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Revision Memo

12/02 Revised decision tree presented as Figure 2.

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SCOPE

This Design Practice provides guidance for free phase hydrocarbon recovery from the subsurface environment. Cleanup of these light nonaqueous phase liquids (LNAPLs) may be an essential source removal step in the overall site remediation process. Removal of dense nonaqueous phase liquids (DNAPLs) is beyond the scope of this design practice. These contaminants pose a different cleanup challenge and many of the remedial alternatives are still in the developmental stages.

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DEFINITIONS

Air Sparging - A remedial method which uses air injected below the water table through vertical wells to volatilize hydrocarbons.

Aquifer - A layer of underground soil or rock in which water collects in quantities sufficient for yields in wells or springs.

Attapulgite Clay - A colloidal, viscosity-building clay.

Bentonite - A low permeability colloidal clay, made up of the mineral sodium montmorillonite (a hydrated aluminum silicate); used as a surface sealant in well bores and in barrier walls.

Bioremediation - The breakdown of contaminants into by-products through biological processes, particularly microbial metabolism. Also "**Biodegradation**."

BTEX - Benzene, Toluene, Ethylbenzene, Xylenes.

Capillary Fringe - The zone at the bottom of the vadose zone where groundwater is drawn upward by capillary forces. This zone is above the water table but the soil is saturated.

DNAPL - Dense Nonaqueous Phase Liquids. Organic liquids with densities greater than water that exist as a separate immiscible phase and tend to accumulate below the water surface at physical barriers (e.g., low permeability strata).

Emulsion - A stable suspension of one liquid in a second immiscible, continuous phase liquid, typically containing surfactant and a high percentage of dispersed phase.

gpm - Gallons per minute. A measure of volumetric fluid flow rate.

HDPE - High Density Polyethylene.

Hydraulic - A process operated by a fluid under pressure.

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Hydraulic Conductivity - A physical property of soil that describes the flow rate of a fluid, such as groundwater or air, through the soil matrix. Values on the order of 10^{-4} cm/s (cm per second) and greater indicate a highly conductive soil.

LNAPL - Light Nonaqueous Phase Liquids - organic liquids with densities less than water that exist in a separate, immiscible phase and tend to accumulate on the water surface.

Oil/Water Separator - Equipment used to separate the hydrocarbon from the water in the liquid emulsions pumped from the subsurface. Simplest form is a settling tank in which the liquids separate naturally over a period of time.

Oleophilic/Hydrophobic Membrane - A membrane that has an affinity for oil and repels water.

Permeability - A measure of the ability of soil to transmit fluid.

Piezometer - A nonpumping well, generally of small diameter with a short well screen, that is used to measure the elevation of the water table.

Pneumatic - A process using compressed air.

Proppant - Hydraulic fracturing fluid that is a slurry mixture of sand and viscous fluid comprised of water, guar gum gel, and an enzyme that breaks down the gel within 24 hours after the sand has been deposited in the fracture.

psi - Pounds per sq in. Measurement of pressure.

PVC - Polyvinyl Chloride. A rigid plastic used for well and remediation system piping.

Radio Frequency Heating - Process that achieves uniform heating of the soil by inserting electrodes and applying radio frequency energy.

Residual LNAPL - LNAPL that is adsorbed to soil particles and thus does not flow.

scfm - standard cu ft per minute. Volumetric rate of flow. Standard conditions are air at 1 atmospheric pressure, 36% relative humidity, and 68°F (20°C) having a specific weight of 0.075 lb/ft³ (1.2 kg/m³).

Smear Zone - Depth in the soil profile in which residual hydrocarbons are adsorbed to soil particles due to water table fluctuations.

Surfactant - A substance capable of reducing the surface tension of a liquid in which it is dissolved. Used to improve surface wetting of soil particles and emulsify hydrocarbons.

Threshold Thickness - Thickness at which a remedial technology is no longer effective at recovering free phase LNAPL.

Unsaturated Zone - Subsurface soil or bedrock, typically above the water table, in which some pore spaces and fractures are not completely filled with groundwater.

Vadose Zone - The zone of soil between the water table and the ground surface that includes the unsaturated zone and saturated soil in the capillary fringe.

VOCs - Volatile Organic Compounds. Organic compounds that have a low boiling point or that evaporate readily under typical environmental conditions.

Volatile - Describes a constituent that evaporates readily under normal pressures and temperatures. The process is referred to as "volatilization."

INTRODUCTION

Hydrocarbons are present in the subsurface in three distinct phases: vapor, liquid, and dissolved. Vapors are generated as liquid and dissolved phase hydrocarbons volatilize. Liquid hydrocarbon is further broken down into free and residual contamination. Free contamination denotes mobile liquid, while residual contamination (sometimes called solid-phase) is liquid adsorbed to soil particles or trapped in pore spaces and therefore is not mobile. In general, as the liquid hydrocarbon density increases or pore space decreases, the residual liquid hydrocarbon concentrations in the unsaturated zone increase. Due to residual contamination, recovery rates typically range in the order of 30% to 50% of the original volume released, with lower recoveries associated with higher residual concentrations. Infiltrating precipitation and passing groundwater in contact with residual or mobile LNAPL can dissolve the soluble components and form an aqueous-phase contaminant plume. [Figure 1](#) demonstrates the typical distribution of LNAPL in the subsurface environment.

This Design Practice covers the remedial technologies in three broad categories: Conventional, Enhanced/Integrated, and Emerging. A conventional technology is one that has a proven track record in the field and thus relative performance can be anticipated for given site conditions. Enhanced/Integrated technologies increase recovery performance of conventional technologies and typically are not meant as stand alone remedial measures. Emerging technologies are those that are currently under development and hence do not have proven track records in the field.

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Each technology is briefly described and a matrix of operating characteristics is included. All costs listed in the tables are in 1996 US Dollars. Cross-sectional drawings of each technology are included.

A Decision Tree ([Figure 2](#)) is provided to facilitate choosing the appropriate technology for specific site conditions. The final choice of an LNAPL remedial alternative, however, is a function of the site-specific characteristics and may differ from those identified by the decision tree.

There are many factors that must be considered when selecting the appropriate remedial alternative(s) for a particular site. These include:

- Nature of the release (e.g., initial date of occurrence, duration, volume, and distribution).
- Physical and chemical properties of the LNAPL (e.g., viscosity, density, composition, and solubility in water).
- Soil properties (e.g., capillary forces, effective porosity, moisture content, organic content, and hydraulic conductivity).
- Geology (e.g., stratigraphy that promotes trapped pockets of free LNAPL).
- Hydrogeologic regime (e.g., depth to water table, groundwater flow direction, and gradient).
- Technology considerations (e.g., availability and cost).
- Regulatory drivers and recovery objectives (e.g., environmentally acceptable end points, risk to potential receptors).

A decision tree is provided to facilitate choosing the appropriate technology for specific site conditions, and guiding readers through the design practice. The final choice of a remedial alternative however is a function of the above listed site specific characteristics and may differ from those identified by the decision tree. It also should be emphasized that field pilot studies provide valuable information necessary for assessing remedial effectiveness and determining optimal operating parameters for the chosen technology.

In certain instances where regulatory drivers are absent, long term solutions are acceptable, or active remediation measures may be ineffective (e.g., formations with $K < 10^{-7}$ cm/s), natural attenuation may be the preferred remedial alternative. Hydrocarbon concentrations will naturally decrease over time as a function of: sorption, dispersion, and biological decay. Sorption is a mechanism in which the hydrocarbon contamination attaches itself to soil particles. This serves to retard the migration of the contaminant. Dispersion is caused by velocity and concentration gradients as the contamination travels through the soil matrix. Dispersion results in dilution of the contaminant. Petroleum hydrocarbons, specifically benzene, toluene, ethylbenzene, and xylene, should naturally biodegrade in the subsurface environment. The drawback to this remedial approach is that long term monitoring is often required to ensure that the contamination is in fact attenuating and does not pose a threat to potential receptors or migration off property.

CONVENTIONAL TECHNOLOGY SUMMARIES

TRENCH AND DRAIN SYSTEMS

Trenches represent the most hydraulically efficient means for removing hydrocarbon from an aquifer by using the natural groundwater gradients to influence contaminant migration into the trench. They are restricted to shallow depths and are typically excavated perpendicular to the groundwater flow direction, downgradient of the free liquid hydrocarbon plume. The trench should generally be as long as the width of the plume and excavated to a depth several feet below the lowest expected fluctuation of the water table or to a lower permeability physical barrier (e.g., a clay layer). Care must be taken not to penetrate the physical barrier during excavation, thus allowing contamination to migrate into underlying soils and/or aquifers.

In situations where soil stability, safety, or other considerations preclude the use of an open trench, the trench can be converted to a drain by backfilling with graded filter material (sand or gravel). Sumps or wells should be installed at intervals along the drain to collect the hydrocarbons. Perforated drain pipes can be installed in the bottoms of the backfilled trenches and connected to the sumps to improve efficiency of the system.

[Figure 3](#) contains cross-sectional and plan drawings of a trench and drain system for LNAPL recovery. For further information on this subject, see Report EE.4M.95 (*Site Characterization and Remedial Technology Selection Guide*).

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	TRENCH AND DRAIN SYSTEMS
CONTAMINANTS	Free phase.
APPLICABILITY	- Sites where geology is heterogeneous and fluid migration is through randomly spaced zones. - Well suited for areas with shallow water tables < 25 ft (7.5 m) and soils with relatively low hydraulic conductivities (e.g., normally consolidated clay, swelling clay, silty clay till) where interception of liquid hydrocarbon in trenches is a more economical alternative than numerous closely spaced recovery wells.
COST	- Collection trenches can range from \$5 to \$28/ft² (\$50 to \$300/m²) for shallow applications; costs increase with depth. - One-pass interceptor trencher: \$50 to \$150/ft² (\$300 to \$500/m²).
TIME	- Installation within several days to several weeks, sometimes months depending on area affected. - Operational life of many years.
DESIGN CONSIDERATIONS	- Investigation of underground utilities and structures is required. - Factors limiting effectiveness of trench and drain systems include: high LNAPL viscosity, high residual water saturation, low permeability, and infiltration from surface water. - Trench width is not a factor in LNAPL migration and therefore the trench should be as narrow as possible to accommodate hydrocarbon recovery equipment while minimizing associated costs (e.g., excavation costs, contaminated soil disposal costs). - Restricted to shallow depths from 0 to 20 ft (0 to 6 m); depth depends on soil stability and available excavation equipment. - Free LNAPL recovery rates must be sufficient to prevent excessive accumulation and subsequent migration of the hydrocarbon around the ends of the trench.
EFFECTIVENESS/ ENHANCEMENTS	- Low permeability barriers (e.g., HDPE flexible membrane liner) can be placed on downgradient edge of a trench/ drain to trap LNAPLs preventing them from migrating further down gradient and help limit surface water recharge. - Pumps or active skimming systems can be used to enhance LNAPL recovery by pumping groundwater/hydrocarbons from the trench, thus providing hydrodynamic control by lowering the water table elevations near the trench and inducing flow of liquid hydrocarbons into the trench/drain. - Recent advances in trenching equipment include installation of drain pipe, filter media, and sump well in a continuous trenching operation at depths up to 24 ft (7.5 m); commonly known as a one-pass interceptor trencher.
PROS	- Quick, cost effective installations are possible if soil conditions are favorable. - Simple operation and maintenance. - Wide commercial availability of materials and equipment. - Complete plume interception. - Compatible with funnel and gate technology for dissolved phase treatment. - One-pass interceptor trencher: fair access, fast, avoids shoring.
CONS	- Depth limited by soil conditions, equipment limitations and access, and soil disposal considerations. - Entire width of plume must be bisected unless hydrodynamic control is established through the use of an active pumping system. - Institutional controls must be used to limit access to open trenches. - Usually requires long-term monitoring.

VERTICAL WELLS

Vertical wells are the most commonly used method to access hydrocarbons in the subsurface environment. A typical well consists of a well casing, well screen, filter pack, annular seal, and surface protection. Properly designed wells are critical to the performance of the system. A thorough understanding of hydrogeologic conditions, aquifer conditions and the most effective well development procedures is required for the design and installation of high-yielding, efficient recovery wells.

A definitive reference book on designing wells is *Groundwater and Wells* (Driscoll, 1986).

Figure 4 shows the typical cross-section of a vertical well used for free LNAPL recovery. For further information on this subject, see Report EE.4M.95 (*Site Characterization and Remedial Technology Selection Guide*).

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	VERTICAL WELLS
CONTAMINANTS	Free phase.
APPLICABILITY	- Areas with many underground obstructions such as pipes and utilities. - Provides considerable versatility with available recovery/remedial technologies. - As depth to water table increases, applicability increases. - As permeability of formation decreases, applicability decreases.
COST	Wells range from \$2k - \$30k, depending on diameter and depth.
TIME	- Installation typically 0.1 to 4 days per well. - Operational life of up to several years.
DESIGN CONSIDERATIONS	- Investigation of underground utilities and structures is required. - Proper design requires a thorough understanding of surficial conditions (e.g., topography, drainage, climate, seasonal variations in the climate, and site access), hydrogeological site characteristics (e.g., type of geology, aquifer porosity, hydraulic conductivity, type of aquifer, recharge/discharge conditions, groundwater gradients), characteristics of contaminants (e.g., chemistry, density, viscosity, reactivity, and concentration). - Critical well parameters include: - Sizing gravel pack for the annular space between the bore hole and screen. - Well diameter chosen must be sufficient to accommodate recovery equipment. - Well screen slot size, filter fabric, and open area to reduce plugging by fines and precipitation of dissolved inorganics. - Well screen should straddle the water table and the floating LNAPL with the top of the screen above the highest anticipated elevation of the hydrocarbon's free surface to allow entry of the free LNAPL into the well. - Optimal design well spacing design depends on remediation objective; if the objective is hydraulic containment and prevention of migration, the wells will be spaced farther apart than if complete plume capture is the objective; fluid flow rate is determined in conjunction with well spacing. - Computer modeling often required to optimize well configuration by predicting plume capture and withdrawal rates.
EFFECTIVENESS/ ENHANCEMENTS	- Used in conjunction with passive and active skimming systems, single pumps, two pumps, vacuum enhanced recovery, dual phase recovery (Bioslurping), fracturing, chemical and thermal enhancement technologies. - Horizontal wells can enhance recovery and decrease well costs in situations where numerous spaced vertical wells can be replaced by a horizontal well.
PROS	- Wide commercial availability of materials, equipment, and contractors with expertise. - Used to gain hydraulic control. - Wide regulatory acceptance. - No depth limitations. - Non-disruptive to on going operations compared to excavation methods. - Useful for long-term monitoring. - Piezometers installed for assessment can be used for remediation.
CONS	- Requires experienced personnel to complete design. - Numerous wells may be required for complete plume capture in soils with low hydraulic conductivities. - Limited applicability at locations with restricted surface access.

PASSIVE LNAPL SKIMMING SYSTEMS

Passive LNAPL skimming systems consist of either collectors or sorbents that can be used to remove floating LNAPL from wells or trenches. Most collectors are designed to float on top of the water table and generally consist of a storage reservoir, vent line, and valve. Free phase LNAPL enters a collector's storage reservoir through a hydrophobic membrane or port at the top of the unit. The accumulated hydrocarbons must periodically be emptied. Sorbents generally consist of packages of material (e.g., polymer beads, graded clays, or peat moss) that preferentially adsorb LNAPL via a wicking action. Spent sorbents must be disposed at landfills or destroyed by thermal treatment.

Figure 5 shows a typical free LNAPL recovery system employing a passive collector.

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	PASSIVE LNAPL SKIMMING SYSTEMS
CONTAMINANTS	Free phase.
APPLICABILITY	- Sites containing small thicknesses of free LNAPL, < 4 in. (0.1 m). - Best suited for formations with high hydraulic conductivities, > 10⁻⁴ cm/s. - Low risk sites where potential receptors are not exposed. - Better for removal of LNAPL from plume center than at downgradient interception.
COST	- Various sizes available to recover 0.5 to 3 gal (2 to 10 L) volumes with capital costs ranging from \$500 to > \$2k depending on size. - Hand bailing typically costs \$500/mo.
TIME	Passive recovery systems operating alone will generally be required to operate for many years.
DESIGN CONSIDERATIONS	- Typically used when hydraulic control of the plume is not critical (e.g., when regulatory or property drivers are not present). - Sorbents excellent for recovery of free hydrocarbon contamination aboveground (e.g., tank pits). - If collector must be emptied more than once a week, active LNAPL recovery systems should be considered. - Available for installation in wells as small as 2 in. (50 mm) in diameter.
EFFECTIVENESS/ ENHANCEMENTS	- Threshold thickness is generally 0.1 ft (30 mm). - Pumps can be used to remove accumulated hydrocarbons in the storage reservoir of collectors. - Effectiveness limited by ability of LNAPL to migrate to extraction point; systems employing hydrophobic membranes may not be well suited for recovery of heavier viscous hydrocarbons (e.g., lubricating and bunker oils).
PROS	- Wide variety is commercially available. - Easily installed. - Technologically very simple resulting in low capital, operation, and maintenance costs. - Rapid deployment makes passive recovery systems ideal for emergency response. - Recovers essentially pure LNAPL thus reducing fluid handling, treatment, and disposal requirements.
CONS	- Does not establish hydraulic control, resulting in low recovery rate and long remediation times. - Will not capture LNAPL downgradient of extraction/collection point. - Manual adjustment generally required when water table fluctuates. - If used for plume interception, close spacing required to avoid plume by-pass.

ACTIVE LNAPL SKIMMING SYSTEMS

LNAPL skimming systems consist of pumps designed to float or be anchored at the hydrocarbon/water interface. They separate the LNAPLs from the groundwater through the use of oleophilic/hydrophobic membranes, density sensitive valves, or by locating the pump intakes in the floating LNAPL layer. Pump operation can be continuous or controlled by conductivity sensors for pump activation.

Figure 6 contains a cross-sectional drawing of a typical skimming system in a vertical well.

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	ACTIVE LNAPL SKIMMING SYSTEMS
CONTAMINANTS	Free phase.
APPLICABILITY	- Best suited for formations with high hydraulic conductivities, $> 10^{-4}$ cm/s. - Best used in trenches with large accumulations of free LNAPL or wells set in areas with large thicknesses of free LNAPL where the skimmer can produce a drawdown in the free LNAPL plume and induce flow of free LNAPL to the trench/well.
COST	- Skimming pumps with installed piping can range from \$2k to \$30k. - Operation, maintenance, and monitoring costs generally $< \\$1k/month$.
TIME	- Extraction points and skimming equipment can generally be installed in days. - Skimming systems operating alone will generally be required to operate for years.
DESIGN CONSIDERATIONS	- Typically used when hydraulic control of the plume is not critical (e.g., when regulatory, migration, or timing drivers are not present). - Essentially pure product recovered thus reducing required fluid handling, treatment, and disposal capacities. - Water table fluctuations may interfere with anchored pump operation. - Surface mounted skimming pumps restricted to < 20 ft (6 m) depth with flows ranging from 0.05 to 5 gpm (0.2 to 19 L/min). - Down-well skimming pumps can remove free LNAPL at depths of up to 250 ft (76 m). - Available for installation into wells as small as 2 in. (50 mm) in diameter. - Viscosity is the most important parameter for selecting active skimming equipment employing oleophilic/hydrophobic membranes. - Density of hydrocarbon is the most important parameter for selecting active skimming equipment using floating intakes because if the float's density is less than that of the hydrocarbon it will rise to the air/oil interface and be ineffective. - Skimming systems using oleophilic/hydrophobic membranes generally remove free hydrocarbon to < 0.01 in. (0.25 mm), while systems with floating intakes typically remove free hydrocarbon to approximately 0.25 in. (6 mm).
EFFECTIVENESS/ ENHANCEMENTS	- Effectiveness limited by ability of LNAPL to migrate to extraction point; systems employing hydrophobic membranes may not be well suited for recovery of heavier viscous hydrocarbons (e.g., lubricating and bunker oils). - Generally not effective when recovery reaches < 10 gallons/month; threshold thickness is generally 0.1 ft (30 mm). - Can operate in pulsed/intermittent modes. - Vacuum trucks can be used to recover free hydrocarbon with similar recovery rates as active skimming systems. - Recovery can be enhanced by placing a water pump at the bottom of the well (see two pump recovery systems) or using Vacuum-Enhanced Recovery.
PROS	- Easily installed, low operation & maintenance costs. - Ideal for emergency response because of rapid deployment. - Little co-produced water requiring storage, treatment, and disposal. - Wide variety is commercially available. - Higher yields than passive systems.
CONS	- Long-term measure. - Downhole systems with membranes and sensors are subject to clogging and fouling. - Limited radius of influence.

SINGLE PUMP LNAPL RECOVERY SYSTEMS

This method, also known as Total Fluids Recovery, is the most commonly applied LNAPL recovery technique. In this system, groundwater and free hydrocarbons are withdrawn from a groundwater extraction well using a single pump, which creates a localized cone of depression in the water table. LNAPL located in the area of groundwater depression migrates toward the extraction well due to the induced hydraulic gradient.

Figure 7 contains a cross-sectional drawing of a typical single pump system for free LNAPL recovery with water table depression.

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	SINGLE PUMP LNAPL RECOVERY SYSTEMS
CONTAMINANTS	Free phase.
APPLICABILITY	- Best suited to formations with high hydraulic conductivities, $> 10^{-4}$ cm/s. - Treatment of LNAPL plumes which require hydraulic control and/or where there is a dissolved organic groundwater plume which requires treatment. - Can also operate in sump wells of interceptor trenches and drains.
COST	- Key cost factors include: waste disposal, potential sale of recovered LNAPL for recycling, on-site equipment rental (e.g., pumps, tanks, treatment systems), installation of permanent equipment, and engineering and testing costs. - One pump systems cost from \$10k to \$25k per installation. - Separators cost from \$5k to \$20k (refer to Design Practice XIX-A1 for further information). - Operation, maintenance, and monitoring costs generally \$1k - \$2k/month.
TIME	Typically used in long-term operations of greater than one year.
DESIGN CONSIDERATIONS	- Practical recovery depths using suction-lift pumps are limited to < 20 ft (6 m). - Tendency for emulsification can be reduced by use of submersible or surface mounted positive displacement pumps (diaphragm, pneumatic, or peristaltic pumps). - Pumps that come in contact with hydrocarbons require ratings appropriate for working in a hydrocarbon environment. - Surface mounted pumps have three advantages over submersible pumps: they are easier to operate and maintain because they are aboveground, they are generally less expensive (submersible pumps must be made explosion proof due to the presence of volatile hydrocarbons and also must be able to pump in corrosive environments), and they generally have a longer life-span (on average, two to three years longer than submersible pumps, which are exposed to gasoline, oil, and other corrosive chemicals); however, they are limited to water depths < 20 ft (6 m). - Single pump systems typically operate from 0.1 to 20 gpm (0.4 to 76 L/min). - Hydrocarbon/water separator needed to treat recovered fluids (refer to Design Practice XIX-A1 for further information on oil/water separators).
EFFECTIVENESS/ ENHANCEMENTS	- Generally restricted to 20 to 50% removal of the total <i>in situ</i> volume of hydrocarbons. - Water table depression results in greater hydraulic control than skimmers for stopping contaminant plume movement by creating a cone of depression enhancing LNAPL recovery. - Vacuum-enhanced recovery most often applied enhancement.
PROS	- Wide commercial availability of materials and equipment. - Cost effective at higher flow rates if an existing industrial sewer system can effectively handle produced water and liquid hydrocarbons. - Simple to operate. - Hydraulic control of plume. - Low operating and maintenance costs. - Water table depression can free trapped residual LNAPL, enhancing recovery.
CONS	- Hydraulic gradient only driving force for LNAPL removal; heavier, more viscous hydrocarbons may not migrate even under large induced hydraulic gradients. - Water table depression can lead to enlargement of the smear zone. - Prone to fouling by iron bacteria. - Tendency to emulsify the hydrocarbon in produced water and increase dissolved hydrocarbon concentrations results in need for aboveground hydrocarbon/water separation system. - Water table depression can lead to foundation stability concerns.

DUAL PUMP LNAPL RECOVERY SYSTEMS

Two pump systems consist of a water table depression pump with an intake near the bottom of the well and a suspended hydrocarbon pump with the intake at or slightly below the free hydrocarbon/water interface. The water table depression pump is used to create a cone of depression in the water table, thus inducing flow toward the well. The suspended hydrocarbon pump removes free hydrocarbon. The pumps may be submersed or surface mounted with automatic controls to cycle them on and off. Pump separation should be maximized to prevent short-circuiting between pumps, i.e., the water table pump drawing hydrocarbons.

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Figure 8 contains a cross-sectional drawing of a typical two pump system for free LNAPL recovery with water table depression.

CONVENTIONAL TECHNOLOGY SUMMARIES (Cont)

	DUAL PUMP LNAPL RECOVERY SYSTEM
CONTAMINANTS	Free phase.
APPLICABILITY	- Typically used when water table depression is necessary to achieve hydraulic control of the plume, when hydraulic conductivities and saturated thicknesses are moderate to large, and when liquid hydrocarbon/water separation facilities are limited or not desirable. - Best suited for formations high hydraulic conductivities, $> 10^{-4}$ cm/s. - Can also operate in sump wells of interceptor trenches and drains to enhance LNAPL recovery
COST	- Key cost factors include: waste disposal, potential sale of recovered LNAPL for recycling, on-site equipment rental (e.g., pumps, tanks, treatment systems), installation of permanent equipment, and engineering and testing costs. - Two pump systems are generally expensive costing from \$20k to \$50k per installation, not including well costs; on average, submersible pumps are 10 to 15% more costly than surface-mounted pumps. - Operation and maintenance costs are much greater for two pump systems than for one pump systems and typically range from \$2.5k - \$4k/month.
TIME	Typically used in long-term operations of greater than one year.
DESIGN CONSIDERATIONS	- Two pump systems require a minimum 6 in. (150 mm) diameter well. - Two pumps are generally set 10 to 15 ft (3 to 4.5 m) apart to ensure adequate drawdown and to ensure that the water table depression pump does not come in contact with LNAPL. - Pumps that come in contact with hydrocarbons require ratings appropriate for working in a hydrocarbon environment. - Surface mounted pumps have three advantages over submersible pumps: they are easier to operate and maintain because they are aboveground, they are generally less expensive (submersible pumps must be made explosion proof due to the presence of volatile hydrocarbons and also must be able to pump in corrosive environments), and they generally have a longer life-span (on average, two to three years longer than submersible pumps, which are exposed to gasoline, oil, and other corrosive chemicals). - Extreme care must be taken during start up and adjustment of two pump systems, pumping rates must be balanced so that liquid hydrocarbon/water interface is maintained at a constant level in the well.
EFFECTIVENESS/ ENHANCEMENTS	- Generally restricted to 20 to 50% removal of the total <i>in situ</i> hydrocarbon volume. - Generally operate at flow rates > 5 gpm (19 L/min); use of two pump system should be evaluated critically at low water production rates < 3 gpm (11.5 L/min). - Vacuum-enhanced recovery most often applied enhancement for formations with hydraulic conductivities $< 10^{-4}$ cm/s.
PROS	- Hydraulic control of contaminant plume. - Wide commercial availability of materials and equipment. - Separation of the LNAPL and water within the well reduces emulsion formation and dissolved contaminant concentrations in co-produced water over single pump systems. - Fully automated to maximize rate of recovery.
CONS	- Hydraulic gradient only driving force for LNAPL removal; heavier, more viscous hydrocarbons may not migrate even under large induced hydraulic gradients. - Water table depression can lead to enlargement of LNAPL smear zone. - Require larger diameter wells than single pump systems. - Prone to fouling by iron bacteria. - Floating pumps hanging up in well as water table changes. - Higher capital, operating, and maintenance costs than single pump systems. - Water table depression can lead to foundation stability concerns. - Installation, initial start-up, and adjustments require experienced personnel.