Use of Laser Induced Fluorescence (LIF), Soil/LNAPL Laboratory Testing, Modeling and Actual Recovery Data to Evaluate LNAPL Mobility, Stability and Recoverability

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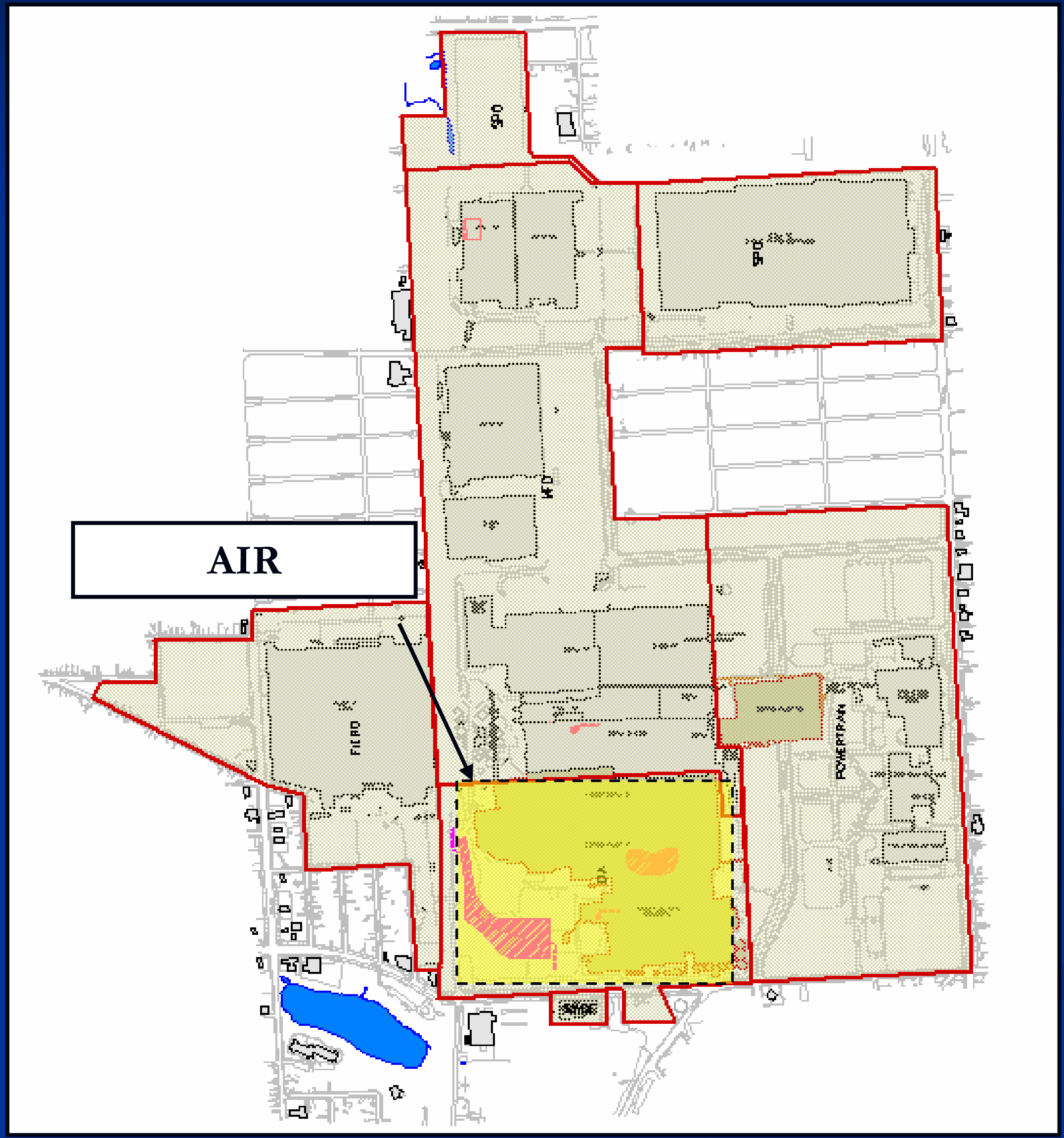
Case Study - Background

- Subject Site – 600 acre General Motors Corporation (GM) manufacturing facility in the U.S.;
- South portion of Site (approximately 100 acres) leased to a 3rd party and undergoing redevelopment for the construction of an 800,000 square foot building;
- Area referred to as Area of Industrial Redevelopment (AIR).

Site / AIR / LNAPL Areas



Background (Cont'd)

- LNAPL was discovered in various areas in the AIR, including an area which in part, was located beneath the proposed building footprint;
- An aggressive LNAPL recovery program was implemented in the footprint area in support of the construction schedule in the AIR (refer to Cushman et al., RemTech 2006); and
- This paper focuses on the LNAPL mobility and recoverability evaluation conducted in the remaining LNAPL areas within the AIR.

Geology/Hydrogeology

- Geology is comprised of low permeability glacial soils (silts and clays with occasional sand seams) with several areas of sand fill material;
- Depth to air/LNAPL interface varies from approximately 15 to 30 feet bgs;
- LNAPL thicknesses vary from a sheen to 12 feet; and
- LNAPL has been fingerprinted as a weathered No. 2 fuel oil/diesel with lesser amounts of No. 6 fuel oil.

LNAPL Mobility Evaluation Methodology

- Conducted Laser Induced Fluorescence (LIF) survey using Rapid Optical Screening Tool (ROST) technology;
- Collected undisturbed soil cores in select locations of soil zones exhibiting varying degrees of relative fluorescence during ROST (greatest to least);
- Submitted soil cores for laboratory photography and testing of key LNAPL mobility parameters;

LNAPL Mobility Evaluation Methodology (Continued)

- Compared laboratory measured LNAPL saturation and corresponding residual saturation values to qualitatively evaluate inherent mobility potential;
- Calculated maximum LNAPL relative permeability, conductivity, mobility and velocity values for each sample location using API/Charbeneau methods; and
- Compared calculated LNAPL velocities to *de minimis* mobility threshold for LNAPL*.

De Minimis LNAPL Velocity*

- It has been suggested that an LNAPL velocity of 1×10^{-6} cm/s or less, represents the *de minimis* mobility threshold for LNAPL (ASTM, 2005);

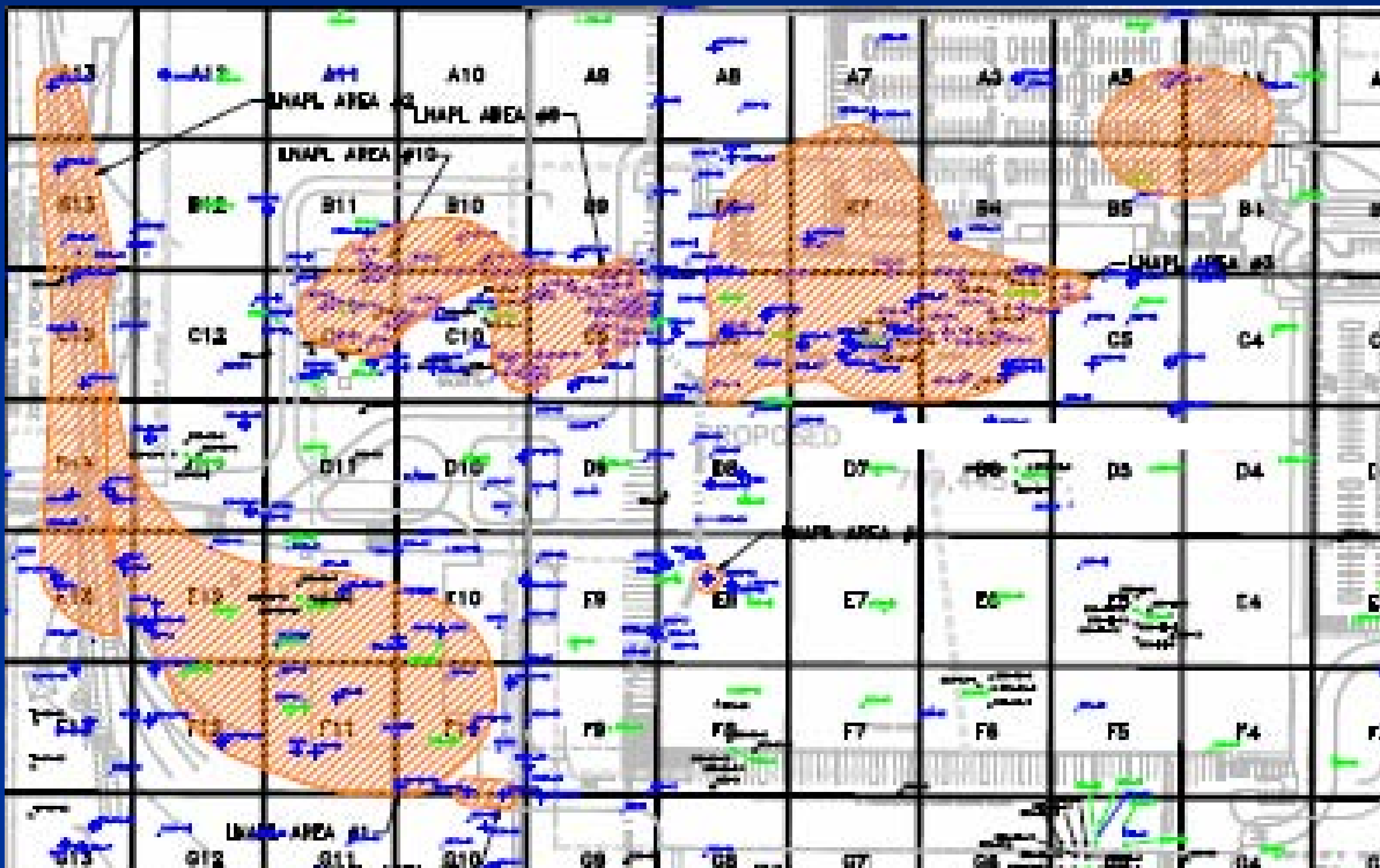
- This threshold plays a critical role in LNAPL mobility evaluations and the potential need for active recovery systems.

LNAPL Delineation – Conventional vs. Innovative

Conventional Delineation

- Conventional LNAPL delineation accomplished using various conventional drilling/direct push methods including hollow stem auger, rotosonic, and Geoprobe;
- Soil screening for LNAPL accomplished using visual and olfactory techniques, field screening (PID, UV light, shake tests, OilScreenSoil-Sudan IV);
- Wells installed in areas with high potential for LNAPL based on soil screening.

LNAPL Delineation – Conventional vs. Innovative



LNAPL Delineation – Conventional vs. Innovative

Sophisticated Delineation

- Advanced 128 ROST points throughout AIR;
- ROST conducted using special Cone Penetration Testing (CPT) rig. Soil classification based on resistance and friction to CPT probe during penetration through ground;
- CPT probe equipped with laser/sapphire window assembly;

LNAPL Delineation – Conventional vs. Innovative

Sophisticated Delineation

- As probe is advanced, laser light is directed through the window and into the subsurface;
- Laser light is absorbed by the aromatic hydrocarbon molecules which causes the molecules to fluoresce;
- A portion of the fluorescence is reflected through the sapphire window and returned via fibre optic cable to the detection system in the CPT rig;

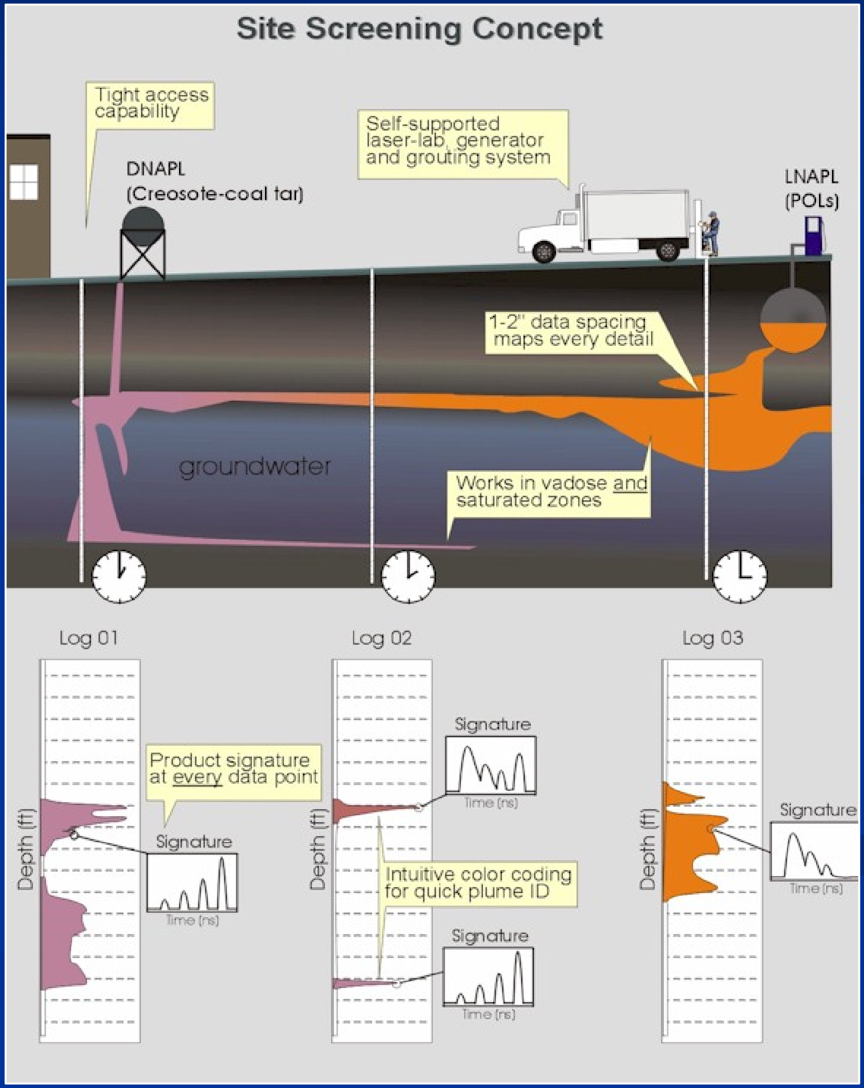
LNAPL Delineation – Conventional vs. Innovative

Sophisticated Delineation

- The emission data from the pulsed laser light is averaged into one reading per second intervals and is recorded continuously;
- Intensity of fluorescence is quantified via comparison against a standard hydrocarbon mixture used to calibrate laser;
- The intensity of the fluorescence is proportional to the amount of hydrocarbon present.

LNAPL Delineation – Conventional vs. Innovative

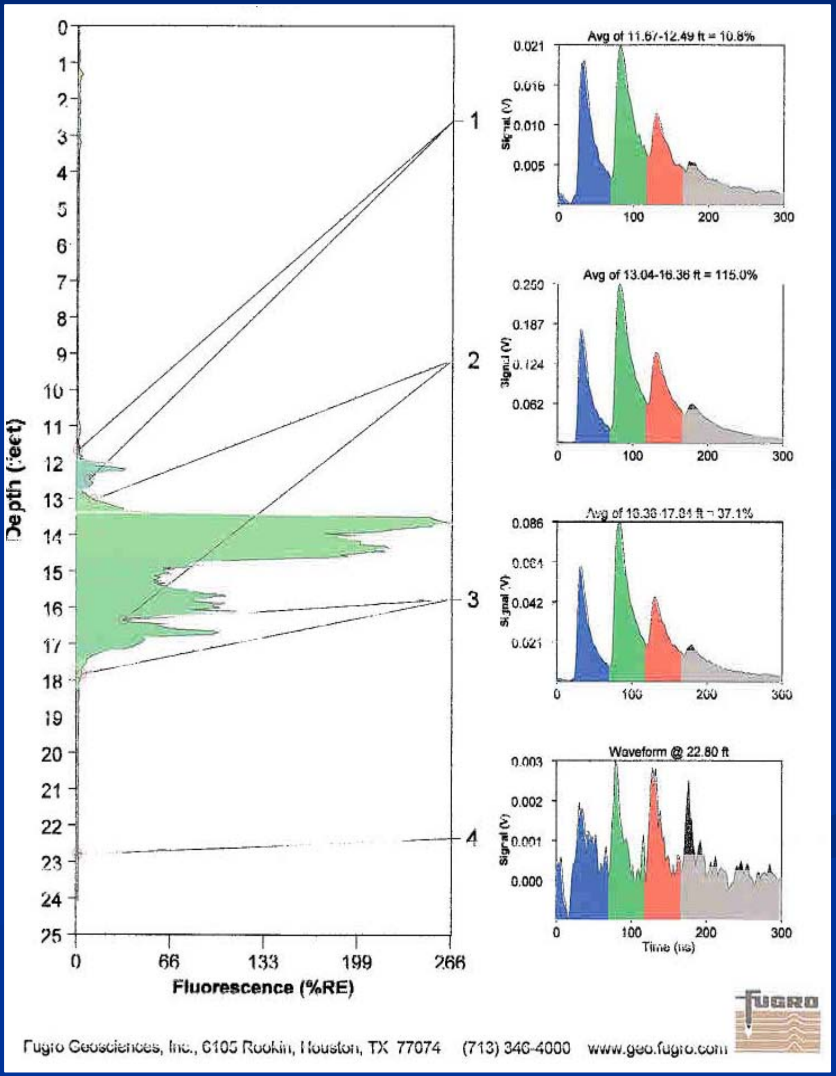
- LIF site investigation technique overview



Source: Dakota Technologies, Inc.

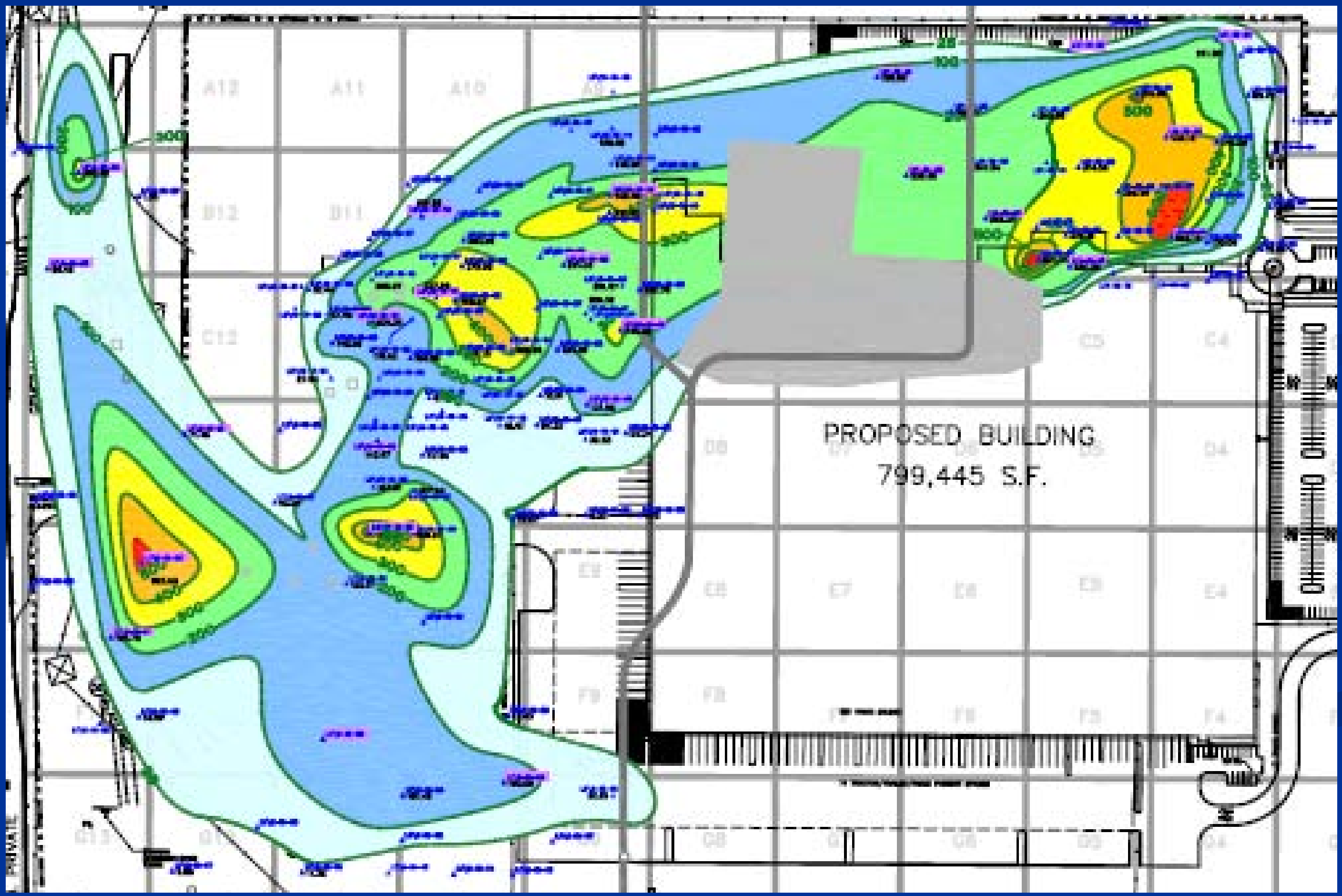
LNAPL Delineation – Conventional vs. Innovative

- ROST output from subject site investigation



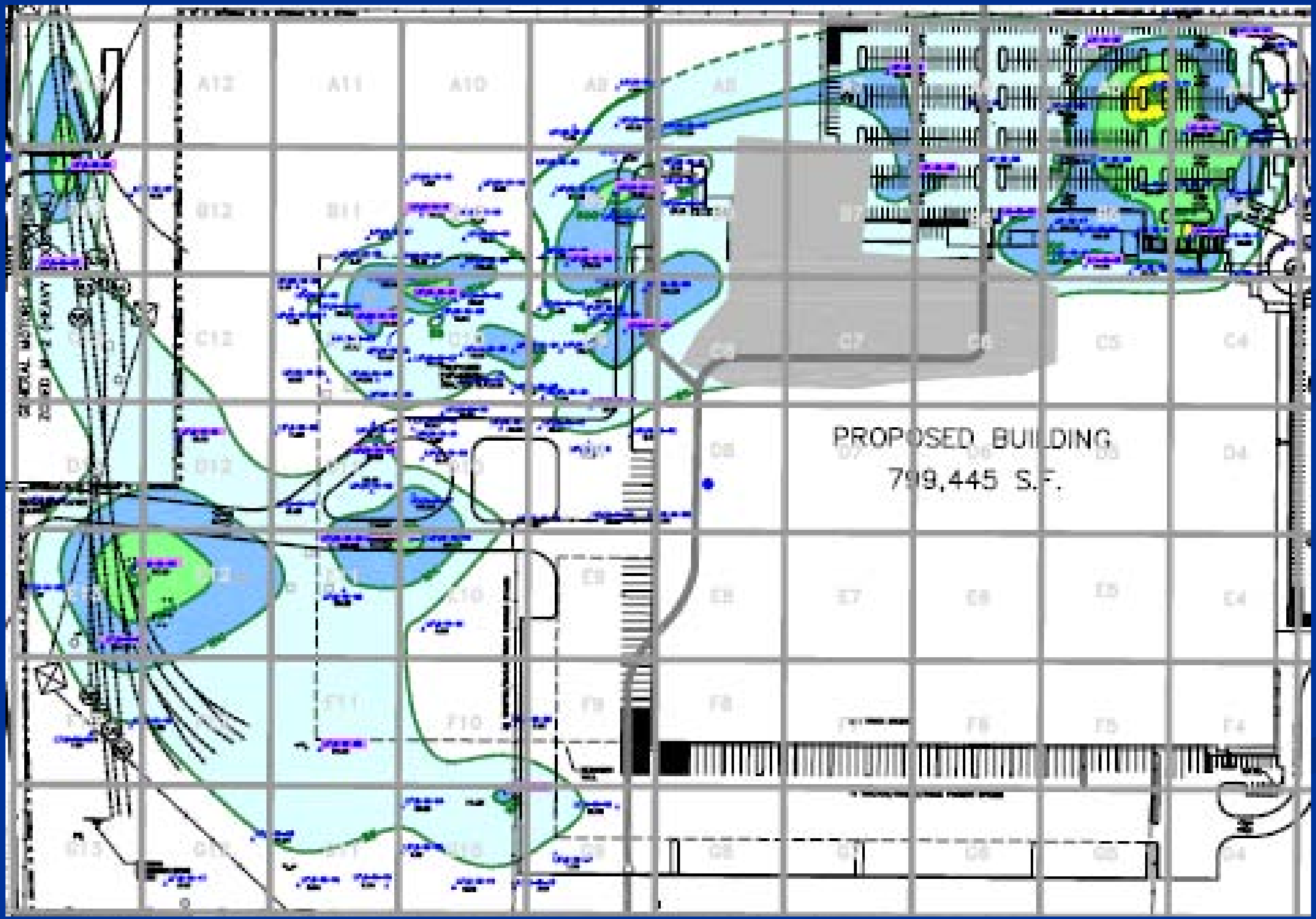
LNAPL Delineation – Conventional vs. Innovative

- Maximum ROST Intensity Plan View



LNAPL Delineation – Conventional vs. Innovative

- Averaged (1-foot thick) ROST Plan View



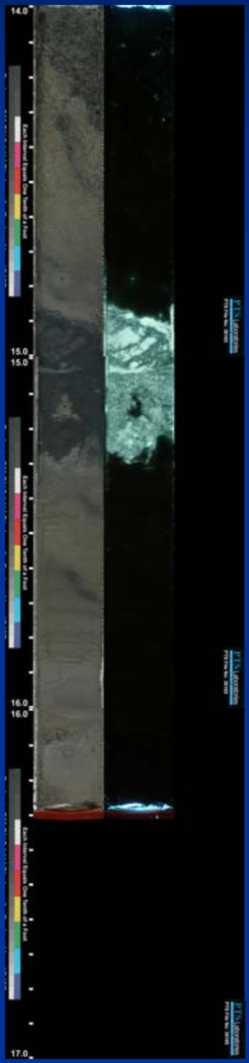
Soil Core Locations

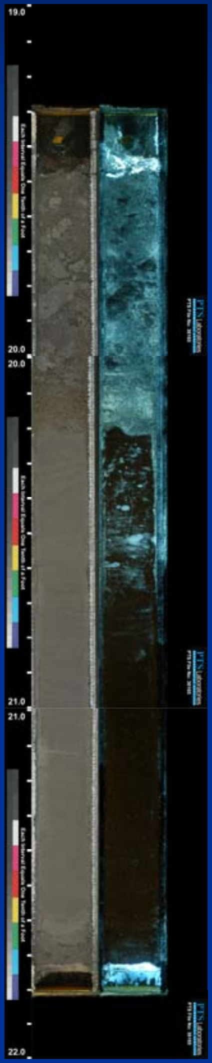
- Based on ROST results, 24 borings were advanced and 'undisturbed' Shelby Tube soil cores collected from areas shown to be LNAPL impacted;
- 7 locations were deemed to be the most impacted with LNAPL based on ROST relative fluorescence readings; 17 locations were deemed to be less impacted to evaluate areas of lesser saturation and LNAPL fringe areas.

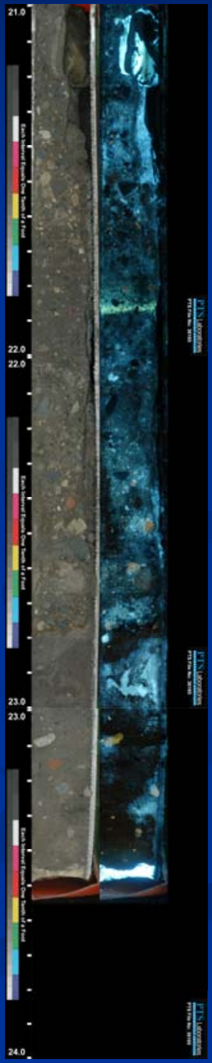
Core Photography

- Soil cores submitted for core photography in both white light and ultraviolet (UV) light;
- LNAPL, when exposed to UV light, fluoresces;
- Intensity of fluorescence corresponds to amount of LNAPL;
- Lighter end hydrocarbons (gasoline/kerosene) tend to fluoresce white/blue; middle ends yellow/gold; and heavy ends red/brown.

Core Photography







Laboratory Testing of LNAPL Mobility Parameters

- Discrete soil zones (0.2') of maximum UV fluorescence (based on qualitative assessment of core photos cross-referenced with ROST results) were submitted for testing of the following parameters:

  - LNAPL saturation and residual saturation;

  - soil grain size analysis, total porosity

- Water/LNAPL samples submitted for testing of density, viscosity and interfacial tensions.

Summary of ROST / Lab Results

ROST DATA						CORE PHOTOGRAPHY DATA													
										SUBSAMPLE DATA FROM LABORATORY TESTING									
										D/I			FPMP			SAT			
Rost ID	Maximum Flourescence (% Response)	Depth (feet bgs)	Thickness (feet)	Thickness Interval +/- 1' from Maximum Response	Average Fluorescence Over 1' Interval (% Response)	Core ID	Observed Impacted Interval(s) (feet bgs)	CPT Soil Type	Interval of Maximum Saturation (feet bgs)	Depth (feet bgs)	Saturation (%)	Residual Saturation (%)	Depth (feet bgs)	Saturation (%)	Residual Saturation (%)	Depth (feet bgs)	Saturation (%)	Selected Corresponding ROST Interval (feet bgs)	Average Fluorescence Over Selected Interval (% Response)
L1_2-03	553.93	14.06	0.42	13.56-14.56	313.21	L1/2-RI-03	13.15-13.25	CLAYS	15.7-15.9	15.5-15.7	1.30	8.10	15.7-15.9	5.30	5.10	15.9-16.1	4.10	13.90-14.10	426.14
							13.6-14.1	CLAYS											
							15.15-15.3	SANDS											
							15.3-15.4	SILTY SAND											
							15.4-15.5	CLAYEY SANDY SILT&SILT											
							15.5-15.75	CLAYEY SILT&SILTY CLAYS											
							15.75-15.8	SILTY SAND											
							15.8-16.1	SANDS											
L1_2-05	157.64	8.41	1.07	7.91-8.91	94.60	L1/2-RI-05	20-21.25	CLAYEY SANDY SILT&SILT	20.1-20.3				20.8-21	14.70	13.10	20.05-20.25	9.50	20.60-20.80	64.71
							21.35-21.65	CLAYEY SANDY SILT&SILT										21.3-21.5	86.17
L1_2-06	190.00	25.11	0.55	24.61-25.61	111.29	L1/2-RI-06	25.2-26	SILTY SAND	25.4-25.6	25.2-25.4	19.80	11.60	25.4-25.6	18.20	16.80	25.6-25.8	11.30	25-25.2	137.50
L1_2-11	194.75	14.40	0.53	13.90-14.90	124.34	L1/2-RI-11	13.05-13.2	CLAYEY SANDY SILT&SILT	14.7-14.9"				13.05-13.25	14.00	12.80	13.8-14	14.20	14.2-14.4	174.74
							13.2-13.6	SILTY SAND											
							13.6-13.65	CLAYEY SANDY SILT&SILT											
							13.65-13.8	SILTY SAND											
							13.8-14.3	CLAYEY SANDY SILT&SILT											
							20.4-20.9	SANDS											
L1_2-21	71.45	14.79	0.21	14.29-15.29	38.19	L1/2-RI-21	13.4-13.45	SILTY SAND	14.9-15.1				14.9-15.1	9.70	8.80	13.45-13.65	9.80	14.75-14.95	49.41
							13.45-13.6	CLAYEY SANDY SILT&SILT											
							13.6-13.8	SILTY SAND											
							14.85-14.95	CLAYEY SANDY SILT&SILT											
							14.95-15.3	SILTY SAND											
L1_2-22	86.48	15.13	0.48	14.63-15.63	41.55	L1/2-RI-22	15.5-16.4	SANDS	15.8-16							15.8-16	5.80	15.1-15.3	70.22

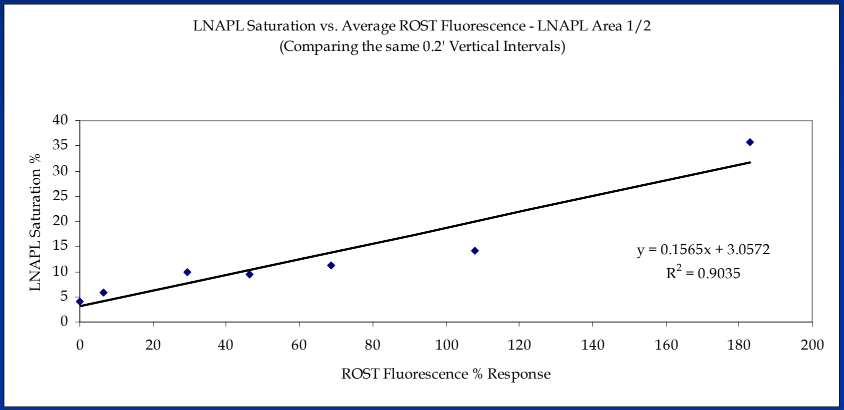
LNAPL Saturation vs. Residual Saturation

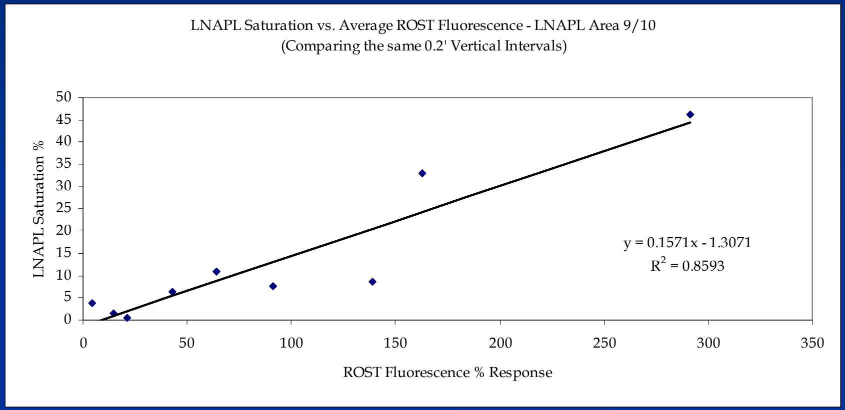
- LNAPL saturations measured using API RP 40 (Dean-Stark);
- LNAPL residual saturations measured using ASTM D425M, Dean-Stark (centrifugal test) and ASTM D6836 (drainage/imbibition capillary pressure test);
- Results indicated that all 24 locations above residual saturation;
- Only 4 locations were more than 25% above residual saturation (based on more conservative centrifugal test).

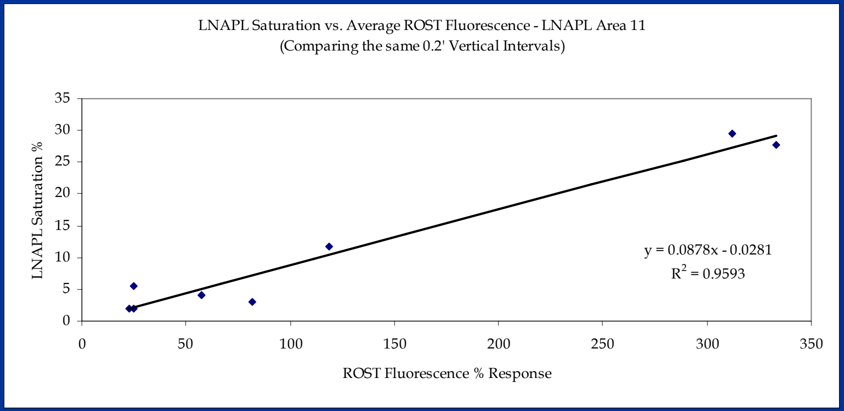
ROST / LNAPL Saturation Correlation

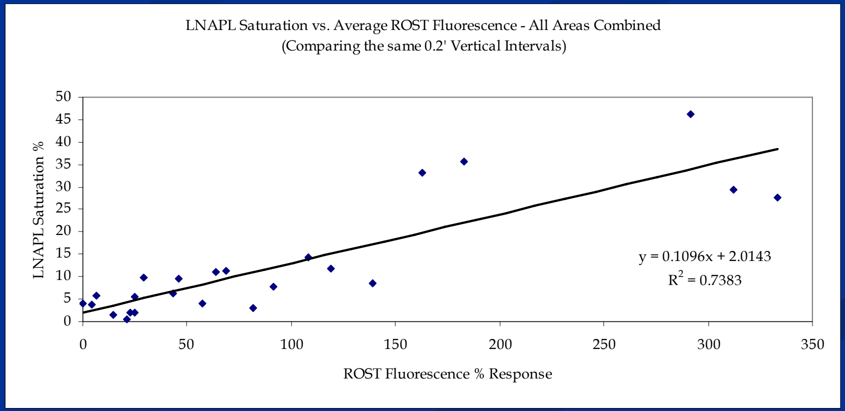
- Plotted ROST fluorescence response against laboratory measured LNAPL saturation to see if a strong correlation could be established for the LNAPL areas;
- Achieved R^2 values of 0.90 for first area, 0.86 for second area, and 0.95 for third area with an overall correlation of 0.74 (Note: Soil types in each area are relatively consistent); and
- Results suggest that LNAPL saturations may be calculated for all 127 ROST points based on these relationships.

ROST / LNAPL Saturation Correlation









LNAPL Mobility Calculations (API, 2004)

- LNAPL mobility is expressed as:

$$M_o = \frac{T_o}{V_o}$$

- Where:
  - M_o = inherent oil mobility (ft/day)
  - V_o = specific oil volume per unit area (ft^3/ft^2)
  - T_o = oil transmissivity (ft^2/day)

LNAPL Mobility Calculations (API, 2004)

$$V_o = \int_{z_1}^{z_2} \phi S_o \, dz$$

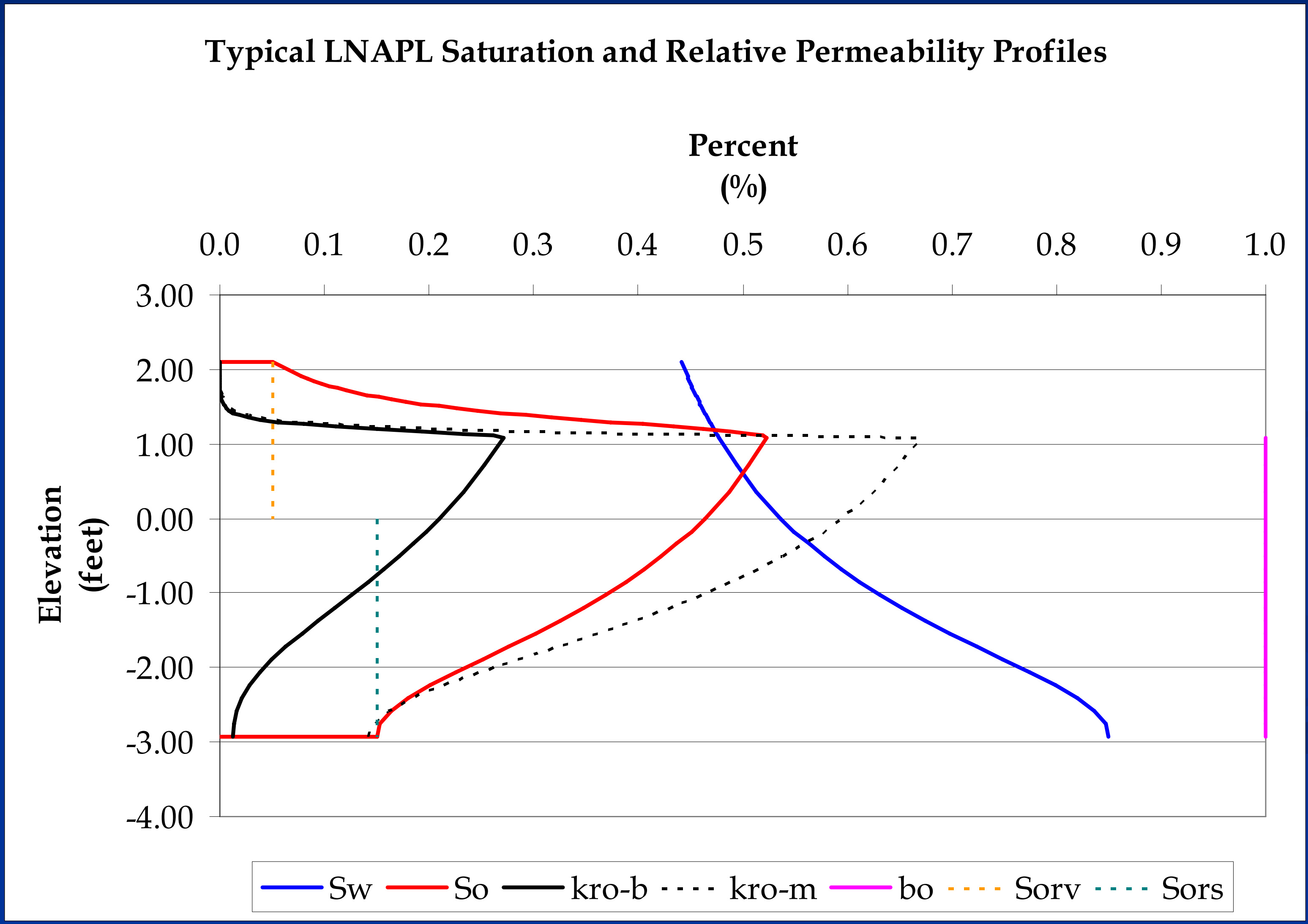
$$\overline{V_o} = b_o \phi \overline{S_o}$$

$$T_o = \frac{\rho_o}{\rho_w} \frac{\mu_w}{\mu_o} \int_{z_1}^{z_2} k_{ro} K_w \, dz$$

$$\overline{T_o} = b_o \overline{K_o}$$

$$\overline{M_o} = \frac{b_o \overline{K_o}}{b_o \phi \overline{S_o}} = \frac{\overline{K_o}}{\phi \overline{S_o}}$$

LNAPL Mobility Calculations (API, 2003)



LNAPL Mobility Calculations

- The laboratory measured LNAPL saturation value was deemed to represent the <u>maximum</u> LNAPL saturation point at the sample location (based on ROST and UV photography), thereby representing the greatest saturation point on the preceding saturation profile;
- This measured <u>maximum</u> saturation was then used to determine LNAPL relative permeability, conductivity, mobility and velocity.

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

LNAPL Mobility Calculations (API, 2003)

$$k_{ro}(S_w, S_o) = S_o^2 \left[\left(\frac{S_t - S_{wr}}{1 - S_{wr}} \right)^{\frac{\lambda+2}{\lambda}} - \left(\frac{S_w - S_{wr}}{1 - S_{wr}} \right)^{\frac{\lambda+2}{\lambda}} \right]$$

$$k_{ro}(S_w, S_o) = S_o^{1/2} \left\{ \left[1 - \left(\frac{S_w - S_{wr}}{1 - S_{wr}} \right)^{1/M} \right]^M - \left[1 - \left(\frac{S_t - S_{wr}}{1 - S_{wr}} \right)^{1/M} \right]^M \right\}^2$$

$$\overline{K_o} = \overline{k_{ro}} K_w \frac{\rho_o \mu_w}{\rho_w \mu_o}$$

LNAPL Mobility Calculations

$$\overline{q_o} = \overline{K_o} i_w$$

$$v_o = \frac{\overline{q_o}}{\phi_{eff}}$$

$$\phi_{eff} = \phi \overline{S_o}$$

$$v_o = \frac{\overline{K_o}}{\phi \overline{S_o}} \cdot i_w$$

$$v_o = M_o \cdot i_w$$

LNAPL Mobility Calculations

Table 6.2

LNAPL Relative Permeability, Conductivity, Mobility and Velocity Calculations[1]

LNAPL Area 9/10

Data Input Values	Location, Data Input and Calculations								
	RI-01	RI-04	RI-12	RI-15	RI-48	RI-49	RI-52	RI-55	RI-59
LNAPL Saturation (S_o)	0.463	0.331	0.086	0.077	0.006	0.063	0.016	0.037	0.110
Water Saturation (S_w)	0.310	0.462	0.819	0.755	0.876	0.743	0.751	0.866	0.639
Total Fluid Saturation (S_t)	0.773	0.793	0.905	0.832	0.882	0.806	0.767	0.903	0.749
Irreducible Water Saturation (S_{wr})	0.148	0.129	0.477	0.150	0.150	0.393	0.441	0.150	0.344
van Genuchten N (N)	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	1.850
LNAPL Density (ρ_o) - (g/cm^3)	0.849	0.849	0.849	0.849	0.849	0.849	0.849	0.849	0.849
LNAPL Viscosity (μ_o) - (cp)	8.280	8.280	8.280	8.280	8.280	8.280	8.280	8.280	8.280
Total Soil Porosity (Φ)	0.403	0.375	0.364	0.389	0.307	0.361	0.398	0.422	0.667
Assumed Average LNAPL Saturation ($S_{o\ avg}$)	0.232	0.166	0.043	0.039	0.003	0.032	0.008	0.019	0.055
Hydraulic Gradient	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Hydraulic Conductivity Water (K_w) - (cm/s)	1.00E-03	1.00E-02	1.00E-02	1.00E-03	1.00E-01	1.00E-02	1.00E-03	1.00E-02	1.00E-04
Calculated Parameters									
Model Parameter 1 (λ)	1.809	1.809	1.809	1.809	1.809	1.809	1.809	1.809	0.662
Model Parameter 2 (M)	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.750	0.459
Maximum LNAPL Relative Permeability (k_{ro})	1.05E-01	4.74E-02	1.83E-03	8.31E-04	4.51E-07	5.19E-04	8.27E-06	1.07E-04	2.97E-03
Maximum LNAPL Conductivity (K_o) - (cm/s)	1.08E-05	4.86E-05	1.87E-06	8.52E-08	4.63E-09	5.32E-07	8.48E-10	1.09E-07	3.05E-08
Maximum LNAPL Mobility (M_o) - (cm/s)	5.78E-05	3.92E-04	5.98E-05	2.85E-06	2.51E-06	2.34E-05	1.33E-07	7.01E-06	4.16E-07
Maximum LNAPL Velocity (V_o) - (cm/s)	2.89E-07	1.96E-06	2.99E-07	1.42E-08	1.26E-08	1.17E-07	6.66E-10	3.50E-08	2.08E-09
Average LNAPL Relative Permeability (k_{ro})	2.63E-02	1.19E-02	4.56E-04	2.08E-04	1.13E-07	1.30E-04	2.07E-06	2.67E-05	2.10E-03
Average LNAPL Conductivity (K_o) - (cm/s)	2.69E-06	1.21E-05	4.68E-07	2.13E-08	1.16E-09	1.33E-07	2.12E-10	2.74E-08	2.16E-08
Average LNAPL Mobility (M_o) - (cm/s)	2.89E-05	1.96E-04	2.99E-05	1.42E-06	1.26E-06	1.17E-05	6.66E-08	3.50E-06	5.88E-07
Average LNAPL Velocity (V_o) - (cm/s)	1.44E-07	9.79E-07	1.49E-07	7.11E-09	6.28E-09	5.85E-08	3.33E-10	1.75E-08	2.94E-09

Notes:

(1) - LNAPL relative permeability calculation for sands based on Burdine Equation 2.26 and Equation 2.27, and for silts based on Mualem Equation 2.28 in American Petroleum Institute (API) Publication Number 4729, *Models for Design of Free-Product Recovery Systems for Petroleum Hydrocarbon Liquids*, August 2003.

(2) - Highlighted data input values were based on laboratory test results for Site-specific soil and LNAPL samples.

(3) - Hydraulic conductivity water values based on laboratory grain size analysis and listed hydraulic conductivity values in Freeze and Cherry. 1979. *Groundwater*, Table 2.2, p. 29. Prentice Hall. 604 p. (coarse sand - 0.1 cm/s; medium sand - 0.01 cm/s; fine sand - 0.001 cm/s; silt - 0.0001 cm/s)

LNAPL Mobility Calculations

- Based on calculation results, only 1 of the 24 locations exhibited an LNAPL velocity in excess of 1 x 10^{-6} cm/s, which represents the *de minimis* mobility threshold for LNAPL (ASTM, 2005);
- Upon re-calculation using assumed <u>average</u> LNAPL saturations, none of the 24 locations exhibited an LNAPL velocity in excess of 1 x 10^{-6} cm/s.

LNAPL Mobility Conclusions

- Based on laboratory measured LNAPL saturations and residual saturations, it appears that 4 locations within the interior portions of the LNAPL areas exhibit a significant potential for inherent mobility;
- Based on LNAPL mobility calculations, it appears that 1 interior location exhibits an LNAPL velocity in excess of the *de minimis* mobility threshold for LNAPL (ASTM, 2005);
- Overall LNAPL areas appear to be stable.

LNAPL Recoverability

- Operated a high vacuum multi-phase extraction (MPE) system in one of the LNAPL areas for 2 months (see Cushman et al., RemTech 2005, for description of system);
- Extraction area included area of maximum LNAPL mobility;
- Recovered approximately 85,000 gallons of water but less than 40 gallons of LNAPL, despite an LNAPL in-well thickness of 6 feet.

LNAPL Recoverability

- Ran LNAPL recoverability simulations using the API Interactive LNAPL Guide Version 2.0 software;
- Assumptions:
  - LNAPL type – diesel;
  - Soil types – medium sand, silt, and clay;
  - LNAPL area dimensions – 200 feet by 200 feet;
  - Apparent LNAPL thickness – 8 feet (model assumes 8 feet LNAPL thickness across the entire 200 feet by 200 feet area);
  - Recovery time – 1 year; and
  - Recovery system – high vacuum extraction applying 18”Hg to 30 extraction wells.

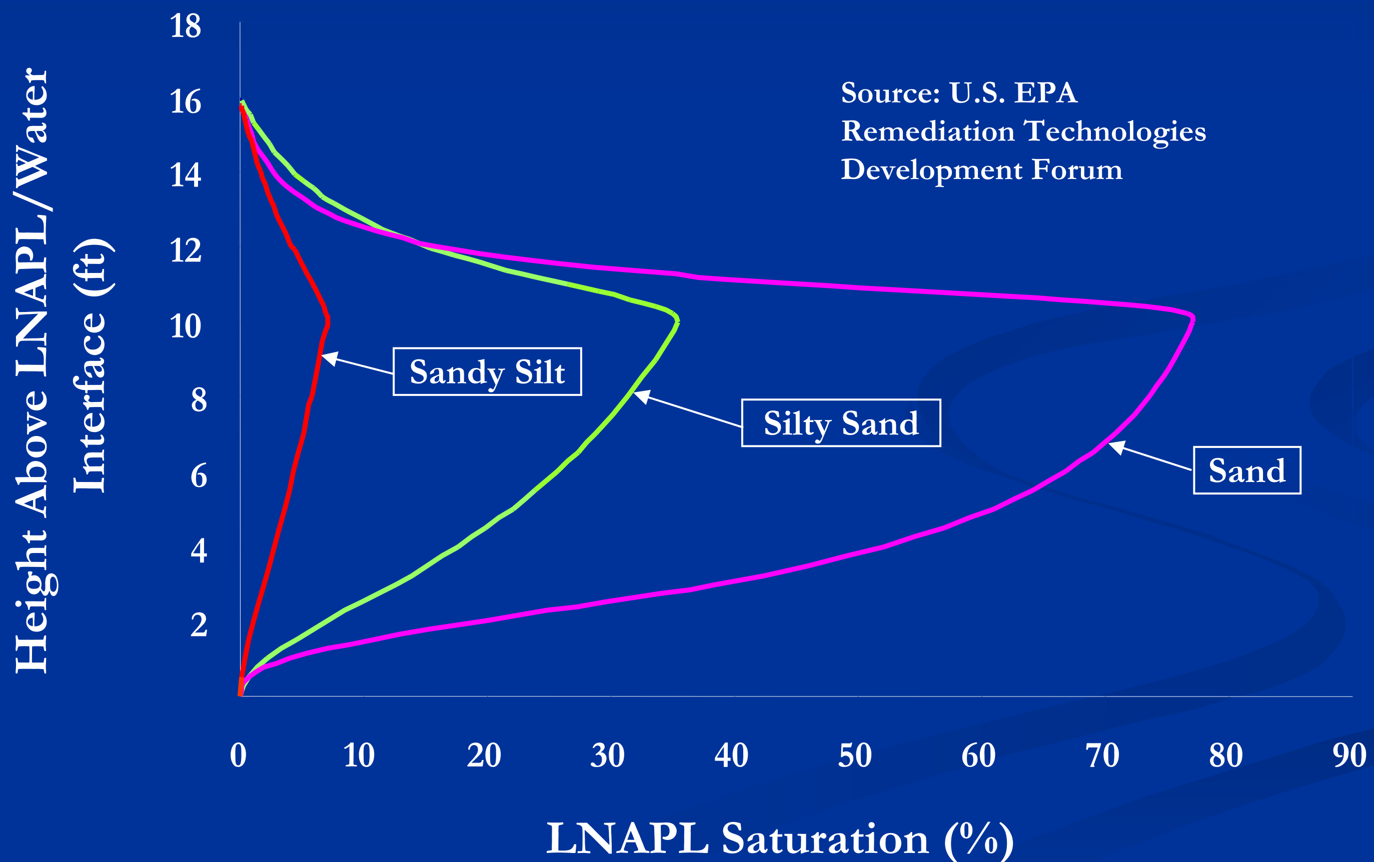
LNAPL Recoverability

- API Model simulation results:

Soil Type	Estimated 1-year LNAPL Recovery (gallons)
Medium Sand	295,000
Silt	4,100
Clay	130

LNAPL Recoverability

10 ft Monitoring Well Thickness and a Diesel Fuel



LNAPL Recoverability

- API model simulations demonstrate that significant in-well thickness (8 feet in this example), particularly in a fine textured soil (silt, clay), does not necessarily mean that the LNAPL is recoverable.
- Evaluations suggest that inherent LNAPL mobility in a given area will not necessarily translate into a high degree of recoverability.
- LNAPL recoverability is best tested with site-specific and technology-specific pilot studies.

Regulatory Feedback

- LNAPL Mobility Evaluation Report yet to be submitted to U.S. Environmental Protection Agency (U.S. EPA).

Acknowledgements

- The authors wish to thank General Motors Corporation for their contributions to this paper and to the ongoing LNAPL evaluation efforts.