DNR REMEDIATION & REDEVELOPMENT PROGRAM GUIDANCE FOR PUBLIC COMMENT

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DOCUMENT TRACKING NUMBER

RR-787

DOCUMENT TITLE

Guidance: Assessment of Sites with Residual Weathered Light Non-Aqueous Phase Liquid

BACKGROUND/SUMMARY

The purpose of this guidance is to help evaluate the environmental impacts of older, weathered petroleum products in the subsurface. The guidance focuses on historical petroleum releases that are no longer spreading; it does not apply to new discharges, non-petroleum contaminants or dissolved plumes.

This is a revision to existing guidance. The guidance was originally drafted in 2008 and last updated in 2014. The updated guidance:

- Incorporates relevant information from the Appendices into the body of the main document; eliminates out of date appendices
- Expanded the table of contents and added table of tables and table of figures
- Includes updated information on assessment and evaluation to meet current practices
- Includes updated figures of conceptional models
- Includes updated references
- Clarifies department recommendations

Additional revision include edits to meet the requirements of the federal accessibility project and include improved formatting, addition of a table of figures and edits to the text for plain language and clarity.

PUBLIC COMMENT PERIOD CLOSE DATE

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Please use subject line: “RR-787 Comments”

Guidance: Assessment of Sites with Residual Weathered Light Non-Aqueous Phase Liquid (LNAPL) (RR-787)

Wis. Admin. Code § NR 708.13

Purpose

The purpose of this guidance is to help evaluate the environmental impacts of older, weathered petroleum products, called weathered light non-aqueous phase liquid (LNAPL), in the subsurface. The focus of the guidance is on historical petroleum releases that are no longer spreading; it does not apply to new discharges, non-petroleum contaminants or dissolved plumes.

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Definitions

Natural source zone depletion (NSZD) means the ongoing loss of petroleum hydrocarbons from the subsurface due to natural biological and physical processes including biodegradation, volatilization, dissolution into groundwater and diffusion of gases to the surface.

LNAPL transmissivity (Tn) means the volume of LNAPL that can flow horizontally through a unit width of aquifer (1 foot wide) under a unit hydraulic gradient (1 foot of LNAPL thickness drop per foot of aquifer length).

Applicability

Responsible parties are required to conduct free product removal whenever it is necessary to halt or contain the discharge of a hazardous substance or to minimize the harmful effects of the discharge to the air, lands, or waters of the state (Wis. Admin. Code § NR 708.13). When required, free product removal shall be conducted to the maximum extent practicable. (Wis. Admin. Code § NR 708.13).

For the purpose of this guidance, the definition of free product includes only light non-aqueous phase liquids (LNAPL) and not dense non-aqueous phase liquids (DNAPL). This guidance helps distinguish sites where weathered LNAPL can be effectively recovered. It provides a step-by-step process to determine if active recovery of the weathered product is needed or if naturally occurring processes can be relied upon to reduce the mass of LNAPL. Active recovery methods like pumping or skimming are effective only if they can remove a meaningful amount of LNAPL. Excavation may also be effective depending on groundwater conditions and on the nature, degree and extent of contamination. Site-specific and science-based metrics such as LNAPL characteristics, plume stability and threats to sensitive receptors can predict if active recovery efforts are likely to reduce risks.

This guidance mainly applies to sites with unconsolidated soil. Bedrock conditions vary widely, so use of professional judgement is recommended to guide testing decisions. Information in the guidance focuses on older releases, often from years to decades ago, where the LNAPL has undergone biodegradation and physical changes. Once released, LNAPL spreads into the soil smear zone – the area where free product occurred in the soil and was then smeared across the soil when the water table fluctuated between historic high and low water table elevations – and becomes trapped by capillary forces in water-filled pores. Over time, the saturation drops to irreducible levels where the LNAPL can no longer move freely, behaving more like sorbed soil contamination than a spreading liquid. When free movement is limited, natural processes can often balance any slow release of dissolved contaminants, especially without nearby risk to receptors.

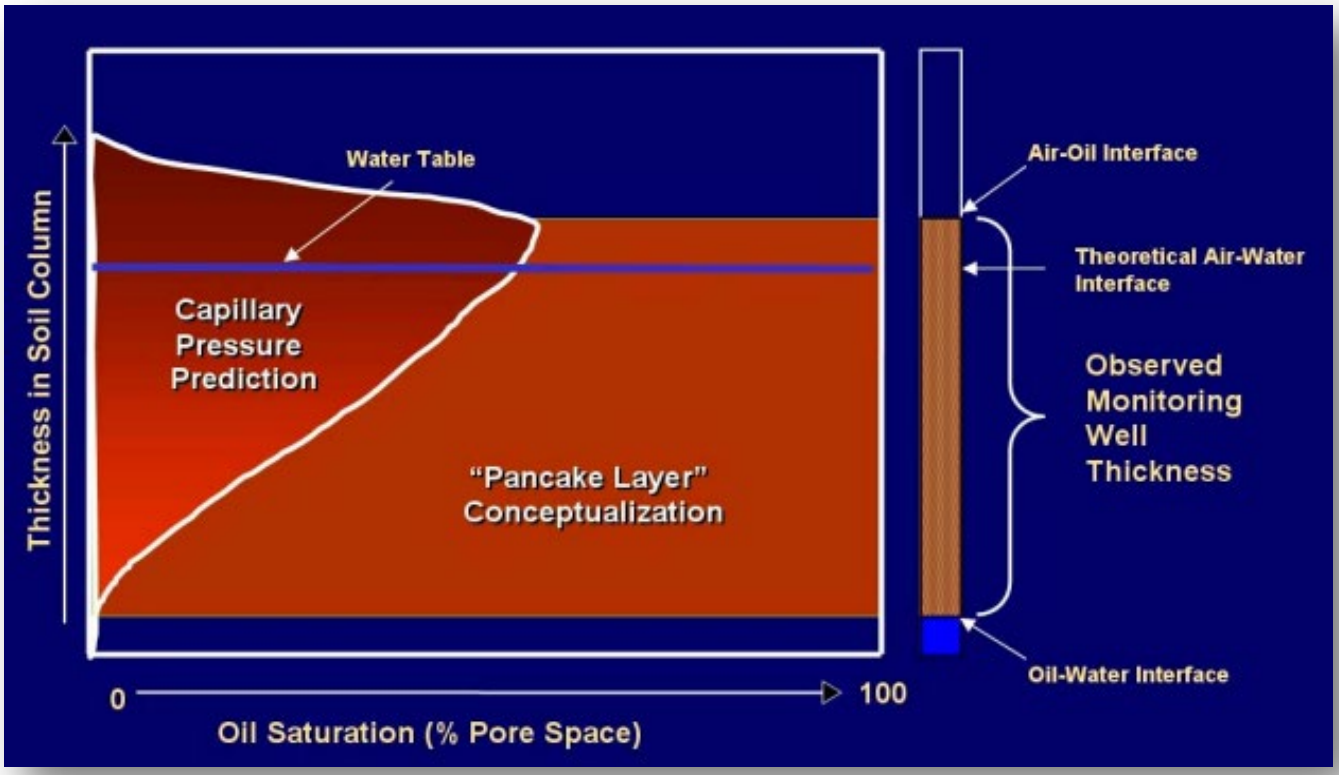
Conceptual Model of LNAPL

Free product observed in monitoring wells does not reliably reflect the mass of mobile LNAPL in the surrounding soil. Historically, LNAPL was conceptualized as a simple “pancake” layer floating on the water table at uniform, high saturation as shown in Figure 1 from the Remediation Technologies Development Forum (RTDF). The thickness in the well was assumed to be equal to the thickness of the LNAPL body in the formation, and the pore space was often treated as nearly filled with LNAPL across the footprint of the plume. However, well measurements exaggerate actual thickness, especially in finer soils, and fluctuate with water levels. Determining true mobility of LNAPL requires the estimation of flow potential based on soil type, and consideration of the LNAPL properties, saturation and changes in the water table. As capillary retention exceeds typical groundwater gradients, the original driving head dissipates and lateral spread of the LNAPL is limited.

An updated conceptual "shark fin" site model illustrates how LNAPL occupies the pore space in a water-wet, variably saturated system, under the assumption of the same soil type (Figure 1). LNAPL saturation is plotted horizontally against depth, with the water table and capillary fringe indicated. Saturation is low at greater depths where water dominates, increases to peak near the capillary fringe just above the water table, and then decreases again upward into the vadose zone where there is more air. The resulting saturation curve has a distinctive "shark fin" (darker orange) shape: a narrow zone of relatively high saturation and potential mobility at the peak, flanked above and below by larger zones where LNAPL is present only at low, largely immobile residual saturations. The shark fin model shows that only a limited vertical interval near the peak of the fin has sufficient saturation for LNAPL to be mobile under pumping or natural gradients; the majority of the LNAPL body is present at lower saturations where it is effectively trapped.

The pancake model (light orange) is presented as a historical conceptualization. The shark fin model, which is consistent with capillary pressure, saturation relationships and field saturation data, is recommended as the primary conceptual basis for interpreting monitoring well observations, estimating LNAPL volumes, and evaluating LNAPL mobility and recoverability.

Figure 1: Comparison of the "pancake" and "shark fin" subsurface conceptual models (RTDF, 2005)

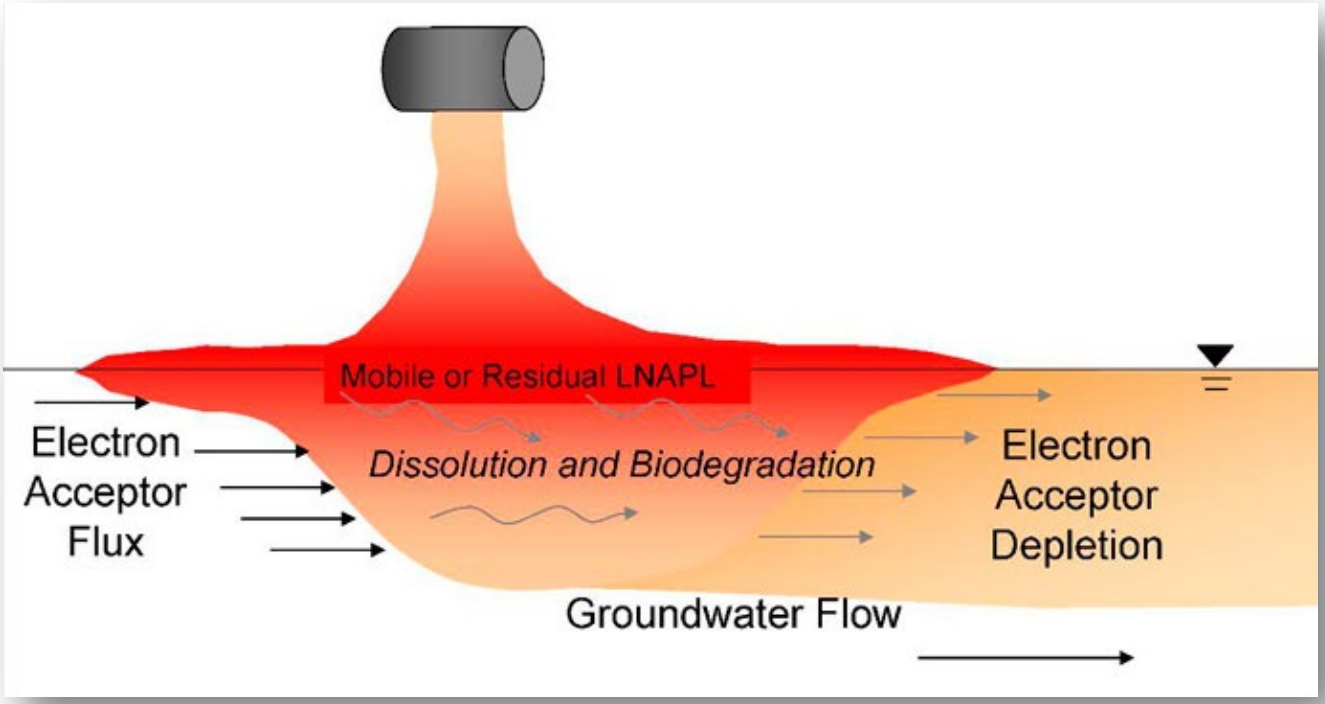


Natural Source Zone Depletion (NSZD)

At many historical petroleum sites, natural source zone depletion (NSZD) processes continuously reduce the remaining LNAPL mass. This guidance considers those natural processes alongside active remedies when evaluating whether additional LNAPL recovery is likely to be beneficial. The

figure below from the Interstate Technology Regulatory County (ITRC) illustrates the mass flux pathways by which LNAPL mass is naturally depleted through groundwater transport processes. Dissolved hydrocarbons are continuously stripped from the LNAPL source zone, transported downgradient, and biodegraded – representing a major component of NSZD (Figure 2).

Figure 2: Groundwater transport-related NSZD processes



Recommendations for Initial LNAPL Assessment Parameters

The DNR recommends gathering eight basic pieces of information at a site with weathered petroleum products to show if the product is mobile, how much exists and if it poses an ongoing risk. These eight steps use readily available data to prioritize sites for further testing. Where transmissivity is low, soils are fine-grained, and plumes are stable, shift focus to monitoring receptors and dissolved/vapor risks rather than chasing immobile product.

Considerations and methods associated with the recommendations are outlined below. Some information may not be needed if excavation is already planned.

Map the LNAPL body and dissolved-phase groundwater plume

Focus on monitoring wells that show measurable product floating (≥0.1 ft) on the water-table – this defines the main LNAPL area. Verify well integrity for any well where LNAPL appears/disappears erratically, product is below the expected smear zone, thickness is inconsistent with neighboring wells and where no LNAPL is observed in adjacent borings. Compromised well seals can allow LNAPL to migrate vertically through the annulus (space between casing and borehole), creating artificial product appearances.

Calculate plume area using Thiessen polygons or contouring for Parameter 3 volume estimation. Use soil samples from the smear zone as supporting evidence if concentrations exceed compound-specific saturation levels (Csat). Remember that use of soil results alone can be misleading since values are based upon individual compounds and do not always predict behavior of real-world fuel mixtures. Fine soils or organic-rich layers often trap higher concentrations of dissolved-phase contaminants without separate-phase product. Install additional wells if needed to reasonably outline the product body and the dissolved-phase plume, focusing on down-gradient and cross-gradient directions of groundwater flow.

Analyze soil types across the smear zone

Use lab sieve tests – not just visual logs – to quantify sand, silt and clay percentages. This is critical because finer soils trap LNAPL more tightly, reducing recoverability. New borings are often required since past logs rarely include this level of detail.

Soil-specific factors derived from well thickness measurements and validated by RTDF/API models are presented below.

Soil-specific volume factors (ft LNAPL/ft well thickness):

- Clean Sand ~ 0.20 ft Soil LNAPL
- Silty Sand ~ 0.07 ft Soil LNAPL
- Loam/Loamy Sand ~ 0.02 ft Soil LNAPL
- Silt/Clay ~ 0.0 ft Soil LNAPL

Estimate total LNAPL volume

Combine soil type with the thickest observed product in wells to calculate a "specific volume" factor. Multiply by the mapped area for a rough total. Refine this later with core samples or transmissivity tests if active recovery seems plausible. Compare to any known leak volumes but prioritize field-based calculations.

Screening Estimate (Well-based)
Formula: $Total\ LNAPL\ Volume\ = Maximum\ Well\ Thickness\ \times Soil\ Factor\ \times Plume\ Area$

Steps:

- Map LNAPL extent (wells with free product, not Csat)
- Find maximum thickness across all wells
- Select factor from sieve analysis (% fines from Parameter 2)
- Measure plume area (Theissen polygons or contouring from Parameter 1)
- Calculate volume (ft^3)
- Multiply the volume in ft^3 x 7.48 gallons/ ft^3 to obtain volume in gallon

Example: (2 ft max thickness in silty sand with a plume area of 5,000 ft^2 area):
2 ft x 0.07 x 5,000 ft^2 = 700 ft^3 LNAPL = ~ 5,236 gallons

Test LNAPL fluid properties

Sample product from wells for lab measurements of density, viscosity, and surface/interfacial tension. These properties directly affect LNAPL mobility and are essential inputs for transmissivity calculations and recovery modeling and include:

- **Density** (g/cm^3 or specific gravity): Determines buoyancy and vertical distribution.
- **Dynamic viscosity** (cP or mPa-s): Resistance to flow; weathering increases it.
- **Surface tension** (LNAPL-air, dynes/cm): Affects capillary entry pressure.
- **Interfacial tension** (LNAPL-water, dynes/cm): Critical for multiphase flow.

Standard ASTM Methods used along with the typical ranges of results at an aquifer temperature of 50 degrees Fahrenheit are summarized in Table 1.

Table 1: Standard ASTM Test Methods

Property	ASTM Method	Typical Range (gasoline/diesel)
Density	D287 or D1481	0.72 - 0.75 g/cm^3 /0.82 - 0.90 g/cm^3
Viscosity	D445	0.5-0.8 cP (fresh gas) / 15-50+ cP (weathered diesel)
Surface Tension	D971 or D3825	20-25 dynes/cm / 25-28 dynes/cm
Interfacial Tension	D971	45-50 dynes/cm / 48-55

LNAPL transmissivity

LNAPL transmissivity (Tn) reflects how much product can flow through the formation under a given gradient and is widely used as a primary indicator of whether active recovery will be effective. In wells with enough product thickness (>0.1 ft) and permeable soils, run a simple baildown or pump test to estimate Tn.

LNAPL transmissivity values provide a direct, qualitative measure of LNAPL mobility and recoverability. Values greater than about 1 ft^2 /day generally indicate that LNAPL is sufficiently mobile to justify consideration of active recovery, particularly where receptors are threatened, or plumes are expanding. Values in the 0.1 to 0.8 ft^2 /day range represent a common decision or endpoint threshold for transitioning from, optimizing, or discontinuing active recovery systems. Transmissivity below about 0.1 ft^2 /day typically confirm that LNAPL has reached residual saturation conditions where further pumping is unlikely to yield meaningful mass removal, and management should shift to monitoring natural source zone depletion, dissolved plume behavior, and receptor protection (ITRC, LNAPL-3).

Check groundwater plume behavior and nearby risks

Review long-term trends at plume margins, centerline, and source wells to see if dissolved-phase concentrations are decreasing, remaining stable, or are increasing. Focus on multi-year patterns, not short-term ups and downs. Note proximity to drinking water wells, surface water bodies, basements or utilities. Sample below LNAPL wells carefully (low-flow methods, no product included) for a snapshot of ongoing dissolution, but do not use for trends.

Estimate Natural Source Zone Depletion (NSZD) Significance

NSZD is the ongoing loss of petroleum hydrocarbons from the subsurface due to natural biological and physical processes. These processes include biodegradation, volatilization, dissolution into groundwater, and diffusion of gases to the surface. NSZD is not a stand-alone justification for inaction. Instead, it is one component of a risk-based evaluation. NSZD may be evaluated using a tiered approach:

- **Screening-level evidence**. If the plume is stable or decreasing, transmissivity is low, and no receptors are threatened, NSZD is likely sufficient, in combination with existing controls, to manage long-term risk.
- **Enhanced lines of evidence**. At more complex or high-risk sites, additional data such as soil gas profiles, temperature anomalies, or other NSZD indicators can be collected to support decisions about scaling back or discontinuing active recovery and relying more on monitored NSZD and natural attenuation.

Track product thickness against water levels

Measure both at the same time over several events. Product often "appears" as the water-table drops (drainage effect) or "vanishes" as the water-table rises (imbibition) - neither proves movement or recovery success. Avoid in-well absorbents, as they skew measurements. Ephemeral product suggests low, discontinuous saturation in soil.

Evaluation of Initial LNAPL Assessment Parameters

The key question for older petroleum sites is not whether any product remains, but whether the remaining product can move and cause unacceptable impacts.

Data from the initial assessment parameters helps to determine whether active LNAPL recovery may be necessary or if monitoring and risk management may suffice. The three parameters that typically have the greatest effect on hydraulic recovery are soil type, LNAPL transmissivity, and free product thickness – shown by sensitivity testing of standard LNAPL recovery models.

Model Sensitivity Results Summary

Model sensitivity testing shows how site conditions affect recovery efficiency (the percentage of mobile LNAPL that pumping can realistically remove). The results outlined in Table 2 use idealized scenarios for relative comparison only. They show how different site conditions can affect LNAPL recovery efficiency.

Model Basis

The results shown in Table 2 are derived from American Petroleum Institute (API) Publication 4729, which implements a van Genuchten-Burdine capillary pressure-relative permeability model calibrated to LNAPL recovery data. The model simulates multiphase flow under artificial pumping gradients using site-specific inputs for:

- Soil capillary pressure-saturation relationships (drainage/imbibition curves)
- Relative permeability functions
- LNAPL fluid properties (density, viscosity, interfacial tension)
- Saturation distributions across the smear zone

Key model assumptions
Uses the van Genuchten capillary pressure function:

$$S_e = [1 + (\alpha h)^n]^{-m}$$

Where S_e is effective saturation, h is capillary pressure head, and α, n, m are soil-specific "curve shape" parameters.

Burdine relative permeability relationships are derived from the same curve.

Tested against field pumping data from gasoline and diesel releases in sand through silty loam soils.

Table 2: Potential for LNAPL Recovery/Mobility

Factor	Baseline (~65% efficiency)	Best Case (~80%)	Worst Case (<20%)
Soil Type (fines content)	Clean sand	Well-sorted gravel	Silt loam/clay
LNAPL Weathering – (fresh vs, aged)	Moderately fresh gasoline	Light fuel	Heavily weathered diesel
Product Thickness	~1 ft continuous	>3 ft	Ephemeral/thin
Typical Weathered Site	25-40% combined factors	N/A	<10%

How to read the modeling results:

- Soil dominates: Clean, coarse sands and gravels allow the highest modeled recovery. As the percentage of fine-grained particles increases in the aquifer, the proportion of LNAPL that can be removed by pumping drops rapidly because more product is trapped as immobile residual saturation.
- Weathering reduces mobility. Older, weathered fuels are typically more viscous and less dense than fresh product. This makes it harder to move through the pore spaces, lowering recovery efficiency even in otherwise favorable soils.
- Product thickness is a proxy for saturation. Thicker, continuous product in wells is generally associated with higher in-situ saturation and better recoverability potential. Thin or intermittent product ("ephermal" thickness that appears and disappears with water level changes) is associated with low or discontinuous saturation and limited recoverability.
- Field performance is often lower than modeled. The model assumes idealized conditions and does not capture all site complexities. In practice, recovery efficiencies at real sites are usually less than the values suggested by these sensitivity runs.

For this guidance, it is recommended that the sensitivity results be used to support, not replace, site-specific decisions considering transmissivity, plume trends and receptor data.

- Where the combination of soil type, product thickness, and weathering suggests recovery efficiencies in the higher range of the modeled results, and where receptors or expanding plumes are a concern, active LNAPL recovery or additional feasibility testing may be justified.

- Where these factors indicate moderate recovery potential, decisions about testing and active recovery should be made on a site-specific basis, considering transmissivity, plume behavior, and receptor conditions.

- Where the modeled efficiency for conditions falls in the low range, especially in fine-grained or highly weathered setting with stable or shrinking plumes, further active LNAPL recovery is unlikely to be effective. In those cases, monitored natural attenuation, natural source zone depletion and receptor protection should be considered rather than additional recovery attempts.

Recommended Evaluation Process

When evaluating LNAPL recoverability, the recommendation is to start with soil type across the smear zone. If soil type varies, professional judgement should be used to pick the dominant type or subdivide the site. Absent receptor risks, the following responses are recommended:

- **Fine-grained soils (predominantly clay/silt or ≥40% fines, like loams or clay loams)**: No further recovery testing is needed. Models show recovery drops sharply in fines-heavy soils – even clean sands with 20-30% fines recover poorly. Weathering and thin product compound this, trapping most LNAPL as immobile residual saturation.

  At these sites, observed plume stability or shrinkage over time is typically consistent with NSZD acting on the source zone, so it may be appropriate for the emphasis to shift to monitoring groundwater and vapors to confirm that natural processes continue to control risk rather than pursuing additional active LNAPL recovery.

- **Mixed soils (20-40% fines, like loamy sands):** If the soils contain 20-30% fines and neither the LNAPL fluid properties nor the apparent thickness or transmissivity suggests high recoverability potential, then no further recovery feasibility testing is warranted.

  Where monitoring data show stable or shrinking dissolved concentrations, this pattern is consistent with NSZD gradually reducing mass in the source zone, and it is recommended that long-term management focus on verifying continued plume stability and receptor protection. Highly weathered LNAPL (common at old sites) flows poorly here.

- **Coarse soils (<20% fines, sand/gravel):** It is recommended that further testing is completed if transmissivity or thickness indicate mobility, or if plumes expand or significant volume exists near receptors. Conversely, if transmissivity tests and long-term groundwater data show low mobility and stable and shrinking concentrations, NSZD is likely providing sufficient ongoing source reduction, and it may be appropriate to forgo additional recovery feasibility testing and focus on monitored natural attenuation and NSZD.

  If parameters already show a stable plume, poor recoverability (low transmissivity, thin/ephemeral product) and no receptor risks, you may skip advanced testing. Active recovery rarely helps in these situations, and it is recommended for consideration only for expanding plumes or direct threats to receptors. In such cases, observed plume stability or shrinkage is often consistent with natural attenuation and NSZD, and further active LNAPL recovery may add little to the reductions already being achieved by natural processes.

Remedial Treatment Considerations

In locations where weathered LNAPL remains, the DNR recommends choosing the best option based upon mobility data, plume behavior and receptor risks from the initial assessment. Active recovery is recommended only if a meaningful portion of mobile product can be removed.

Passive LNAPL Remediation

Hand bailing or in-well absorbent (socks/canisters) recover little product – typically only product in the well screen, not the surrounding soil. Water-table fluctuations refill wells naturally, masking progress. Hand bailing may be inexpensive, but also ineffective at mature sites.

Because passive recovery removes only a small fraction of the total LNAPL mass and natural water level fluctuations will continue to move product in and out of these wells, this method does not materially change long-term risk or the overall balance between the source and the dissolved plume. At mature sites, NSZD processes typically remove more mass from the source zone over time than passive bailing or absorbent systems.

Excavation Treatment

Excavation works best in shallow, accessible smear-zone soils under known source areas where the benefits outweigh the costs. In order to effectively demonstrate this, consider the estimated contaminant mass to be removed, disposal needs, and dewatering challenges. In coarse sands/gravels, sidewall collapse or high groundwater may limit the depth of excavation.

The DNR does not recommend excavation extending into clean overburden soil to chase thin, immobile product. The DNR recommends that low permeability backfill is used to avoid re-mobilizing contamination. Where monitoring data indicate that dissolve-phase concentrations are stable or decreasing and transmissivity is low, NSZD is likely already reducing the source zone at a meaningful rate. Long-term monitoring of groundwater and vapors may be more appropriate than intrusive excavation in terms of both effectiveness and cost.

Active Treatment – Additional LNAPL Feasibility Testing

It is recommended that active treatment systems (such as pumping, skimming, vacuum extraction or multi-phase extraction) be considered only after all the initial LNAPL parameters have been evaluated. The tiered evaluation process will tend to focus feasibility testing on sites with permeable aquifer soils, appreciable LNAPL transmissivity that indicate greater mobility, a significant, continuous-phase volume and evidence that natural processes alone (NSZD and natural attenuation) are not sufficient to maintain stable or shrinking dissolved plume conditions or to protect receptors.

In summary, additional feasibility testing and active LNAPL recovery are generally viewed as time-limited tools used to accelerate risk reduction where mobility is high, and receptors are at risk. As these sites mature, transmissivity declines, and NSZD and natural attenuation take over as the primary mechanism of source control, and in such cases, it is appropriate to scale back or discontinue active systems and rely on long-term monitoring to ensure that these natural processes continue to protect receptors.

Core Analysis, Laser Induced Fluorescence Survey and Baildown Tests

Undisturbed Core Sample Analyses

Undisturbed core analyses and capillary pressure tests provide detailed information on porosity and irreducible saturations, which can greatly improve recovery modeling. In practice, these advanced tests generally are reserved for sites where there is strong reason to believe that optimized recovery could significantly reduce risk and where decisions about expensive systems depend on better estimates of product mobility.

Laser Induced Fluorescence (LIF) Surveys

Laser induced fluorescence (LIF) technology uses product fluorescence to vertically define the LNAPL smear zone. When conducted in conjunction with cone penetrometer (CPT) and rapid optimal screening tool (ROST) technologies, it provides an indication of the vertical heterogeneity of the soils across the smear zone and a qualitative indication of LNAPL saturation, respectively. Using multiple borings during the survey, one can better define the horizontal extent of the LNAPL. The LIF/ROST results are only qualitative, and do not provide parameter inputs to the LNAPL recovery models. However, once actual saturation data are available (undisturbed core analyses), the LIF/ROST results can be better qualified.

LNAPL Baildown and Pump Testing

If a sufficient thickness of LNAPL is present and the soils are permeable (reasonable recovery time), an "LNAPL only" baildown and/or pump test may be attempted. However, conducting such tests, especially recording the product and water level data concurrently, is technically difficult and is not recommended unless permeable soils and a significant thickness of product is present. Modified (from groundwater) analyses can then be performed on the recovery curve to provide an estimate of the LNAPL conductivity. The conductivity can be used as an input to LNAPL recovery models for the design phase of active treatment systems.

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