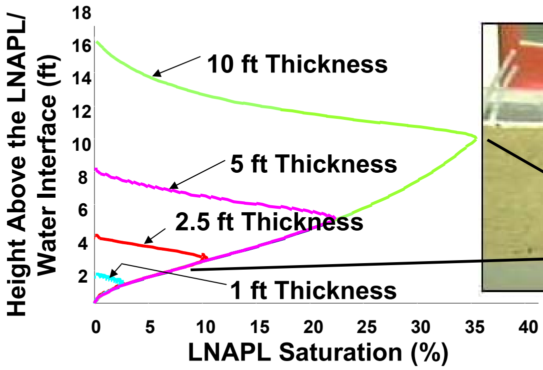
Photographs under white light and ultraviolet light

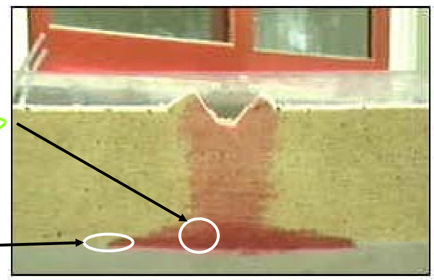
Varying saturations due to grain size and/or depth

42

Analogy to LNAPL Body

- More LNAPL mass in the core (greater thickness)
- Less LNAPL mass at the perimeter (less thickness)





Modified from Schwille, 1988

Slide 42

NAPL plume core has higher thickness and a corresponding larger sharkfin as compared to the plume edge.

43

Pancake vs. Vertical Equilibrium Model

Why important?

- Pancake concept results in overestimation of LNAPL volumes based on thickness observed in a well
- LNAPL generally does not occur as a distinct layer floating on the water table at 100% or uniform LNAPL saturation
- Unrealistic expectations of recovery due to incorrect site conceptual model
  - Uniform saturations
  - Uniform LNAPL distributions

Slide 43

Same thickness in a well could mean a completely different mass (and mobility, which will be discussed later) in a gravel versus a clay.

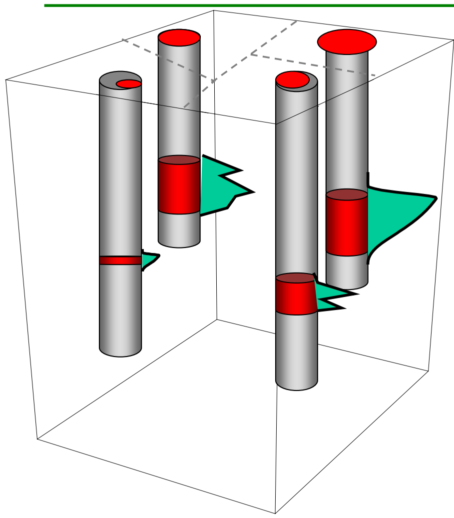
A good understanding of the vertical distribution of LNAPL can help with getting a good estimate of the size of the problem and to focus remedial efforts on the right zone.

LNAPL Volume Estimates

- To understand the scale of the problem
- May not be necessary at all sites
  - Necessity and rigor of estimate depends on site-specific drivers
- Total volume includes recoverable LNAPL and residual LNAPL
- Tend to be order of magnitude estimates

45

An Example Volume Estimation Technique



- Specific Volume, v_i
- Area represented by a well, A_i

- Establish saturation profile at each location
  - Measured or modeled
- Estimate the LNAPL specific volume at each location
  - v_1, v_2, v_3, v_4
- Assign representative areas for each boring/well
  - A_1, A_2, A_3, A_4
- Calculate volume in each representative area
  - A_1v_1; A_2v_2 ; A_3v_3 ; A_4v_4
- Integrate to obtain total volume
  - $A_1v_1 + A_2v_2 + A_3v_3 + A_4v_4$

Slide 45

Other methods include

e.g., (1) 3-d interpolation of LNAPL saturation data

(2) Contouring using any standard software. Will need some post-processing to get volume from contours.

Question and Answer Break

47

Section 3: How LNAPL Distributes Vertically (continued)

Vertical Equilibrium Exceptions

48

Common (mis) Perceptions about LNAPL

- LNAPL enters the pores just as easily as groundwater
- You can recover all LNAPL
- All the pores in an LNAPL plume are filled with LNAPL
- LNAPL floats on the water table or capillary fringe like a pancake and doesn't penetrate below the water table
- Thickness in the well is exaggerated by a factor or 4, 10, 12, etc.
- LNAPL thickness in a well is always equal to the formation thickness
- If you see LNAPL in a well it is mobile and migrating
- LNAPL plumes spread due to groundwater flow
- LNAPL plumes continue to move over very long time scales

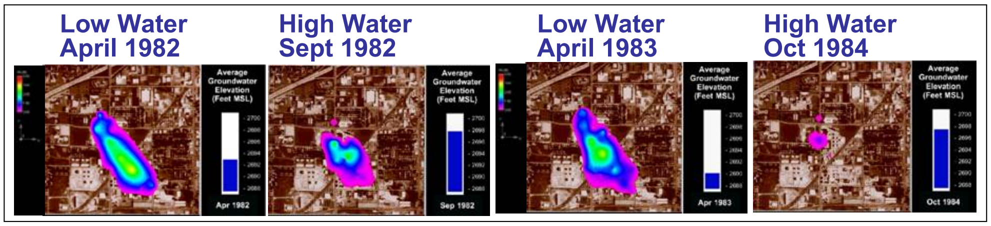
Slide 48

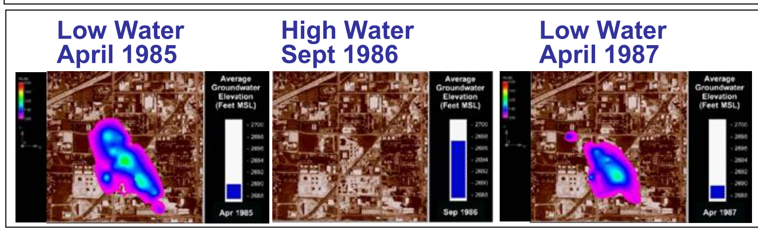
Well thickness is not always equal to formation impacts. Some examples follow.

49

Example Seasonal LNAPL Redistribution

LNAPL Monitoring Over Time Refinery





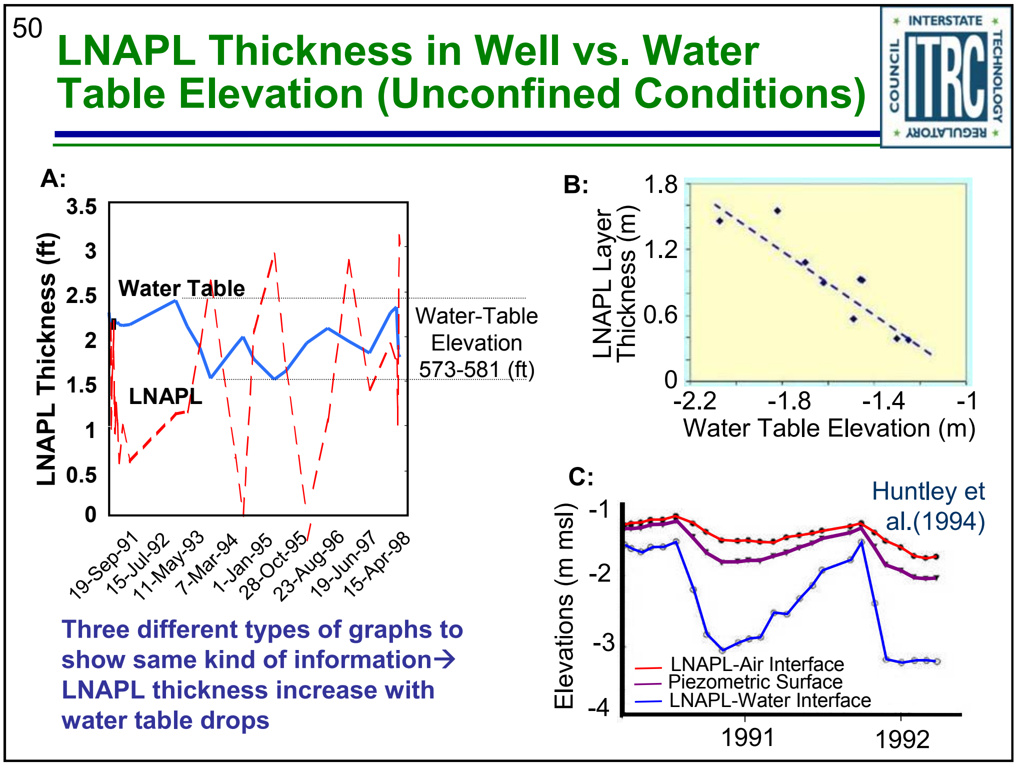
From API Interactive NAPL Guide, 2004

- **Measured LNAPL Depth in Monitoring Wells : 0 to 3 feet**
- **Seasonal Water Table Variation : 8 foot range**

Slide 49

The attached movie stills illustrate a diesel plume in a gravelly sand aquifer that is characterized by seasonal water table fluctuations. The extent and product thickness were measured from over 50 wells across the site from April 1982 to April 1987. The apparent well product thickness measurements range from 0 to 4 feet. The groundwater level fluctuates approximately 8 feet seasonally. The blue gauge on the right side of the picture provides the average water level, and the legend in the upper left hand portion of the picture documents the LNAPL plume thickness. The movie clearly illustrates the influence of water table fluctuations in trapping LNAPL as water floods the oil profile and in the subsequent drainage of LNAPL from the unsaturated zone. During the time period of the movie, recovery systems were operational, which resulted in the continual loss of product from the aquifer.

Video at: Link



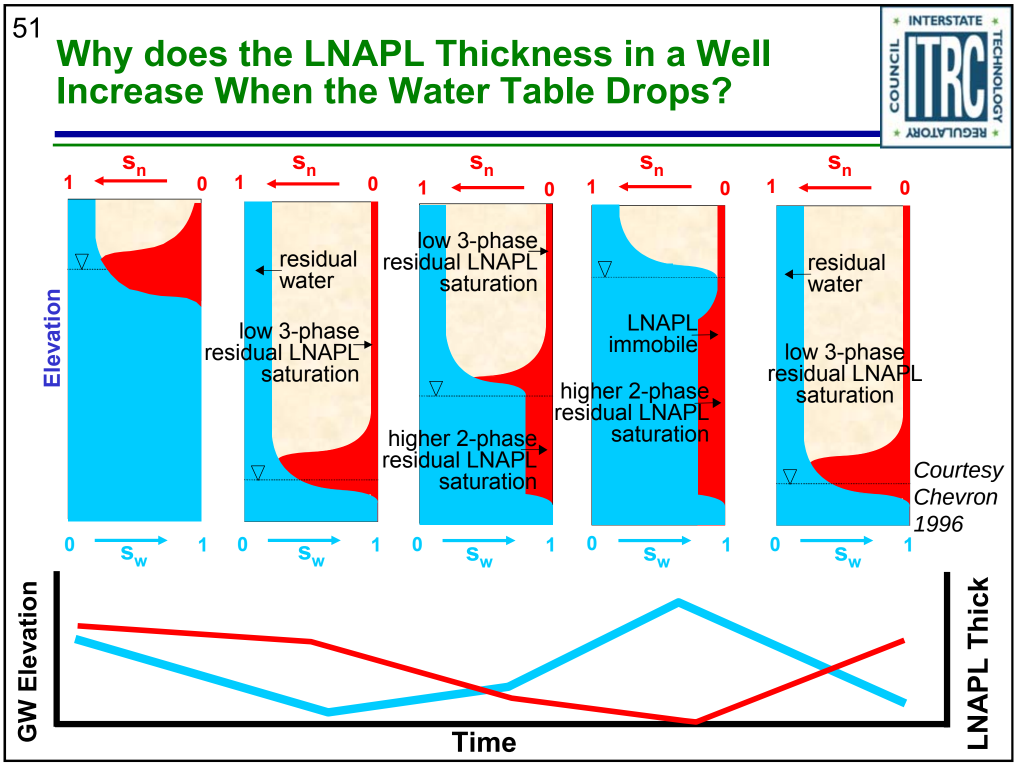
Slide 50

Panel A shows a temporal graph with Time on the x axis and LNAPL thickness and water table elevation on the two y axes. The red line is the measured thickness of LNAPL in the monitoring well. The blue line represents the change in water table elevation.

Panel B shows GW elevation plotted against LNAPL thickness.

Panel C shows elevations of the top of LNAPL in red, LNAPL-Water interface in blue and the piezometric surface in purple.   As the piezometric surface goes up the LNAPL thickness, which is the distance between the red and blue lines, goes down

What is usually observed here in all hydrographs is that, when the water table elevation decreases, the LNAPL thickness in the monitoring well increases, and vice versa. While changes in the measured LNAPL thickness often are attributed to a redistribution of LNAPL in the aquifer as the water-table elevation changes, this is only part of the story. Two phenomena cause this:



Slide 51

Phenomenon 1: Vertical redistribution of LNAPL (shown in panels above)

Frame 1: LNAPL present is a well at ant time 0.

Frame 2: Water tables drops with LNAPL creating smear zone is soil.

Frame 3: Water table rises, entrapping LNAPL in the soil.

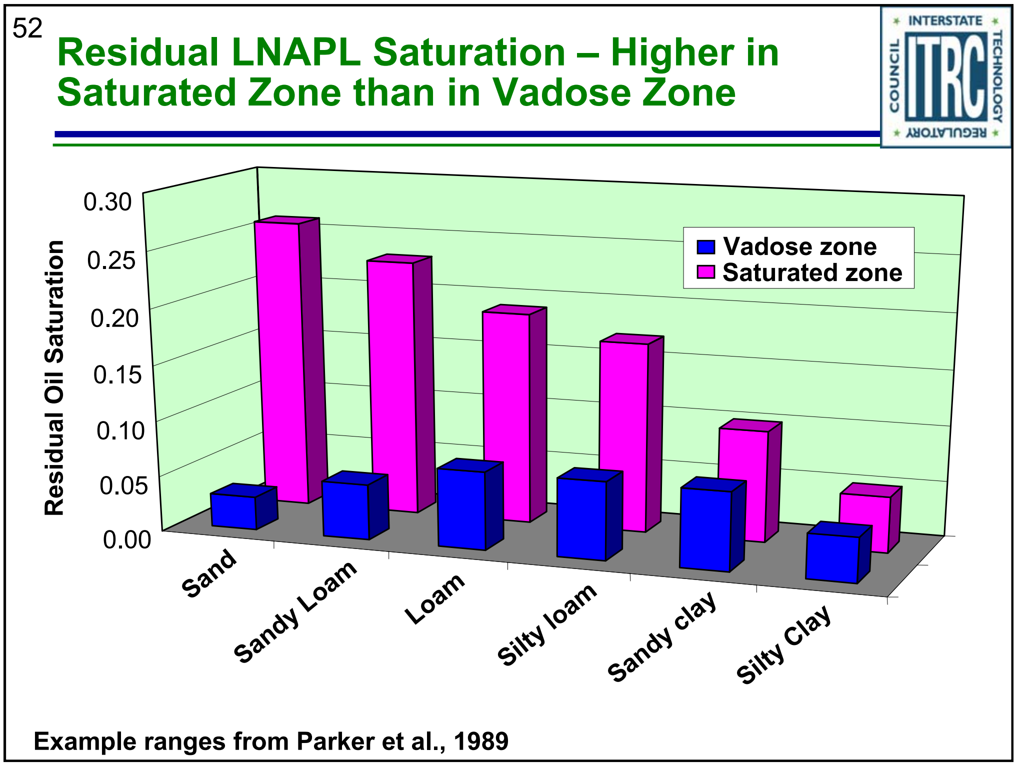
Frame 4: At water table maximum, LNAPL may be entirely entrapped.

Frame 5: As water table declines, LNAPL drains from soil.

Phenomenon 2:

Flow of LNAPL into/out of the well from/to the soil.

Reference: Kemblowski and Chiang Groundwater in 2000.



Slide 52

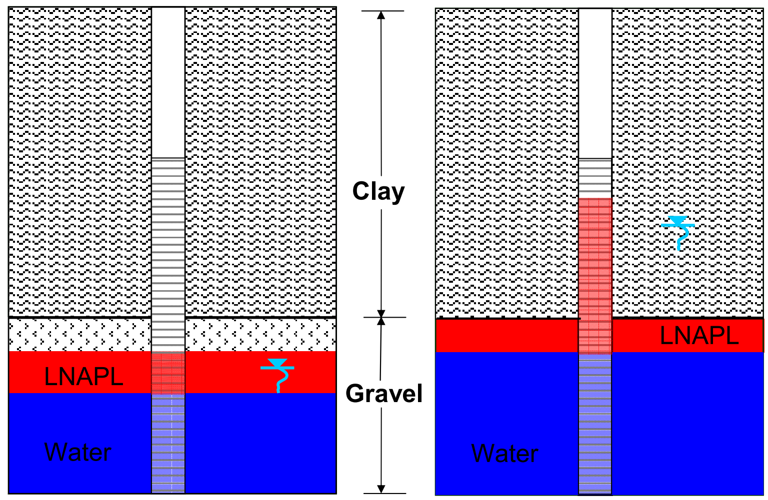
Residual saturations in vadose zone are lower than those in the saturated zone

Easier to recover from a 3-phase system – this is why lowering of the water table may help LNAPL recovery

But if dewatering clay or silty clay, still will not get much LNAPL (little difference in the saturated zone and vadose zone residual saturations

53

LNAPL Thickness in Well Increases with Increase in Water Level? Bottom Filling of Well



Monitoring well is a giant pore!

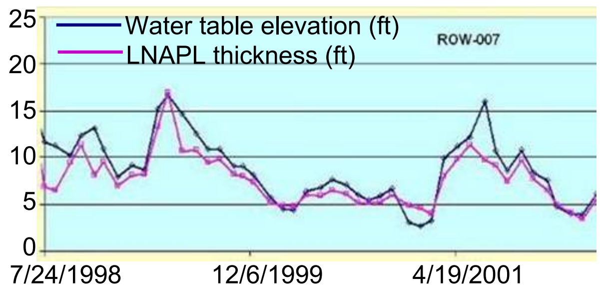
Slide 53

Left side: LNAPL in unconfined condition. Thickness in well is similar to that in the formation. Water table fluctuation will have an inverse relationship to the LNAPL thickness.

Right side: LNAPL/aquifer under confined condition. As the piezometric surface rises, the confining pressure on the LNAPL rises, resulting in an increased thickness in the well. That is, an increase in piezometric surface results in increase in LNAPL thickness under confined conditions.

LNAPL Thickness versus Potentiometric Surface Elevation (Confined Conditions)

Confined systems have matched potentiometric surface and LNAPL thickness response (must factor in density ratio of the two fluids)

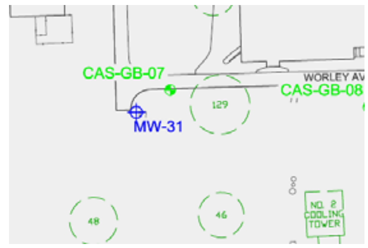


In confined conditions, as groundwater increase LNAPL thickness increases. With recharge, water table rise intercepts confining clay and confined conditions develop. Increase in potentiometric surface results in increase in LNAPL thickness. LNAPL forced into the well and floats to top of potentiometric surface.

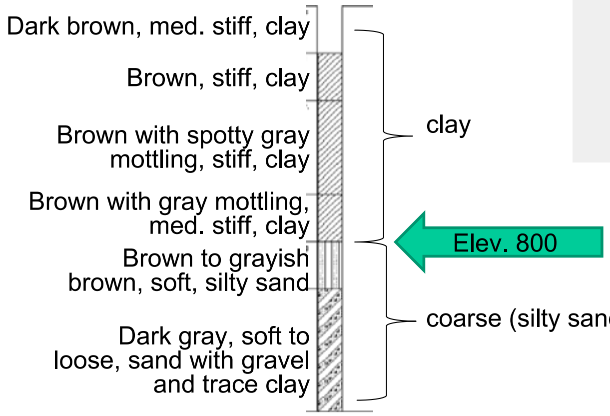
55

LNAPL Thickness Vs. Potentiometric Surface Elevation (Confined)

Location of CAS-GB-07 relative to MW-31



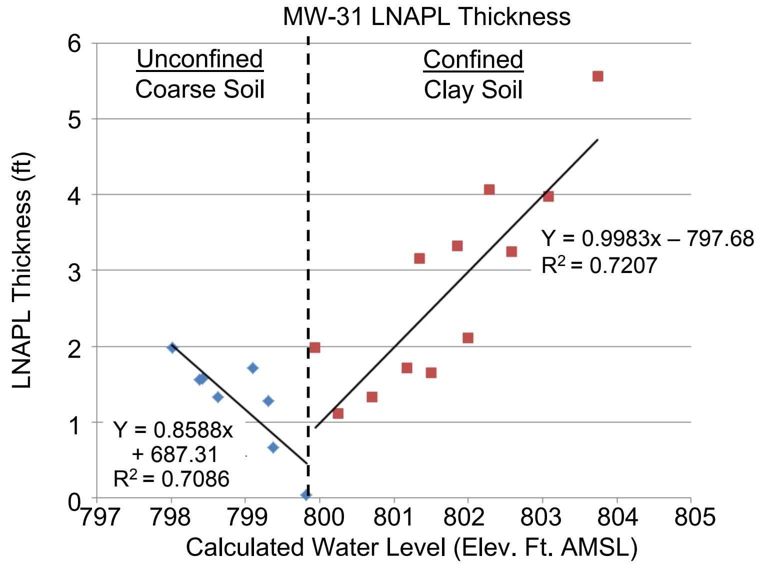
From log for CAS-GB-07



Shown here and the next slide is a detailed example of the unconfined LNAPL that transitions to confined conditions (conceptually depicted on slide 53). Note the coarse grained soils below elevation 800 in the boring log and Clay (fine grained soils above)

LNAPL Thickness Vs. Potentiometric Surface Elevation

Conceptual Challenges – Confined



Left Hand Side: Water table in gravel (unconfined condition), LNAPL moves up and down with water table fluctuations, with inverse LNAPL thickness change

Right Hand Side: With recharge, water table rise intercepts confining clay and confined conditions develop. Increase in potentiometric surface results in increase in LNAPL thickness. LNAPL forced into the well and floats to top of potentiometric surface.

Note that the change in trend lines fits very well with the lithology change at elevation 800 ft noted in the previous slide. When the Potentiometric surface is in the coarse grained interval the LNAPL thickness behaves as expected for an unconfined condition. When the Pot Surface is above elev 800 (in the fine grained interval (aquitard)) the LNAPL thickness behaves as expected for confined conditions.

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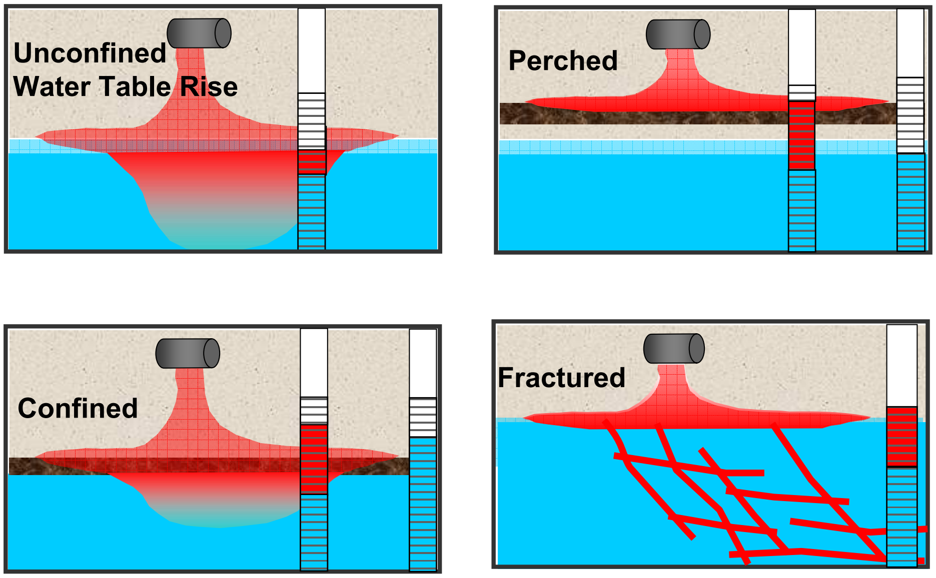
Well Thickness versus Formation Thickness



Slide 57

No shark fin saturation in these situations:

Water table rise. Smear zone is thicker than what is in the well

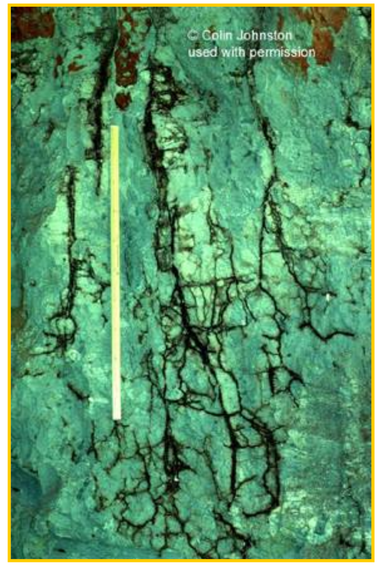
Perched: LNAPL flows into well, which acts like a conduit.

Confined: discussed previously

Once equilibrium is reached, LNAPL thickness in well will equal the continuous LNAPL column formed through connected fractures (macropores). Volume in formation is limited to the fractures.

Macro Pores/Secondary Porosity

- Macropores (fractures, root holes, etc) - low displacement head (hd)
- Very low LNAPL volume in the macropore, but LNAPL potentially would still show up in a well



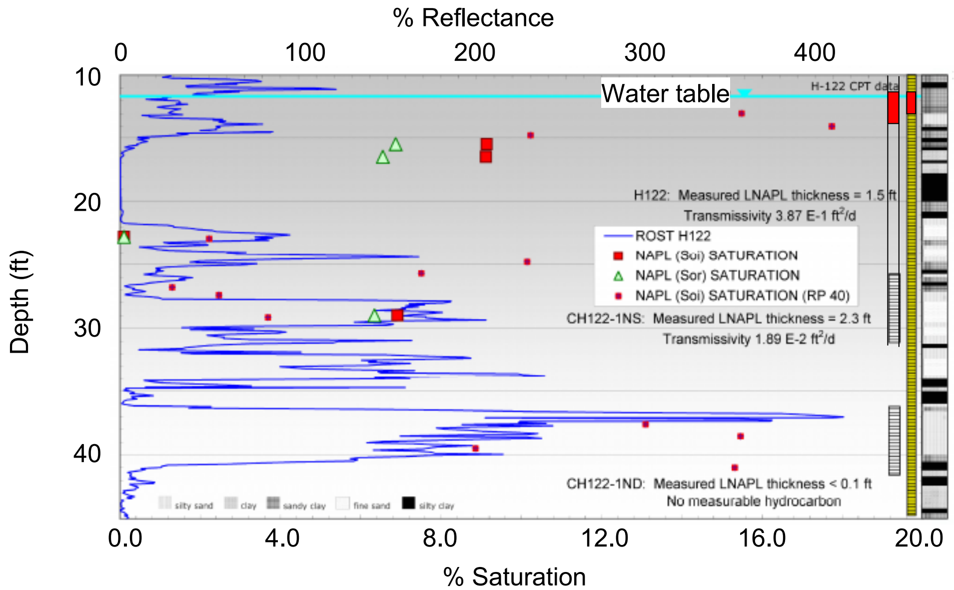
Slide 58

Left photograph: Beaumont clay. LNAPL only in fractures or macropores, seen as white halos. Easy to miss during sampling.

Right photogram: Show the scale of fractures. The yellow bar is a 1-m ruler.

59

Water Table Rise



Slide 59

Example of a site where water table rose over time by several feet

Relevant information to focus on in the graph is the ROST signal (blue line) and measured LNAPL thickness in well on the right.

The smear zone extends down to 40 ft bgs where the water table was historically. The measured thickness of LNAPL is 2-3 ft, and is fed from the trapped LNAPL below the water table.

Modeling this without considering the history of the site, well construction etc. would yield a sharkfin that is limited to the top 2-3 ft.

LNAPL Behavior and Distribution

- LNAPL is distributed at varying saturations vertically (always less than 100%)
- LNAPL saturation depends on soil type and capillary pressure
- Under unconfined conditions LNAPL thickness in wells can be correlated to its saturation in the formation
- Under perched, confined or fractured systems well thickness cannot be used to predict LNAPL saturations or impacted thickness in the formation
- LNAPL thickness and response to water level can be different for different aquifer systems

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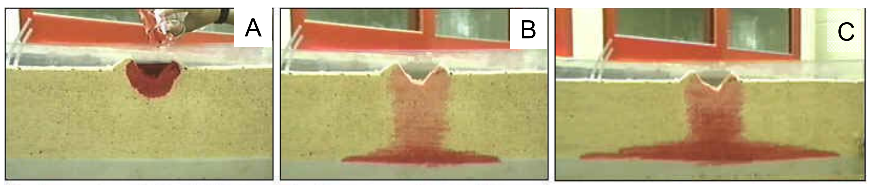
Section 4: How LNAPL Moves

- Section 1: LNAPL definitions and concerns about LNAPL
- Section 2: How LNAPL enters soil and aquifers
- Section 3: How LNAPL distributes vertically
- Section 4: How LNAPL moves



Modified from Schwille, 1988

No associated notes.

62

Common (mis) Perceptions about LNAPL

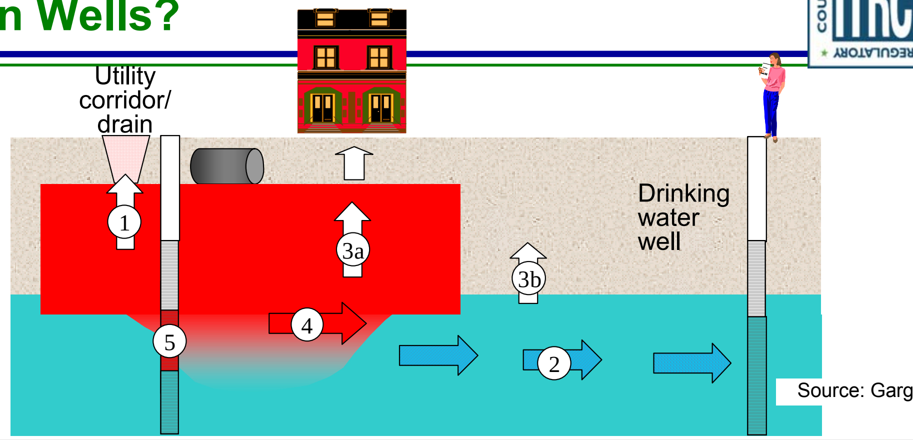
- LNAPL enters the pores just as easily as groundwater
- You can recover all LNAPL
- All the pores in an LNAPL plume are filled with LNAPL
- LNAPL floats on the water table or capillary fringe like a pancake and doesn't penetrate below the water table
- Thickness in the well is exaggerated by a factor or 4, 10, 12, etc.
- LNAPL thickness in a well is always equal to the formation thickness
- If you see LNAPL in a well it is mobile and migrating
- LNAPL plumes spread due to groundwater flow
- LNAPL plumes continue to move over very long time scales

Slide 62

Misconception because common assumption is LNAPL pore entry is analogous to that of water. LNAPL and groundwater are generally similar but there are some differences/considerations that should be accounted for during multi-phase flow:, e.g., relative permeability and pore entry pressure. These are discussed later in this presentation.

63

What Happens When LNAPL is in Wells?



LNAPL emergency issues when LNAPL in the ground	LNAPL considerations when LNAPL in the ground (evaluated using standard regulations)	Additional LNAPL considerations when LNAPL in wells (not evaluated using standard regulations)
(1) Vapor accumulation in confined spaces causing explosive conditions ***Not shown*** - Direct LNAPL migration to surface water ***Not shown*** - Direct LNAPL migration to underground spaces	(2) Groundwater (dissolved phase) (3a) LNAPL to vapor (3b) Groundwater to vapor ***Not shown -*** Direct skin contact	(4) LNAPL potential mobility (offsite migration, e.g. to surface water, under houses) (5) LNAPL in well (aesthetic, reputation, regulatory)

Before considering how LNAPL moves, it is helpful to consider broader considerations for management of LNAPL and the regulatory context for LNAPL mobility.

We begin with LNAPL emergency issues described in left panel, which include safety issues due to explosion and direct contact with LNAPL. In the middle panel, the vapour and groundwater pathways are highlighted. These are common risk pathways that are addressed by most state and federal regulations. The right panel addresses the additional considerations when LNAPL is present in wells, which is potential LNAPL mobility or other aspects that may be relevant due to presence of LNAPL in wells, such as aesthetic considerations, reputation or liability. The focus of the subsequent slides is the fourth point, which is LNAPL mobility. Although many regulatory frameworks have general provisions based on LNAPL presence in wells, such as recovery of LNAPL to the extent practicable, there are few regulations that address LNAPL mobility in detail. In part, our goal here today is to present the science to enable such regulations to be developed.

Notes on potential revisions:

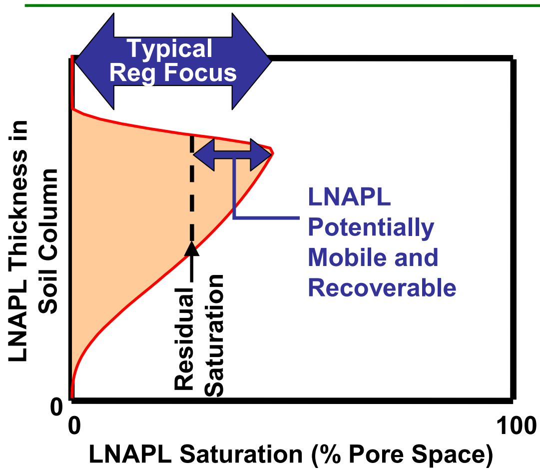
Change title to “LNAPL Management Considerations”

LNAPL emergency issues is typically addressed in regulations. My experience is that virtually all regulations have general prohibitions and cautions respecting factors given.

Replace “evaluated using std. regs) with “typically addressed by regulations”.

Potentially Mobile Fraction of the LNAPL Distribution

Source: Garg



LNAPL mobility is the additional consideration due to exceeding residual saturation

Key Point: LNAPL potentially mobile only if the saturation exceeds residual saturation

As previously discussed, the LNAPL saturation will vary in the soil column. While the typical regulatory focus addresses the whole spectrum of issues associated with LNAPL, the LNAPL mobility is the additional consideration due to exceeding residual saturation.

The key point is the LNAPL is potentially mobile only if the saturation exceeds residual saturation

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Darcy's Law for LNAPL and LNAPL Conductivity

- LNAPL and groundwater co-exist (share pores)
- In an water/LNAPL system, not just dealing with a single fluid (groundwater or LNAPL)
- Darcy's Law governs fluid flow
- Darcy's Law applicable to each fluid (water/LNAPL) independently

Just as Darcy's Law governs the flow of groundwater, it also controls the movement of LNAPL, however, the LNAPL and groundwater co-exist and share pores, so we are not just dealing with characterizing the flow of a single fluid. As will be subsequently shown on slides, Darcy's Law is applicable to each fluid independently.

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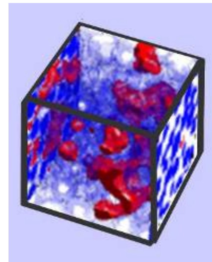
Darcy's Law for LNAPL

Darcy's Law for water flow: $q = K\,i$ [1]

Darcy's Law for LNAPL flow: $q_o = K_o\, i_o$ [2]



- Adjustment to Darcy's Law for LNAPL

$K_o = k_{ro}\, k\, \rho_o\, g / \mu_o$ [3]

$K_o = k_{ro}\, K_w\, \rho_o\, \mu_w / (\rho_w\, \mu_o)$ [4]

k = intrinsic permeability
k_{ro} = relative permeability of LNAPL
g = gravitational coefficient
ρ_o = LNAPL density
ρ_w = density of water
μ_o = LNAPL viscosity
μ_w = water viscosity
i_o = LNAPL table gradient
K_w = saturated hydraulic conductivity
K_o = LNAPL conductivity

Parameter	Parameter Trend	K_o	Effect on LNAPL Flow (q_o)
Relative Permeability of LNAPL (k_{ro})	↑	↑	↑
LNAPL Density (ρ_o)	↑	↑	↑
LNAPL Viscosity (μ_o)	↑	↓	↓

This slide begins with the simple Darcy's Law for fluid flow for both water and LNAPL in equations 1 and 2. For LNAPL, the specific discharge, q subscript o, is a function of the LNAPL conductivity and LNAPL gradient. Equations 3 and 4 are two expressions that relate oil conductivity to permeability. The first equation relates the oil conductivity to the relative permeability of LNAPL, the intrinsic permeability of the porous media, and properties of water. The second equation relatives the oil conductivity to the relative LNAPL permeability, saturated hydraulic conductivity and properties of oil and water. These are important equations used by models for predicting LNAPL mobility.

It is also worthwhile exploring how changes in parameters affect the LNAPL flow. An increase in relative permeability of LNAPL increases the oil conductivity and flow rate. The relative permeability of LNAPL varies over many orders of magnitude. Likewise an increase in density also increases the LNAPL flow rate, however, since changes in density are small, this is not an important parameter with respect to mobility. The third variable, viscosity, is of moderate importance, with an opposite trend shown where an increase in viscosity decreases the LNAPL flow rate.

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LNAPL Conductivity is Also Dependant on Viscosity of the LNAPL

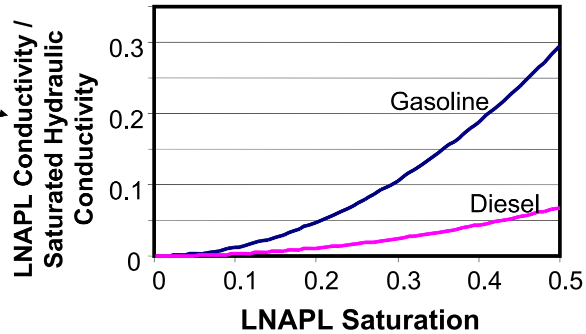
$q_o = K_o \, i_o$

$K_o = k \, k_{ro} \rho_o g / \mu_o$

$= k_{ro} K_w \rho_o \mu_w / \rho_w \mu_o$

Terms defined in previous slide

K_o/K_w →



Key Points: **For a given LNAPL saturation, higher LNAPL viscosity → *lower* LNAPL conductivity**

For a given LNAPL viscosity, higher LNAPL saturation → *higher* LNAPL conductivity

This slide illustrates both how the LNAPL saturation and viscosity influence the ratio of the LNAPL conductivity to saturated hydraulic conductivity. First, an increase in saturation results in an increase in this ratio, or in other words, the LNAPL mobility. The viscosity is indirectly evaluated through model predictions for two petroleum products with different viscosities. For example, for a saturation of 0.3, the LNAPL mobility as expressed by this ratio is about 4 times higher for gasoline than diesel. While there are typically distinct differences between different petroleum products, it is important to note that there may be mixtures of different products at sites and also weathering that occurs over time, which may change viscosity. For this reason, the viscosity of the LNAPL is typically measured when evaluating mobility.

To summarize these relationships, the LNAPL conductivity decreases as the viscosity increases. For LNAPL saturation, the LNAPL conductivity increases as the saturation increases.

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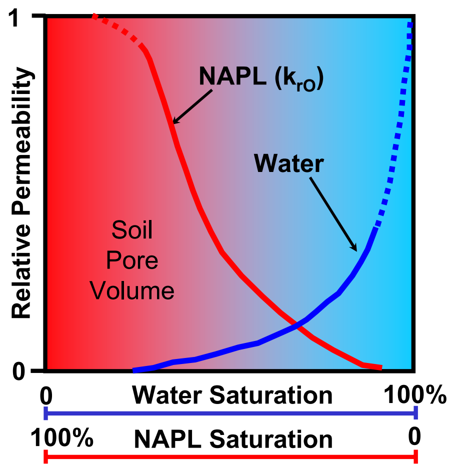
Relative Permeability (k_r)

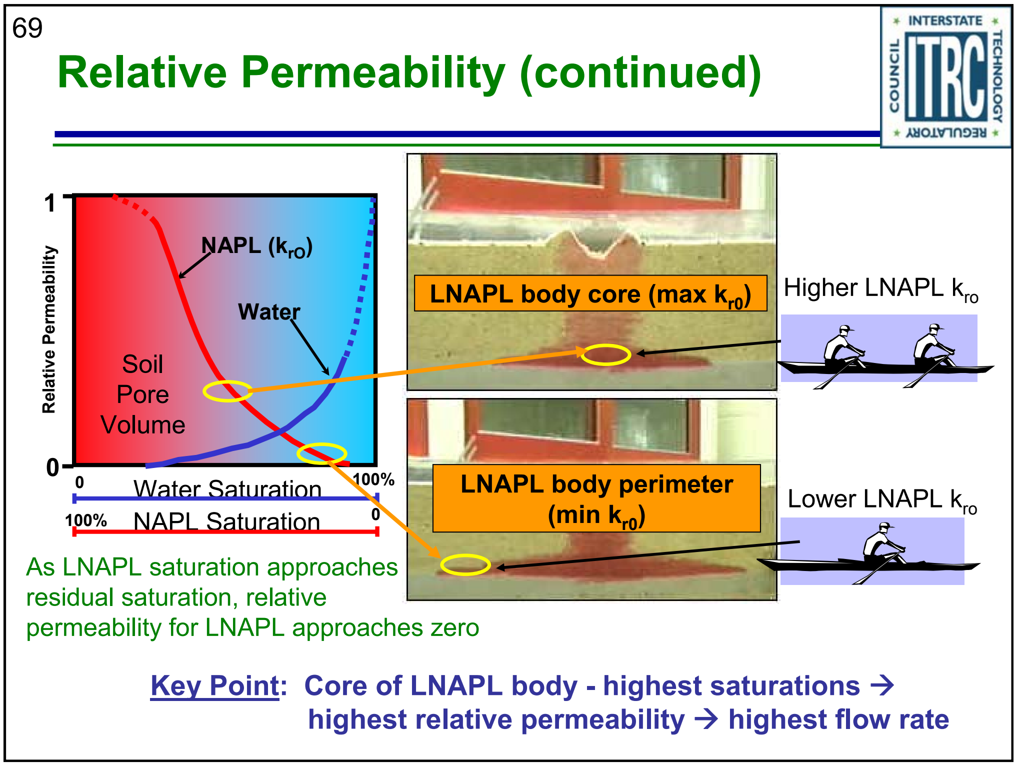
Definition: Porous media ability to allow flow of a fluid when other fluid phases are present



Consider water/LNAPL in soil:

- Saturation → relative permeability
- Relative permeability of soil for water or LNAPL at 100% saturation = 1
- Relative permeability for both LNAPL and water decreases rapidly as saturation declines from 100%
- Below residual saturation, flow decreases exponentially
- Relative permeability of LNAPL (k_{ro}) and relative permeability of water inversely related

The relative permeability is the ability of fluid to flow in porous media when other phases are present. For LNAPL, the saturation is related to the relative permeability as shown in the figure. At 100% saturation, the relative permeability is one. As the saturation decreases from 100%, the relative permeability for both LNAPL and water decrease rapidly, with the decrease following an exponential trend. The relative permeability of LNAPL and water are inversely related.



This slides relates the relative permeability to saturations that one would expect in different parts of the LNAPL plume. In the core of the plume, the LNAPL saturation is higher, which also results in higher relative permeability to LNAPL. Near the edges of the LNAPL plume, the LNAPL saturation will be lower, and consequently the relative permeability will also be less. We have shown the contrast in relative permeability to be analogous to rowers, relative to the core of the plume there are two rowers, whereas near the perimeter of the plume there is only one rower. If we move even further to the edge of the plume there may be no mobility or no rower

Not shown in this slide is the influence of the LNAPL gradient. During earlier time periods after a release, there is greater mounding of LNAPL and higher gradient. As the LNAPL spreads laterally, the LNAPL gradient will decrease.

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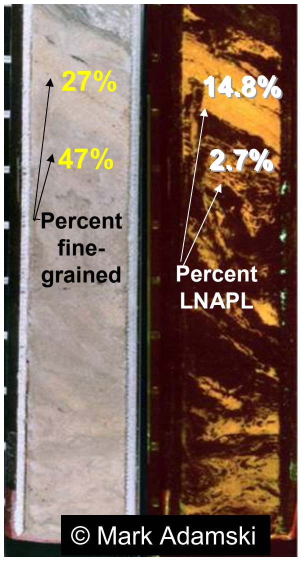
Relative Permeability (continued)



Soil with fluorescing LNAPL

Higher LNAPL saturation in coarser-grained soil

- LNAPL relative permeability is not uniformly distributed – soil heterogeneity controls
- Higher LNAPL saturation in coarser-grained soil
  → higher relative permeability
  → higher potential LNAPL flow rate

The purpose on this slide is to illustrate how soil heterogeneity will influence LNAPL flow. The photograph show a soil core that is split in half, on the left, the core shows the contrast between coarse-grained soil that is lighter coloured, and finer-grained soil, that is darker. On the right is the fluorescence, where the brightest orange region shows the highest LNAPL content, which coincides with the coarser-grained soil, as expected. The key point of this slide is that coarser-grained layers will have higher LNAPL saturation, higher relative permeability and higher potential LNAPL flow rate.

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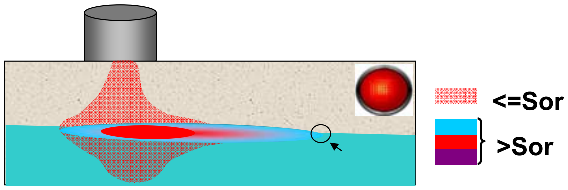
Displacement Head and LNAPL Migration



- There is a minimum LNAPL displacement entry pressure or displacement head (h_{dn}) that must be overcome for LNAPL to migrate into water-wet pores - this minimum displacement head can be related to the thickness of LNAPL in the formation
- If LNAPL thickness is less than this minimum thickness, then no LNAPL movement into water-wet pores occurs
- Field scale observations of LNAPL are consistent with LNAPL bodies that stop spreading laterally due to displacement entry pressure
- A quantitative understanding of the displacement head and relationship to LNAPL thickness thresholds in monitoring wells is an area of active research and debate

Key Point: Water acts as a capillary barrier against continued LNAPL spreading

While we have been focussing on LNAPL conductivity and movement, it is important to come back to concepts relating to displacement head and LNAPL migration.

An important concept is that there is a minimum LNAPL displacement entry pressure or head that must be overcome in order for LNAPL to move into water-wet pores.

This displacement head in turn can be related to the thickness of LNAPL in the formation.

If the LNAPL thickness is less than minimum entry head than no LNAPL flow occurs.

As indicated earlier a model based on LNAPL spreading that is controlled by the displacement entry pressure is consistent with field scale observations

There are quantitative models, such as those developed by Dr. Randall Charbenau for the American Petroleum Institute, that have been developed that link the minimum thresholds for mobility to thickness of LNAPL in wells, however, this is still an active area of research and debate

Again the key point is that water acts as a capillary barrier against continued LNAPL spreading

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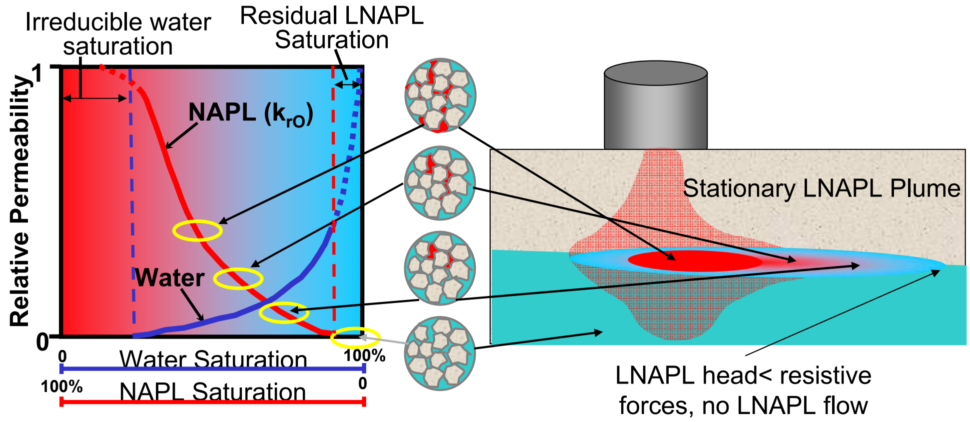
LNAPL Plumes

Conceptual LNAPL saturation conditions after LNAPL plume spreading stops



- Saturations/relative permeability decreases away from plume core
- At plume edge LNAPL saturation and thickness in a well is > 0, but stable due to displacement head
- LNAPL in the plume core can be mobile, but plume footprint (extent) is stable

This slide brings together the two concepts we have been discussing. On the left is the relative permeability relationship indicating potential mobility for NAPL saturations greater than residual saturation. On the right is the conceptual model that shows how the spreading of the LNAPL is controlled by the resistive forces at the perimeter of the plume. The key point is that potential LNAPL mobility within the core of the plume does not necessarily equate to spreading of LNAPL or an expanding LNAPL footprint.

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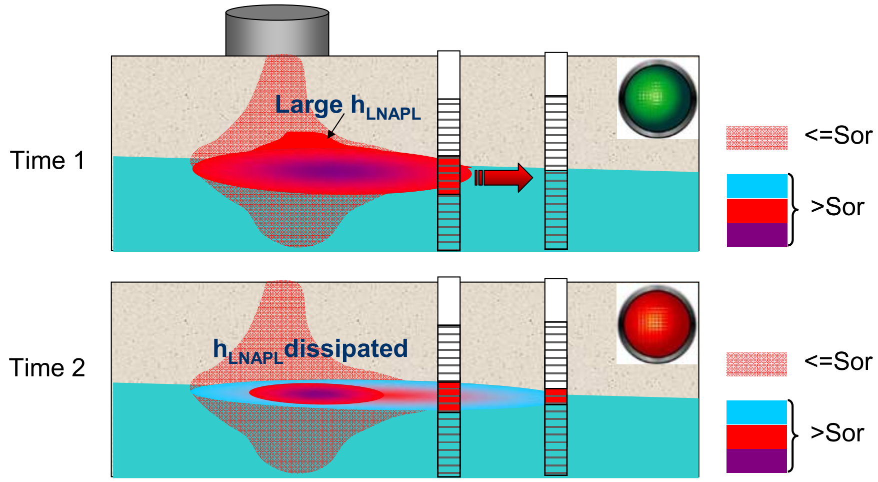
LNAPL Mobility



Key Point: Once the LNAPL head dissipates, it is no longer sufficient to overcome LNAPL entry pressure and LNAPL movement ceases

The timescale over which there will be LNAPL mobility is also an important consideration. At early times is e next two slides summarize the concept that there must be a minimum LNAPL head to overcome the LNAPL displacement entry pressure for LNAPL mobility to occur. At early times after a LNAPL release, there is a large LNAPL head and LNAPL movement occurs. A later times, the head has dissipated and there is not long sufficient head to overcome the displacement entry pressure.

Case Examples

What we have observed at sites

- LNAPL can initially spread at rates higher than the groundwater flow rate due to large LNAPL hydraulic heads at time of release
- LNAPL can spread opposite to the direction of the groundwater gradient (radial spreading)
- After LNAPL release is abated, LNAPL bodies come to be stable configuration generally within a short period of time

The next three slides present case studies on LNAPL mobility. Before looking at specific cases, the general observations are that:

LNAPL can initially spread at rates higher than groundwater flow

LNAPL can spread in the opposite direction to groundwater flow direction due to mounding of LNAPL and radial spreading, and finally,

LNAPL bodies tend to come to stable configurations in relatively short time periods

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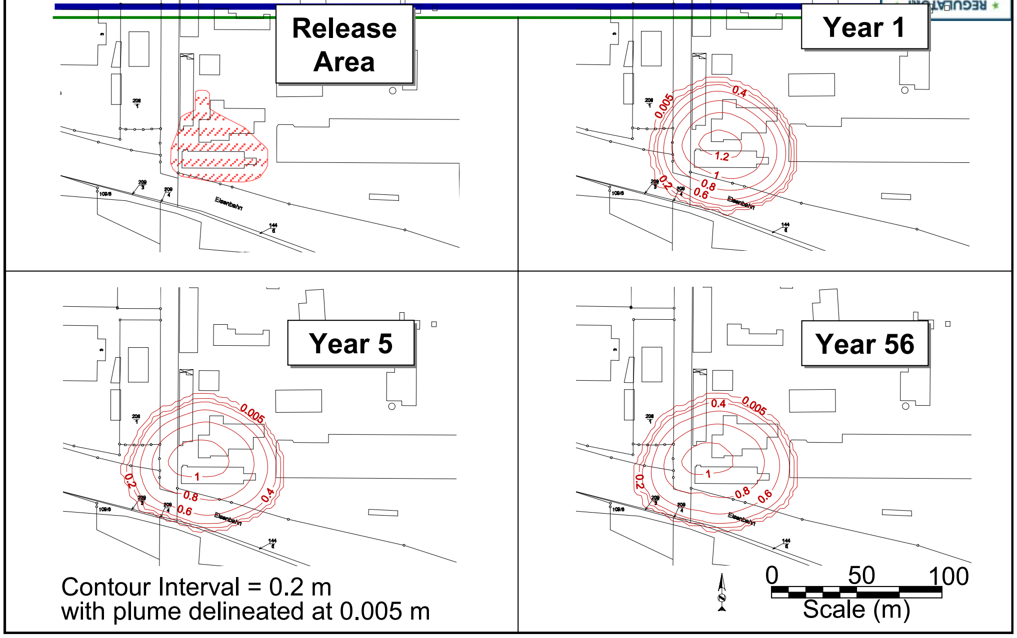
Case Example 1: Simulated LNAPL Release



The first case example shows the simulated migration of a LNAPL release involving about 1,500 m3 of product over a 56 year period. The images represent the predicted well-product thickness measurements. While the growth in the plume from release to Year 1 is clear, the plume appears to grow only slightly over the next 55 years.

For these simulations, a relatively small groundwater gradient was assumed and the groundwater is predicted to move about 600 meters. In contrast, the LNAPL has spread over an approximately 100 m.

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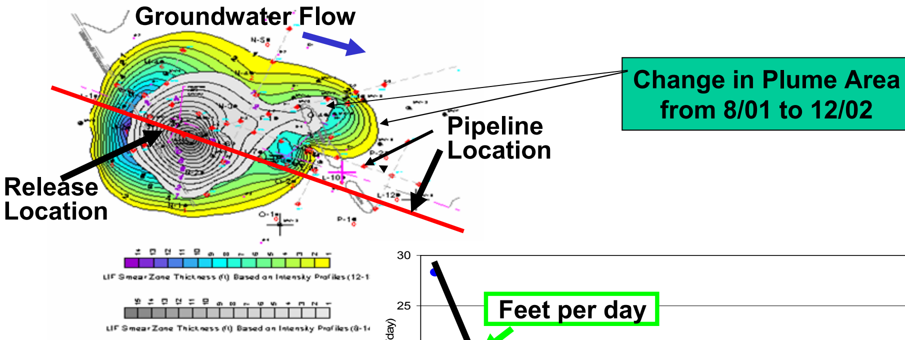
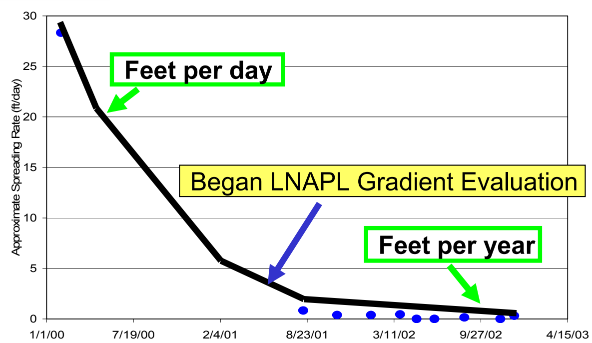
Case Example 2: LNAPL Release and Spreading



- Sweet Texas Crude
- Unknown release volume



The second case example is measured data at a pipeline site crude oil release. The upper left figure is a plan showing the spread in the LNAPL thickness over time. The grey area represents the spread between when the release occurred, in February 2000 and October 2001. The blue and yellow zone represents the additional spreading between October 2001 and December 2002. An important characteristic shown in this figure is that the LNAPL spreads radially from the release location and not only in the direction of groundwater flow.

The figure in the lower right shows the estimated rate of LNAPL spreading, which initially was on the order of a few feet per day, and after about a year and half, decreased to few feet per year.

After December 2002, no additional LNAPL was observed to migrate in sentinel wells surrounding the release area. The LNAPL plume is considered to be functionally stable, which refers to a state or condition where there is some vertical and lateral redistribution of LNAPL, but where additional movement is relatively minor and should not impact ongoing plume management objectives.

The dissolved concentrations in groundwater are also monitored routinely and indicate that the dissolved plume is also reaching a stabilized footprint around the LNAPL smear zone. The dissolved plume behavior can be used to infer LNAPL stability, if dissolved plume is stable or shrinking, the LNAPL is unlikely to be expanding.

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Lines of Evidence of LNAPL Footprint Stability

1. Monitoring results (assumes adequate well network)
   - Stable or decreasing thickness of LNAPL in monitoring wells
   - Sentinel wells outside of LNAPL zone remain free of LNAPL
   - Stable or shrinking dissolved phase plume
2. Calculated LNAPL Velocity
   - Estimate K_o from:
     - Baildown test at peripheral wells
     - Measured LNAPL thickness, soil capillary parameters, model that assumes static equilibrium (e.g., API Interactive LNAPL Guide)
   - Measure i_o
   - $q_o = K_o i_o$
   - $v_o = q_o / (\phi S_o)$

Porosity * LNAPL saturation ~ typically 0.2 to 0.03

The emerging approach for evaluating LNAPL mobility is a multiple lines of evidence approach. The intent here is to provide an overview of this approach, the technical regulation that the ITRC LNAPL team is developing will provide additional details.

The first line of evidence and typically the primary and most important one are monitoring results. Assuming that there is an adequate monitoring network and sufficient temporal data, there are several factors that are evidence for a stable footprint, which are a stable or decreasing thickness of LNAPL in monitoring wells, sentinel wells outside of the LNAPL zone that remain free of LNAPL and a shrinking dissolved phase plume

The second line of evidence involves calculating the potential LNAPL velocity using Darcy’s Law. The key parameter, which is the LNAPL conductivity, may be estimated from bail down tests, or from the measured LNAPL thickness, soil capillary parameters and model that assumes static equilibrium. The API Interactive LNAPL Guide is one tool that may be used to estimate the LNAPL velocity using this model. Some guidance documents have suggested that the calculated LNAPL velocity be compared to a de minimus LNAPL velocity below which one would generally not be concerned with LNAPL mobility. It is important to recognize that use of Darcy’s Law would be precluded for some site conditions, such as a fractured bedrock site.

New emerging method for estimating LNAPL tracer dilution method

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Lines of Evidence of LNAPL Footprint Stability (continued)

3. Measured LNAPL thickness less than a threshold thickness in wells required to invade water-wet soil pores (displacement entry pressure model)
4. Recovery rates
   - Decreasing LNAPL recovery rates
5. Age of the release
   - Timing of release (if known)
   - Weathering indicators
6. Field and laboratory tests
   - Centrifuge tests and measured saturation and residual saturation values

The third line of evidence is to compare the measured LNAPL thickness to a calculated threshold LNAPL thickness in wells required to invade water-wet pores based on the displacement entry pressure model. There is still some debate on the use of the this model as indicated earlier in this training.

The fourth line of evidence are recovery rates observed as LNAPL is removed from a well. Although not directly correlated to LNAPL mobility, declining recovery rates would generally indicate reduced potential for LNAPL mobility

The fifth line of evidence is the age of the release, when known. If a relatively long time has transpired since the release there is reduced potential for mobility due to smearing of LNAPL within soil and weathering of LNAPL through dissolution, biodegradation and volatilization

The sixth line of evidence are field and laboratory tests. While these a indirect indicators, if for example measured LNAPL saturations are less than residual saturation obtained from centrifuge test, then there will likely be little potential for LNAPL mobility. However, these tests are approximate and for example centrifuge tests would tend to over predict mobility

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Section 4 Summary: LNAPL Migration Dynamics

(mis) Perceptions: LNAPL plumes can spread indefinitely
LNAPL plumes spread due to groundwater flow

- Potential LNAPL velocity may be estimated from Darcy's Law
- The LNAPL relative permeability is a key parameter for LNAPL flow, and is a function of the LNAPL saturation
- The displacement pore entry pressure must be exceeded for LNAPL to enter a water-filled pore
- Once the LNAPL release stops, LNAPL near the water table will eventually cease to spread as the resistive forces in soil balance the driving forces (LNAPL head) in the LNAPL pool
  - Smaller releases will stop migrating sooner
  - Continuing releases will result in a growing plume
- LNAPL plume may be stable at the LNAPL fringe, but there may be local re-distribution within the LNAPL core

As this point, I would like to summarize what we have learned about LNAPL migration. First of all, potential LNAPL velocity may be estimated from Darcy's Law. A key parameter for LNAPL mobility is relative permeability, which is a function of saturation.

It is important to recognize that once LNAPL release stop, LNAPL near the water table will eventually cease to spread at resistive forces. Smaller releases will stop migrating sooner, however continuing releases will result in a growing plume.

While a LNAPL plume or body may be stable, there may be redistribution within the LNAPL core and varying thickness of LNAPL observed in wells.

Summary of LNAPL Basics

- LNAPLs are not distributed vertically in a "pancake" fashion, but are distributed according to vertical equilibrium as a multiphase
- LNAPL saturations are not uniform, but are controlled by soil heterogeneity
- The specific volume of LNAPL within soil will be greater in coarse than fine grained soil for a given LNAPL thickness
- As the LNAPL saturation increases, the relative permeability and potential LNAPL velocity also increases

No associated notes.

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Summary of LNAPL Basics (continued)

- 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
- LNAPL 3-part Internet-based training
  - Part 1 – basic principles for LNAPL distribution and mobility
  - Part 2 – LNAPL assessment, LNAPL Conceptual Site Model, and LNAPL recovery evaluation
  - Part 3 – identify the LNAPL concerns or risks and set remedial objectives and technology-specific remediation goals and performance metrics
- 2-day classroom training: Light Nonaqueous-Phase Liquids (LNAPLs): Science, Management, and Technology on October 16-17, 2012 in Novi, Michigan (Detroit Area)

Coming in 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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Thank You for Participating

- 2nd question and answer break
- Links to additional resources
  - http://www.cluin.org/conf/itrc/iuLNAPL/resource.cfm
- Feedback form – *please* complete
  - http://www.clu-in.org/conf/itrc/iuLNAPL/feedback.cfm

Need confirmation of your participation today?

Fill out the feedback form and check box for confirmation email.

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

Your feedback is important – please fill out the form at:
http://www.clu-in.org/conf/itrc/iuLNAPL/feedback.cfm

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✓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

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✓Submit proposals for new technical teams and projects