LNAPL Volume and Mobility Estimation to Assess When to Stop Active Recovery

by Louis Sabourin, P.Eng. and David Tarnocai, P.Geo.
Presentation Outline

• Introduction, Issue and Importance
• LNAPL Migration & Concept in Subsurface
• Properties that affect LNAPL Volume and Mobility
• Study Methodology
• Case Studies (Site A Louis & Site B David)
  – Background: History and Remedial System
  – LNAPL and Soil Properties
  – Volume and Mobility Estimates
  – Remedial System Performance/ Final LNAPL
• Sensitivity Analysis
• Conclusions
Introduction

• Application of the API Interactive LNAPL Guide to estimate the volume and mobility of LNAPL at two former petroleum fuel storage facilities:
  – Site A impacted by Gasoline/Diesel
  – Site B impacted by Jet Fuel

• The Interactive LNAPL Guide is a web available system that includes:
  – educational information
  – assessment tools
  – other useful info on LNAPL
Issue and Importance

• In the past decade, complete LNAPL removal was considered fundamental to site closure

• This was before understanding:
  – LNAPL movement and removal limitations
  – LNAPL plume stability/Natural attenuation

• More recently, industry/consultants started to ask:
  – What is the practical extent of LNAPL removal?
  – When can LNAPL be declared immobile and not likely to impact surrounding areas?

• This study aimed at finding answers to these questions for two sites
LNAPL Migration in Subsurface

Major Factors of influence:

• LNAPL properties
  – Density
  – Viscosity
  – Interfacial and surface tension

• Soil Properties
  – Soil texture/porosity
  – Permeability
  – Capillary pressure vs saturation

After API, 2003
Effect of LNAPL Properties

Release of 1 M US Gal (4 ML) in sand for 5 years
Effect of Soil Properties

Release of 1 M US Gal (4 ML) of gasoline for 5 years

After API, 2003
Concept of LNAPL in Subsurface

Vertical Profile in Soil

- Water Table
- "Pancake Layer" Concept
- "Multi-Phase" Concept
- Residual saturation

Elevation in Soil Column

LNAPL Saturation (% Pore Space)

Monitoring Well

- Air-LNAPL Interface
- Theoretical Air-Water Interface
- Observed Monitoring Well Thickness
- LNAPL-Water Interface

Responsible, Practical, Innovative and Cost-effective Environmental Solutions.
Methodology - LNAPL Volume

- Well product thicknesses contoured and areas calculated

- An LNAPL saturation profile for each contour interval (average product) is defined using soil and LNAPL properties based on LNAST from API

- By integration of the saturation profile over the contour area, the volume of LNAPL is calculated
Methodology - LNAPL Mobility

• The inherent mobility of an LNAPL in a porous medium is calculated using (API, 2003):

\[
M = \frac{k \, kr_{\text{LNAPL}} \, \rho_{\text{LNAPL}} \, g}{\mu_{\text{LNAPL}} \, n \, S_{\text{LNAPL}}} = \frac{K_{\text{LNAPL}}}{n \, S_{\text{LNAPL}}}
\]

where:

- \(k\): permeability of the porous media (L\(^2\))
- \(kr_{\text{LNAPL}}\): relative permeability of the porous media to LNAPL (varies with \(S_{\text{LNAPL}}\)) (dimensionless)
- \(\rho_{\text{LNAPL}}\): density of LNAPL (M/L\(^3\))
- \(g\): gravitational constant (L/T\(^2\))
- \(\mu_{\text{LNAPL}}\): dynamic viscosity of LNAPL (M/LT)
- \(n\): porosity of the porous media (dimensionless)
- \(S_{\text{LNAPL}}\): fraction of pore space saturated with LNAPL (dimensionless)
- \(K_{\text{LNAPL}}\): LNAPL conductivity (L/T)
Case Study – Site A Background

• Former Bulk Fuel Plant
• LNAPL discovered on-site in 1998 (Gasoline/Diesel)
• Geology: Fine sand
• Hydrogeology:
  \[ K = 10^{-5} - 10^{-6} \text{ m/s} \]
  Groundwater flow to southwest (5-25 m/y)
• Remedial Technologies
  2001-2005: Dual-Phase High Vacuum Extraction (DPVE)
Site A - Layout and Surrounding Use

Legend:
- PROPERTY LINE

- FORMER LOADING DOCKS
- FORMER U/G FUEL TANK
- FORMER A/G TANK FARM
- FORMER WAREHOUSE
- FORMER OFFICE BUILDING

- ROADWAY
- STREET

- (RESIDENTIAL)
- (COMMERCIAL/INDUSTRIAL)

- (RESIDENTIAL)
- (COMMERCIAL/INDUSTRIAL)
- (RESIDENTIAL)
- (COMMERCIAL/INDUSTRIAL)
Site A - LNAPL and Soil Properties

• LNAPL Properties based on Analytical Results
  
  LNAPL = Diesel Fuel (~80%) and Gasoline (~20%) Mixture  
  $\rho = 0.81 \text{ g/ml}$, $\mu = 1.7 \text{ cP}$, $\sigma_{ow} = 27.9 \text{ mN/m}$, $\sigma_{ao} = 25.6 \text{ mN/m}$,

• Soil Properties based on Huntley & Beckett (2002) and LNAPL Guide Default Program Parameters
  
  Fine Sand  
  Van Genuchten $\alpha = 7.5 \text{ m}^{-1}$, $n = 1.9$  
  Residual Water Saturation = 0.32  
  LNAPL Residual Saturation = 0.20  
  Total Porosity = 0.43
Site A - Initial LNAPL Volume/Mobility

- Volume/Mobility estimated using site monitoring data collected prior to DPVE

- Spring 1999 LNAPL thickness and area:
  Up to ~0.9 m (680 m²)

- Total estimated volume of LNAPL initially present in the plume:
  Approx. 13,000 L

- Highest LNAPL mobility:
  0.8 m/day at $S_{LNAPL} = 0.4$
DPVE started 2001

Initial DPVE hydrocarbon recovery rate \( \sim 20 \text{ L/day} \)

Total volume recovered \( \sim 5,800 \text{ L (45\%)} \)

Final DPVE hydrocarbon recovery rate \( < 2 \text{ L/day} \)
Site A – Final LNAPL Distribution

LNAPL areal extent reduced considerably to:
~100 m² (680 m²)

By 2005, LNAPL thickness in wells reduced to:
~0.45 m or less (~0.9 m)

Highest LNAPL mobility:
0.2-0.4 m/day at $S_{LNAPL} = 0.1-0.2$
(0.8 m/day at $S_{LNAPL} = 0.4$)

Majority of LNAPL below residual and essentially immobile
Case Study – Site B Background

- Former Airport Fuel Storage Facility
- LNAPL discovered on-site in 1998 (Jet A-1 Fuel)
- Geology: Fine sand
- Hydrogeology
  \[ K = 2 \times 10^{-6} \text{ m/s} \]
  Almost flat gradient (no clear groundwater flow direction – divide)
- Remedial Technologies
  - 2002-2006: Low Vacuum Enhanced Product Skimming
Site B - LNAPL and Soil Properties

- LNAPL Properties based on Analytical Results

  LNAPL = Jet A-1
  \( \rho = 0.81 \text{g/ml, } \mu = 1.6 \text{ cP, } \sigma_{ow} = 25.2 \text{ mN/m, } \sigma_{ao} = 26.6 \text{ mN/m, } \)

- Soil Properties based on Huntley & Beckett (2002) and LNAPL Guide Default Program Parameters

  Fine Sand
  Van Genuchten \( \alpha = 7.5 \text{ m}^{-1}, n = 1.9 \)
  Field residual water saturation = 0.32
  LNAPL field residual saturation = 0.2
  Total porosity = 0.43
Site B – Initial LNAPL Volume/Mobility

- Volume/Mobility estimated using site monitoring data collected prior to skimming
- Spring 2002 LNAPL thicknesses and area: **Up to ~ 2.4 m (1150 m²)**
- Total estimated volume of LNAPL initially present in the plume: **Approx. 67,000 L**
- Highest LNAPL mobility: **0.2 m/day at S_{LNAPL} = 0.6**
Site B - Remedial System Performance

Vacuum skimming started in 2002 at low vacuum followed by moderate vacuum in 2003.

Vacuum skimming recovery rate ~ 7 L/day

Total volume recovered ~5,500 L (<10%)

Final recovery rate <0.5 L/day
Site B – Final LNAPL Distribution

LNAPL areal extent reduced to:
~ 700 m²  (1150 m²)

By 2005, LNAPL thickness in wells reduced to:
~0.39 m or less  (2.4 m)

Highest LNAPL mobility:
0.07 m/day at $S_{\text{LNAPL}} = 0.24$
(0.2 m/day at $S_{\text{LNAPL}} = 0.6$)

Majority of LNAPL essentially immobile in absence of significant thickness and gradient
Sensitivity Analysis – VG Properties

• LNAPL properties determined by analysis

• Site specific van Genuchten properties not available. Default VG Properties in the LNAPL Guide based on “typical values”. Use of “typical” soil capillary properties contributes to variability in volume estimates

• van Genuchten $\alpha$ is inversely related to capillary fringe height with coarse materials displaying relatively high values

• van Genuchten $n$ is a function of the pore throat distribution with high values indicating greater pore size uniformity
# Sensitivity Analysis – VG Properties

<table>
<thead>
<tr>
<th>Simulation</th>
<th>VG $\alpha$ m$^{-1}$</th>
<th>VG $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case – Site A (Huntley &amp; Beckett, 2002)</td>
<td>7.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Base Case – Site B (Huntley &amp; Beckett, 2002)</td>
<td>7.5</td>
<td>1.9</td>
</tr>
<tr>
<td>High ($\mu+2\sigma$) (coarse materials with uniform sized pore size)</td>
<td>19.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Low ($\mu-3\sigma$) (fine materials with non-uniform pore size)</td>
<td>7.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Sensitivity Analysis – Results

<table>
<thead>
<tr>
<th></th>
<th>Base Case (L)</th>
<th>High ( n ) and ( \alpha ) (m(^{-1})) (L)</th>
<th>Low ( n ) and ( \alpha ) (m(^{-1})) (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>13,000</td>
<td>27,800</td>
<td>10,000</td>
</tr>
<tr>
<td>Site B</td>
<td>67,000</td>
<td>110,000</td>
<td>65,500</td>
</tr>
</tbody>
</table>

LNAPL volume estimate within each contour interval varied by up to a factor greater than 6. Total volume estimates varied by up to a factor of 3 in the above cases.
Conclusions

• Interactive LNAPL Guide an interesting tool to assess LNAPL Volume & Mobility and help substantiate exit criteria for LNAPL recovery

• Volume estimates can be sensitive to LNAPL and soil properties and should therefore not be taken as absolute values

• In our cases, mobility estimates of $10^{-2}$-$10^{-1}$ m/day suggest plume stability under limited gradient

• This model provides a secondary line of evidence in addition to field evidence (reduced LNAPL thicknesses, limited recovery rates and plume stability) to support site closure
THANK YOU!

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