CHAPTER V

HYDROCARBON RECOVERY SYSTEMS/EQUIPMENT

CHAPTER V

HYDROCARBON RECOVERY SYSTEMS/EQUIPMENT

The selection of a hydrocarbon recovery system and its associated equipment is based on specific remedial objectives, design constraints, and site conditions. Hydrocarbon recovery systems are chosen to satisfy remedial objectives involving the control of petroleum hydrocarbon migration, maximum free product recovery, and simultaneous free product and vapor phase collection. Design constraints governing the selection of recovery systems may be site specific, such as limited access to wells. Other constraints may involve conflicts between free product recovery and other aspects of the corrective action; for example, a pump-and-treat remedy may adversely affect free product recovery by smearing the zone of free product.

The general site conditions affecting product recovery are the volume of the free product, its type and areal extent, and the depth at which it is located. Hydrogeologic conditions such as permeability and groundwater flow also influence the selection and design process of recovery systems.

Four general techniques or approaches are used to recover free product:

- Free product removal/skimming systems.
- Free product recovery with water table depression.
- Vapor extraction/groundwater extraction.
- Dual phase (liquid and vapor) recovery.

A description and applicability for each of these techniques is summarized in Exhibit V-1. Further detailed discussion on the applicability of these methods is provided later in this chapter. Exhibit V-2 provides a comparison of the general features of these techniques.

Each of these methods involves the installation of recovery equipment (*e.g.*, skimmers, pumps, filters, or absorbent materials) in wells,

Exhibit V-1

General Approaches To Free Product Recovery

Free Product Recovery Approach	Description	Applicability
Skimming Systems	Free product is recovered from a well or trench without recovering groundwater.	Small volumes of free product are removed because of limited area of influence in open trenches or excavations. Often used during emergency or short-term remedial actions.
Free Product Recovery With Water Table Depression	Free product is recovered from a well or trench along with groundwater. Groundwater is pumped to create cone of depression in water table to expand area of influence.	Requires moderately permeable to permeable subsurface materials (silts, sands, and gravels). Can be used in settings with deep water tables. Often used in long term (>1 year) remedial actions. Produced groundwater can be expensive to treat.
Vapor Extraction/ Groundwater Extraction	Vacuum is applied to well(s) above water table to recover vapor phase and residual hydrocarbons and to help maintain high water table. Free product and/or groundwater is recovered from wells by pumps.	Low to moderately permeable materials (silts, silty sands). Often used to enhance recovery of hydrocarbons.
Dual-Phase Recovery	Both liquids and vapors are recovered from same well. Groundwater production is minimized, and water table is stabilized.	Generally low permeability materials (clay, clayey silts, silts, silty/clayey sands). Requires surface seal (either naturally occurring clay or man-made) to prevent short-circuiting of vacuum.

EXHIBIT V-2

Comparison Of General Features
Of Free Product Recovery Systems

System	Provide Hydraulic Control	Install in Excavations	Require Specialized Wells	Provide Fluid Separation	Produce Ground water	Product Recovery Rate	Capital Costs	Operation and Maintenance Costs
Skimming	No	Yes	Depends on diameter of skimmer	Yes	No	Low	Low -med	Low
Water Table Depression	Yes	Yes	No	Yes—dual-pump systems No—single pump systems	Yes	Low-high depends on volume of recoverable free product and formation characteristics	Low-high depends on number of pumps and complexity of system	Low-high depends on number of pumps and complexity of system
Vapor Extraction/ Groundwater Extraction (VE/GE)	Yes	No	Yes	No	Yes	Low-high depends on volume of recoverable free product and formation characteristics	Med-high	Med-high
Dual-Phase Recovery	Yes	No	Yes	No	Yes	Low-high depends on volume of recoverable free product and formation characteristics	High	High

trenches, or excavations. Other aspects of free product recovery systems consist of phase separation, storage, and treatment processes. In addition, groundwater pumped in conjunction with free product recovery must be discharged. Collection and treatment equipment must also be monitored and maintained during operation.

This chapter describes each of the four recovery approaches with respect to its applicability, general design considerations, required equipment, system operation and maintenance, and the monitoring and termination of recovery activities.

Free Product Removal/Skimming Systems

The goal satisfied by skimming systems is the collection of free product with little or no recovery of water. In general this approach involves using skimming devices to remove product floating on the water table in excavations, gravel-filled trenches, and wells. This type of system is commonly used in interim remedial actions.

Applicability

Free product removal using skimming equipment is applicable in settings where long-term hydraulic control of the dissolved hydrocarbon plume is not required. In most settings skimmer operations will not control the liquid hydrocarbon plume. The most common use of these systems is inclusion in an interim action where free product has entered open excavations. In general, skimming systems are applicable to settings in which the amount of free product is small and exists in permeable conduits such as utility bedding or buried underground open structures. The hydraulic conductivity should be greater than 10^{-4} cm/s to ensure a sufficient influx of free product to the skimmer. Skimmers may also be used in conjunction with other free product removal programs such as in monitoring and extraction wells for water table depression methods.

General Design Considerations

When hydraulic control of the contaminated region is not necessary, then skimmers are typically located in permeable conduits where significant free product is present. Skimmers are available for installation in wells from 2 inches in diameter up to several feet in diameter. Skimmer equipment may also be used in excavations and trenches which may be open for very short term or emergency operations. For long-term operations, skimmers are placed in wells and in gravel-filled trenches with sumps. Recovery may be enhanced by use of hydrophobic gravel packs in wells. Field studies by Hampton *et al*. (1992) have shown that gravel packs constructed from hydrophobic materials allow for free product to enter wells and sumps more rapidly. Recovery rates for long-term operations are generally very low, with the exception of skimmers that are used in open excavations where rates of a few gallons per minute are feasible.

If hydraulic control of the contaminated region is deemed necessary, then skimmers should be located in trenches along the full width of the plume at its downgradient edge. The trench should be excavated several feet below the seasonally low water table to allow for fluctuations over time. For longer term operations, the trench should be filled with gravel or sand, as shown in Exhibit V-3. An impermeable partial vertical liner at the downgradient side of the trench will also prevent migration of the product contaminant plume. A sump should be located at areas where free product is present and at low water table elevations.

Equipment Description

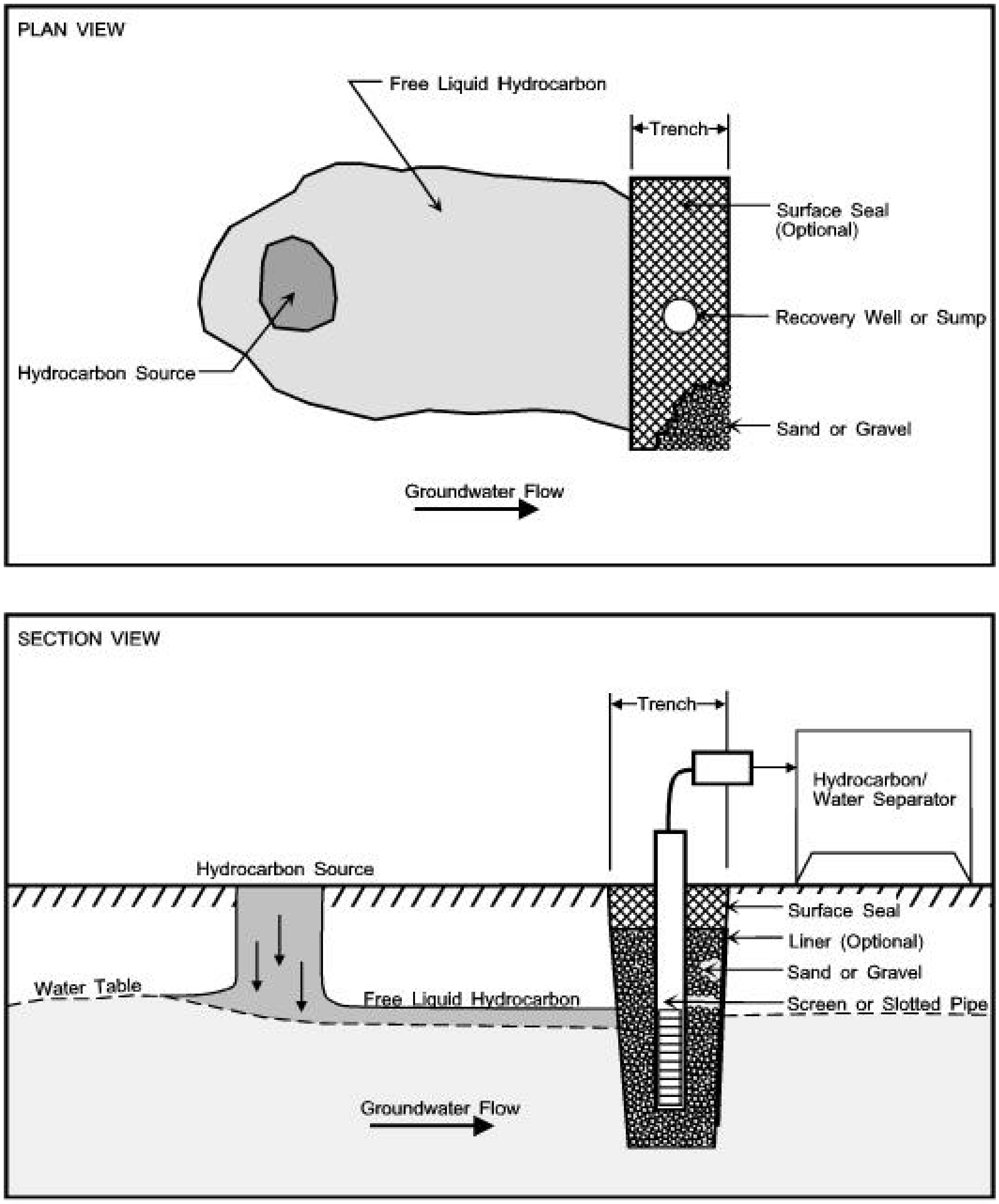
The selection of skimming equipment will be based primarily on the size of the recovery installation (well, trench, excavation) and expected rate of recovery of free product. Two types of skimming equipment are available. Mechanical skimming equipment actively extracts free product from recovery initiation, whereas passive skimming equipment accumulates free product over time. Exhibit V-4 summarizes the applicability, advantages, and disadvantages of the common types of skimming systems.

Mechanical Skimming Systems. Mechanical skimming systems rely on pumps (either surface mounted or within the well) or other motors to actively extract free product from the subsurface. The more common forms of mechanical skimming systems are:

- Floating (large)
- Floating (small)
- Pneumatic Pump
- Belt Skimmer

Exhibit V-3

Interceptor Trench With Skimming Equipment



Source: API, 1996. A Guide to the Assessment and Remediation of Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted courtesy of the American Petroleum Institute.

Exhibit V-4

Applicability of Skimming Systems

	Recommended Minimum Well Diameter	Relative Capital Costs	Relative Operating Costs	Relative Maintenance Costs	Potential For Product Removal	Product Recovery Rate	Advantages	Disadvantages
Mechanical Skimmers								
Floating							No water produced; skims thin layers; moves with fluctuating groundwater tables	Limited radius of influence; clogging of screen; limited to shallow (less than 25 ft.) applications
Large Saucer	36"	M-H	M	M	M	L-H (depends on volume of recoverable free product and formation characteristics)		
Small Float	4"	M-H	M	M	M	L-M		
Pneumatic Pump	4"	M includes comp-ressor	M	M	M	L-M	Can be adjusted so that very little water is produced; skims very thin layers; pumps are durable	Limited radius of influence; requires manual adjustments; clogging of screens and intake valves
Belt Skimmer	2"	M	M	L	L	L	Skims very thin layer; simple operation and maintenance	Belts have limited capacity; low removal rates
Passive Skimmers								
Passive Bailer/Filter Canister	2"	L	L	L	L	L	Low capital cost; simple operation and maintenance	Low removal rates
Passive Absorbent Bailer	2"	L	L	L	L	L	Low capital cost; simple operation and maintenance	Must be replaced manually; low removal rates

L - Low; M - Moderate; H - High

Large floating skimmers can remove product at a fairly high rate (up to 5 gpm). Each skimmer has a large hydrophobic screen that allows only product into the pump body. These skimmers are generally limited to shallow applications (less than 20 feet) and may require a well or sump that has a 24-inch-diameter or greater. Small float systems require 4-inch or larger wells for operation. They are limited to depths of 30 feet or less. This type of skimmer typically uses a floating screen inlet to capture the product and is contained in a pump device or bailer. A variation on floating skimmers employs a floating (or depth-controlled) intake equipped with conductivity sensors that activate surface mounted pumps when liquid hydrocarbons have accumulated to a sufficient thickness. Belt skimmers use a continuous loop of hydrocarbon absorbent material that slowly cycles down into and out of the well, soaking up product as it moves through the water surface. These skimmers are simple mechanical systems that can operate in 4-inch or larger wells, but they are perhaps best suited for skimming sumps. Pneumatic skimming systems may have a top intake that allows skimming of fluids from the liquid hydrocarbon/water interface (as in Exhibit V-5), or they may have a density-sensitive float valve that permits the passing of water before the valve seats.

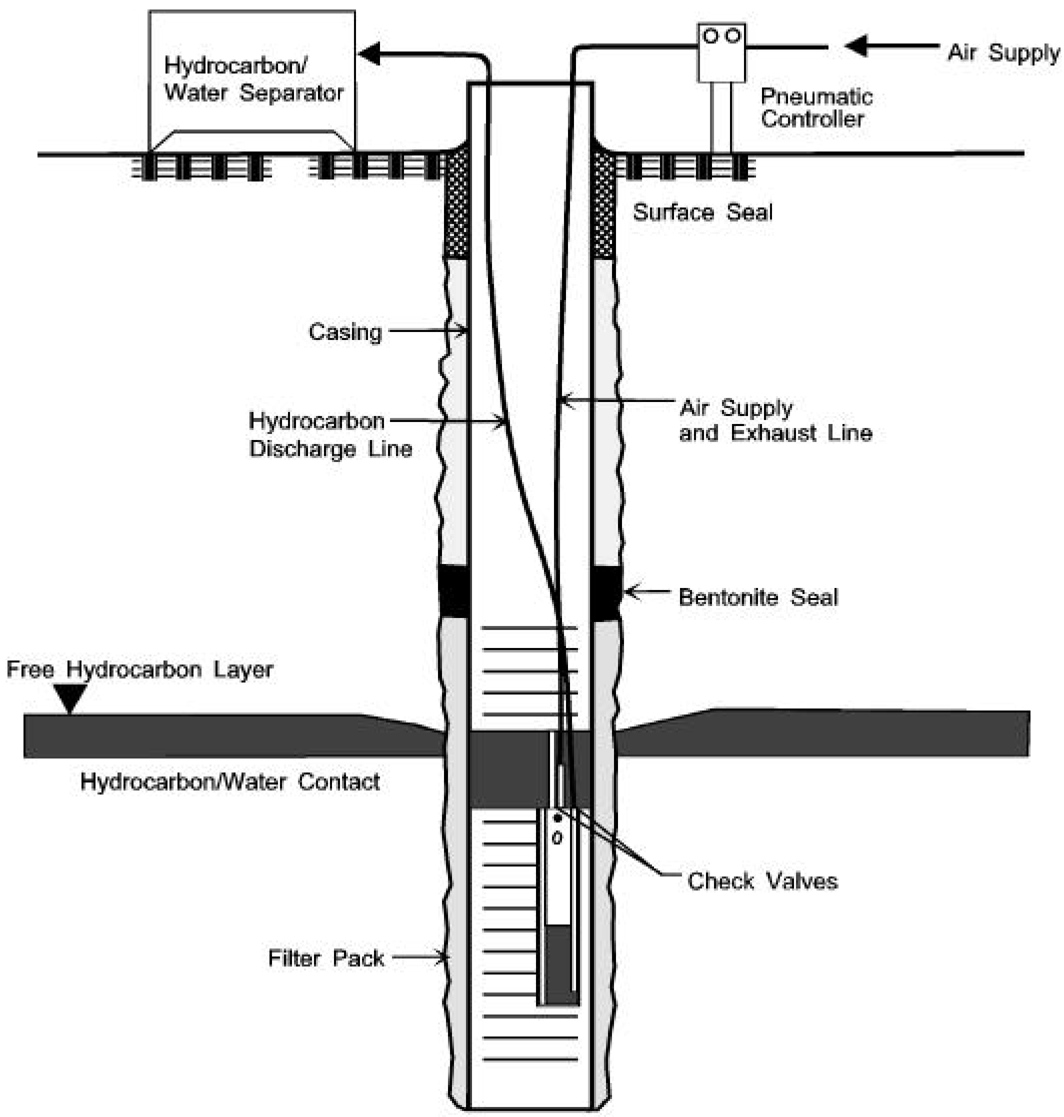
Passive Skimming Systems. Passive skimming systems do not actively pump free product; instead they slowly accumulate it over time. There are two basic forms of passive skimmers:

- Filter canisters
- Absorbent bailers

Filter canisters are lowered into 2-inch or greater diameter wells so that they contact the layer of free product floating on top of the water surface. The filter is constructed of a hydrophobic material which allows only free product to enter. Gravity causes the liquid hydrocarbons to trickle through the filter and then flow into the bottom of the canister where the product is stored. Canisters can store between 0.5 and 2 gallons of free product. The product can be removed automatically by a suction pump or manually by pulling up and emptying the canister (EPA, 1992). Absorbent bailers are simple skimming devices which are suspended in the well across the surface of the free product layer. Attached material absorbs product from the water surface and must be periodically removed and disposed.

Exhibit V-5

Pneumatic Skimmer In A Single Well



Source: API, 1996. A Guide to the Assessment and Remediation of Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted courtesy of the American Petroleum Institute.

System Startup

The startup operations for skimmer systems, not including treatment systems, are relatively straightforward and of short duration (a few days). The following activities are applicable, in general:

- Set the skimmer equipment at proper levels in each well or sump.
- Inspect all mechanical and electrical components of skimmers and collection system, and oil/water separator.
- Monitor the recovery rate of fluids.
- Sample the fluids collected and inspect them for water content and/or emulsification. Modify skimmer settings as necessary to minimize water production.

After the startup activities have been completed, a brief startup summary report should be prepared.

Operations And Maintenance

After the startup activities have been completed, normal operations and maintenance (O & M) activities begin. These activities include:

- Measure the thickness of free product and water and product elevations in monitor and skimmer wells or sumps.
- Record the amount of product collected at all recovery points.
- Inspect all electrical and mechanical components of skimming and collection systems and oil/water separator.
- Maintain and repair all equipment as necessary, or as recommended by equipment vendor.

Typically, these activities are performed every two weeks. Most states require reporting at least quarterly.

Termination Criteria/Monitoring

The free product skimming system should be operated until it is no longer recovering significant amounts of hydrocarbons (*e.g.*, less than 2 gallons per month). After the system operations have been suspended, the free product thickness levels should be monitored on a monthly or quarterly basis to ensure that significant accumulations of product do not return to the wells. A threshold level of hydrocarbon thickness (*e.g.,* 0.1 foot) may be used as an action level to restart the recovery system. The termination criteria should also specify the period during which thickness should be monitored (*e.g.*, 2 years of quarterly monitoring) with no exceedance of threshold hydrocarbon thickness.

Free Product Recovery With Water Table Depression

This method of recovery creates a depression of the water table so that any free product is directed toward pumping wells within the plume area. Both free product and groundwater are produced during recovery operations. The design of these systems is constrained by the need to minimize drawdown of the water table. Minimizing drawdown will reduce both the volume of coproduced water as well as the smearing of free product along the drawdown surface. Exhibit V-6 shows a pumping recovery system capture zone.

Applicability

Product recovery systems utilizing water table depression are most applicable when hydraulic control of the hydrocarbon plume is necessary. These systems can operate in a wide range of permeability values and geologic media. However, because of the costs associated with the separation and treatment of dissolved hydrocarbons, these systems are better suited for formations of moderate to high permeability (greater than 10^{-4} cm/s). Typically, free product recovery with water table depression is used in long-term operations of greater than one year.

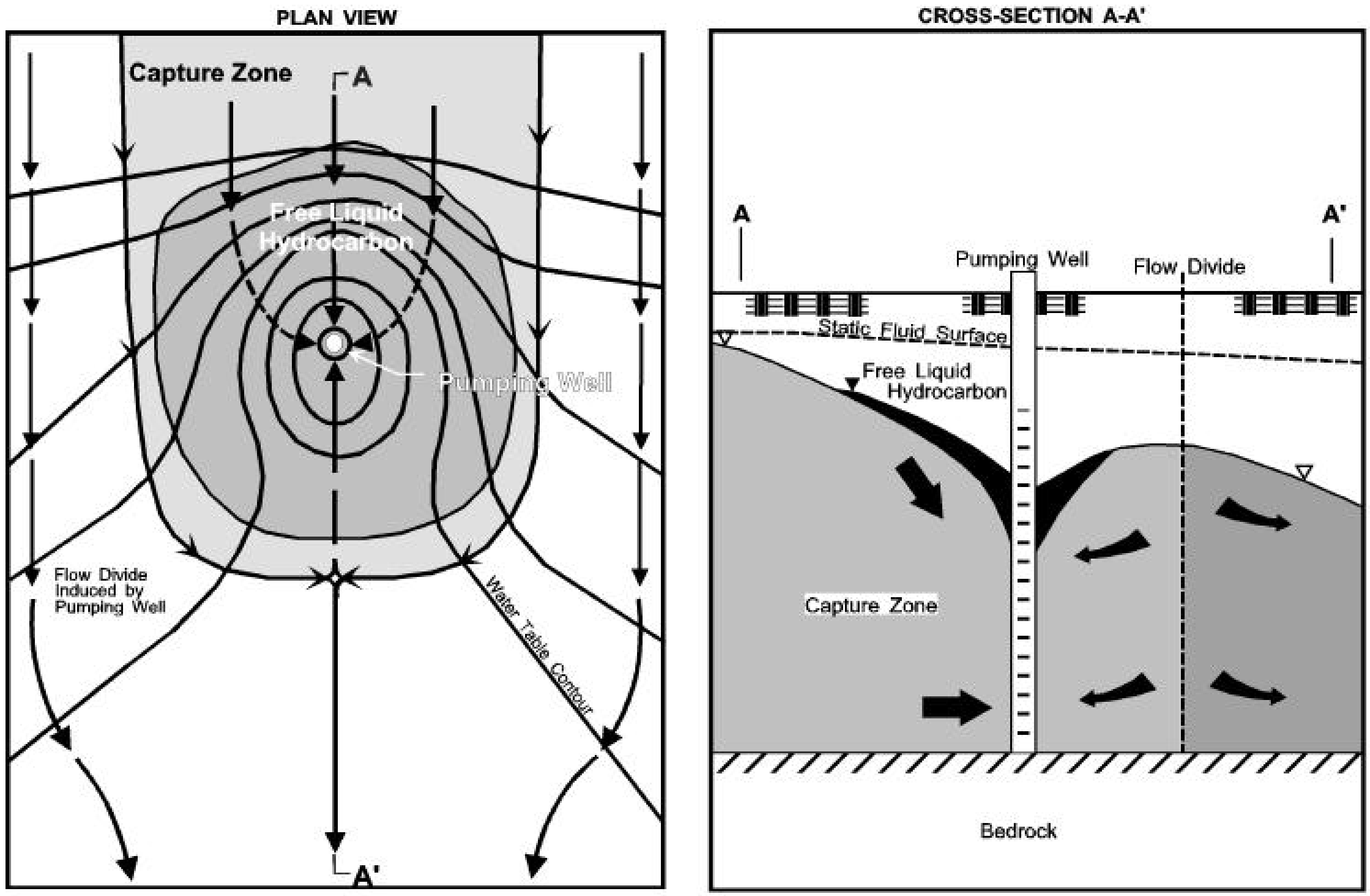
General Design Considerations

The major design components of a free product recovery system using water table depression consist of:

- Number, location, and depth of wells and drains
- Pumping rates or fluid control levels
- Disposition of treated groundwater (discharge)
- Pump selection

Exhibit V-6

Pumping Recovery System Capture Zone



Source: API, 1996. A Guide to the Assessment and Remediation of Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted courtesy of the American Petroleum Institute.

The primary constraints on the design include the need to minimize pumping rates and drawdowns but still provide hydraulic control of at least the free product plume. At some sites, discharge of treated groundwater to surface water may not be possible because of state or local regulations. At these sites, the design needs to address the impact of subsequent recharge to the aquifer.

Recovery Well/Drain Network Design

The success of a free product recovery system using groundwater depression depends upon selecting the number and location of wells and setting pumping rates or fluid control levels in a manner such that the system pumps as little groundwater as necessary while collecting as much free product as possible as quickly as possible. Design of a recovery system can be based on the results of a simplistic basic analysis or a more sophisticated modeling analysis.

Basic Analysis. The basic analysis requires knowledge of the most fundamental groundwater principles and equations. Typically such an analysis can be conducted using nothing more sophisticated than a hand-held calculator. This approach to the design of a system for free product recovery with water table depression is applicable to simple hydrogeologic settings with small free product plumes. Probably the most significant limitation of this method is that, because it considers only groundwater flow rates, it does not provide an estimate of the time that will be required to recover free product present at a site. The basic approach involves four steps:

1. Determine the amount of groundwater flowing through the plume area.

2. Set the total pumping rate of recovery system, usually 50 percent or 100 percent greater than the groundwater flow through the plume.

3. Determine the number of wells from which to extract groundwater, but minimize drawdown in areas of free product.

4. Locate wells to maximize recovery of free product.

Determining the amount of groundwater flowing through the free product plume requires site-specific information: Dimensions of the plume, hydraulic gradient, aquifer saturated thickness, and hydraulic conductivity. An estimate of the groundwater flow rate through the plume is calculated using Darcy’s Law.

To account for uncertainty in the site data and to provide a margin safety should the actual groundwater flow rate be higher than the estimate, the total pumping rate is typically set at 50 percent to 100 percent higher than the estimated groundwater flow rate.

Once the total pumping rate is determined, the next consideration is the minimization of drawdown. Large drawdowns in the free product plume are undesirable because they can result in free product being drawn to lower elevations in the aquifer where it may become immobilized and not subject to recovery (smearing). Simple equations for steady-state flow can be used to estimate flow to a well (or drain) for a desired drawdown. These calculations will determine the number of wells or size of drains.

After the required number of wells has been determined, their locations must be determined. For hydraulic control, the wells are best placed near the downgradient end of the free product plume. Other considerations in locating the wells include the amount of free product at the proposed location and accessibility. If the optimal well locations are in areas having small amounts of recoverable free product, then it may instead be advantageous to place additional wells in the areas where free product can be recovered at higher rates. Terrain and land use may limit accessibility to optimal locations. Proximity to fragile environments (*e.g.*, wetlands) or underground utilities may preclude siting of a recovery well(s) in the optimal location.

An example of the basic analysis used to determine the number of wells and the total pumping rate is presented in Exhibit V-7. In this example, the Theim Equation is used to compute drawdowns at the pumping well. This equation does not consider the combined drawdown of several wells: The water levels within the overlapping cones-of-depression would be lower as a result of well interference. If several wells are determined to be necessary, the number determined using the Theim Equation should be considered as the minimum; however, because of well interference and increased drawdown, the pumping rates will need to be reduced somewhat to minimize smearing.

Exhibit V-7

Procedure To Determine Number Of Wells
And Total Pumping Rate Using Water Table Depression

Setting: Free product plume is 100 feet wide in an aquifer 25 feet thick with a hydraulic conductivity of 5 feet per day and a hydraulic gradient of 0.006 feet per foot.

Step 1: Determine groundwater flow through the plume using Darcy's Law.

$$Q_{gw} = W \cdot B \cdot K \frac{\Delta h}{\Delta L}$$

where:

W = width of the plume

B = saturated thickness of the aquifer

K = average hydraulic conductivity

$\frac{\Delta h}{\Delta L}$ = hydraulic gradient (the difference in groundwater elevation between two points in the direction of flow, divided by the distance between those two points)

Q_{gw} = 100 ft x 25 ft x 5 ft/day x 0.006 ft/ft

= 75 ft^3/day = 0.39 gallons per minute

Step 2: Set the design total pumping rate at Q_{gw} + 100% Q_{gw} = 150 ft^3/day.

Step 3: Determine the maximum pumping rate for single well without interference using Theim Equation.

$$Q_{max} = \frac{S_{max}\left(2p\ \ B\ K\right)}{\ln\left(W / r_W\right)}$$

where:

the radius of influence is assumed to be the width of the plume (W)

r_w = the well radius

S_{max} = maximum allowable drawdown to minimize smearing (assume 1 ft)

$$Q_{max} = \frac{1\ ft\ \left(2 \times 3.14 \times 25\ ft \times 5\ ft / day\right)}{\ln\left(100\ ft / 0.166\ ft\right)} = 123\ ft^3 / day$$

For a desired maximum drawdown next to the well, the maximum pumping rate is about 123 ft^3/day, which is less than the total pumping rate of 150 ft^3/day. Two pumping wells should be used at this site.

Modeling Analysis. The most reasons cited for not using models to aid in the design of free product recovery systems are complexity of use and cost. However, for large free product plumes and serious contamination problems, the cost of the modeling study may more than pay for itself if the result is a more efficient and cost-effective remedial design than would have otherwise been possible. Because of their speed and flexibility, many models can be used to quickly examine different remedial designs without the time and expense associated with extensive field testing. For example, different well locations can be tested, wells can be added or eliminated, and pumping rates and schedules can be adjusted to achieve an optimal design. Three types of models are available:

- Analytical models of capture analysis based on groundwater flow.
- Numerical (finite-difference or finite-element) models for groundwater flow and capture analysis.
- Numerical models of multiphase flow.

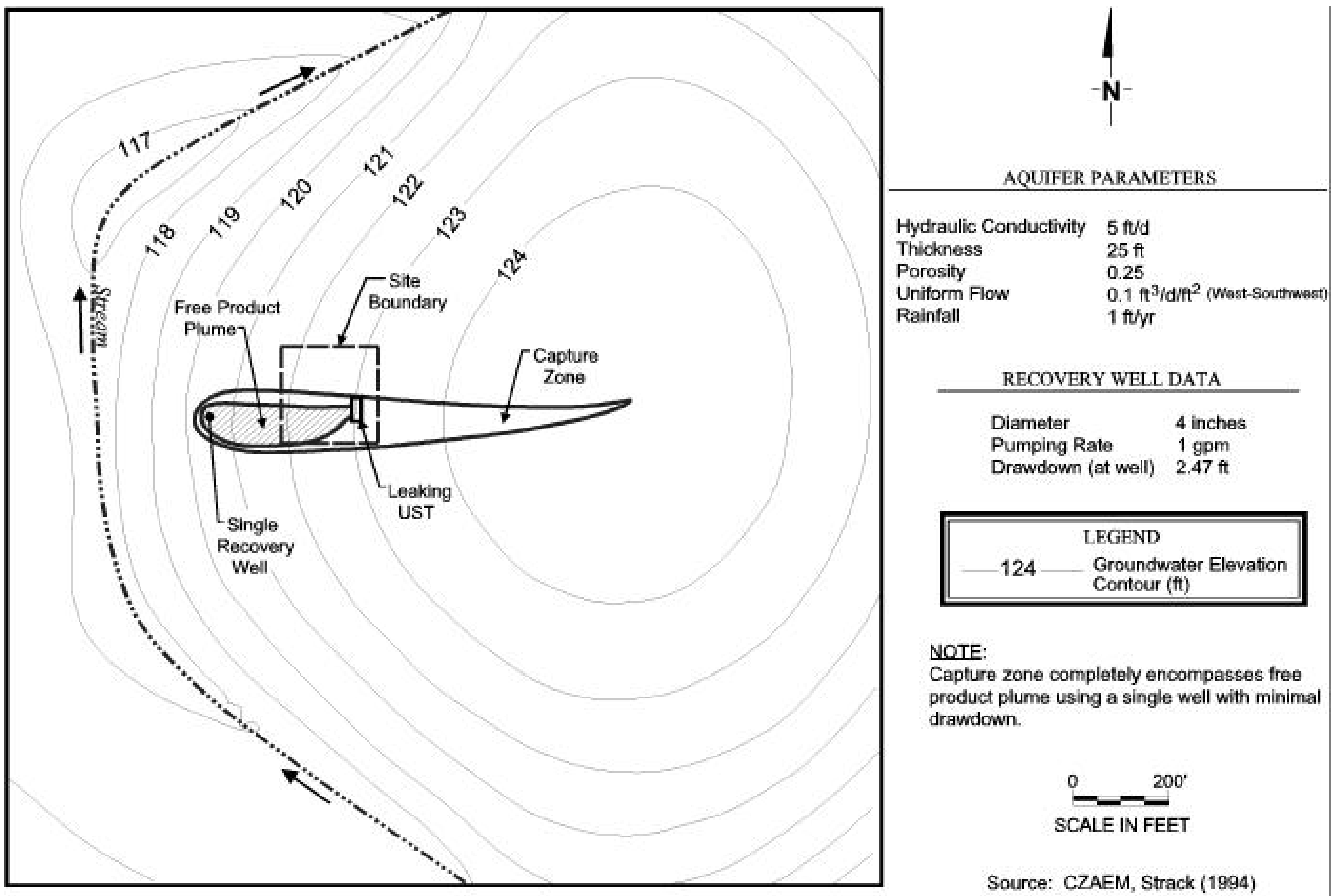
Analytical groundwater models of capture analysis provide for detailed evaluation of a recovery system design without the expense and complexity of the numerical modeling approach. Analytical methods such as those developed by Strack (1994) may be applied for capture analysis and optimal well and drain placement at smaller sites. The objective is to create a capture zone that completely encompasses the free product plume. An example of such an application is illustrated in Exhibit V-8.

Numerical groundwater flow models may also be used to perform a capture analysis for a recovery system. The USGS model MODFLOW (McDonald and Harbaugh, 1984) is one such model that is frequently applied. A numerical groundwater flow model can simulate three-dimensional flow conditions and heterogeneous conditions that cannot be simulated by the analytical models.

Multiphase flow models are capable of simulating the flow of free product as well as groundwater. Ideally, they can predict free product recovery rates and show how the free product plume will evolve over time. The complex models are rarely used in the design of free product recovery systems because they are expensive to run, and they require specialized modeling expertise and data that are generally not available or easily collected at UST sites. However, at sites with large spills or large volumes of free product in the subsurface, multiphase flow models may be useful design tools.

Exhibit V-8

Sample Capture Zone Analysis



Discharge Of Treated Groundwater

Free product recovery using groundwater depression can generate large quantities of co-produced groundwater. Discharge of water is a necessary element of the free product recovery design. Two options for the disposal of recovered groundwater include:

- Surface water or POTW discharge
- Recharge to water-bearing geologic formation

Because of the cost of treating contaminated groundwater, discharging it to a publicly owned treatment works (POTW) is preferred (provided the state regulations allow for it and the facility will accept discharges and has the hydraulic capacity). Some pretreatment, such as phase separation, may be required before discharging to the sanitary sewer. Surface water discharges usually require a National Pollutant Discharge Elimination System (NPDES) permit and, thus, have greater treatment demands and costs. Recharge to the aquifer must be considered carefully, as it may directly affect contaminant capture. If water is recharged within the free product plume, it may negate the hydraulic containment provided by pumping. Water recharged to the aquifer outside of the free product plume may alter the migration of the dissolved product plume. Reinjection or recharge may be evaluated using the same methods used for capture analysis.

Equipment

A variety of pumps in one or two configurations will provide water table depression. The types of pumps include diaphragm, centrifugal, submersible, pneumatic, and vacuum. All pumps should be rated for operation in a hydrocarbon environment. The applicability and advantages of the various pump configurations are summarized in Exhibit V-9. There are two common configurations of pumps:

- Single-pump systems or total fluids systems which simultaneously collect both free product and groundwater in each installation.

- Two-pump or dual-pump systems consist of one pump which recovers only free product while another pump extracts groundwater and provides the desired level of drawdown.

Exhibit V-9

Applicability Of Water Table Depression Equipment

	Recommended Minimum Well Diameter	Recommended Minimum Value for K (cm/s)	Relative Capital Costs	Relative Operating Costs	Relative Maintenance Costs	Potential For Product Removal	Product Recovery Rate	Advantages	Disadvantages
Single-Pump Systems									
Diaphragm Pump	2"	$> 10^{-4}$	L	L	L	L	L-M	Low cost; low maintenance surface mounted pumps; easy to maintain low flows	Pumps water and product; requires O/W separator; limited to shallow (less than 20 ft.) applications
Centrifugal Pump	2"	$> 5 \times 10^{-3}$	L	L	L	L	L-M	Low cost and maintenance	Level sensor and O/W separator required
Submersible Pump	4"	$> 10^{-2}$	M	M	L	L	L-M	No depth limitation; ease of installation; removes product and water; creates capture zone	Flow usually greater than 5 gpm; requires O/W separator and water treatment; emulsification of product in water
Pneumatic								Operates over wide range of flow rates; will pump from deep, low permeability aquifers	Requires air compressor system and water treatment; recovered fluids are emulsified
Top Filling	4"	$> 10^{-3}$	M	M	M	M	L-M		
Product Only	4"	$> 10^{-4}$	M	M	M	M	L-M		
Two-Pump Systems									
GWP and PP (separate product and level sensors)	4"	$> 10^{-2}$	H	H	H	H	L-H	Can be set to skim product with little smearing	Proper adjustment can be time-consuming
GWP (steady operation) with PP (with product sensor)	6"	$> 10^{-2}$	H	H	M	H	L-H	Can create large cone-of-depression to expedite recovery	Somewhat larger recovery well required; may require O/W separation
GWP (steady operation) with PP (floating, skimming type)	6"	$> 10^{-3}$	H	H	M	H	L-H	Can create large cone-of-depression to expedite recovery; can skim product	Somewhat larger recovery well required

K - Hydraulic Conductivity; L - Low; M - Moderate; H - High; GWP - Groundwater Pump; PP - Product Pump; O/W - Oil/Water

Single-Pump Recovery Systems. Single-pump systems produce both water and hydrocarbons. Depending on the depth to water, the pump may be surface mounted and operated by a suction lift, or it may be submersible. Single-pump systems are most applicable in settings where the soil has low to moderate permeability. The systems are simple to install and consist of a drop tube, the suction lift or submersible pump, a liquid level sensor, and an above ground phase separation unit. A single pneumatic, submersible pump system is shown in Exhibit V-10.

Single pumps may operate well below 5 gpm (as low as 0.1 gpm) to as high as 20 gpm. The pumps usually operate on an intermittent cycle actuated by a liquid level sensor. All pump types have a tendency to emulsify liquid hydrocarbons in water thus increasing the dissolved concentration in the produced groundwater. As a result, above ground separation and perhaps other levels of treatment are necessary components of these systems.

Two-Pump Recovery Systems. The objectives of two-pump recovery systems are to optimize the cone-of-depression to achieve maximum product recovery while minimizing smearing and prevent mixing of free product with water which would then require separation. Three basic configurations of two-pump systems are summarized in Exhibit V-9. All of these systems employ one pump that produces groundwater to create the cone-of-depression and a second pump to collect free product. Groundwater pumping rates can be adjusted to some degree to control the depth of drawdown. This is accomplished by either intermittantly operating the groundwater depression pump, or regulating its pumping rate. Free product recovery is controlled by either a floating skimmer or a hydrocarbon detection probe which activates the pump when there is a sufficient accumulation of free product. By carefully balancing the pumping rates for groundwater and free product, emulsification of oil can be minimized or eliminated, which negates the need for oil/water separation. A dual-pump system that employs a hydrocarbon detection probe is depicted in Exhibit V-11.

System Startup

Initial start-up of pumping systems involves the following steps:

! Optimize hydraulic control of plume and fluid levels in the system wells.

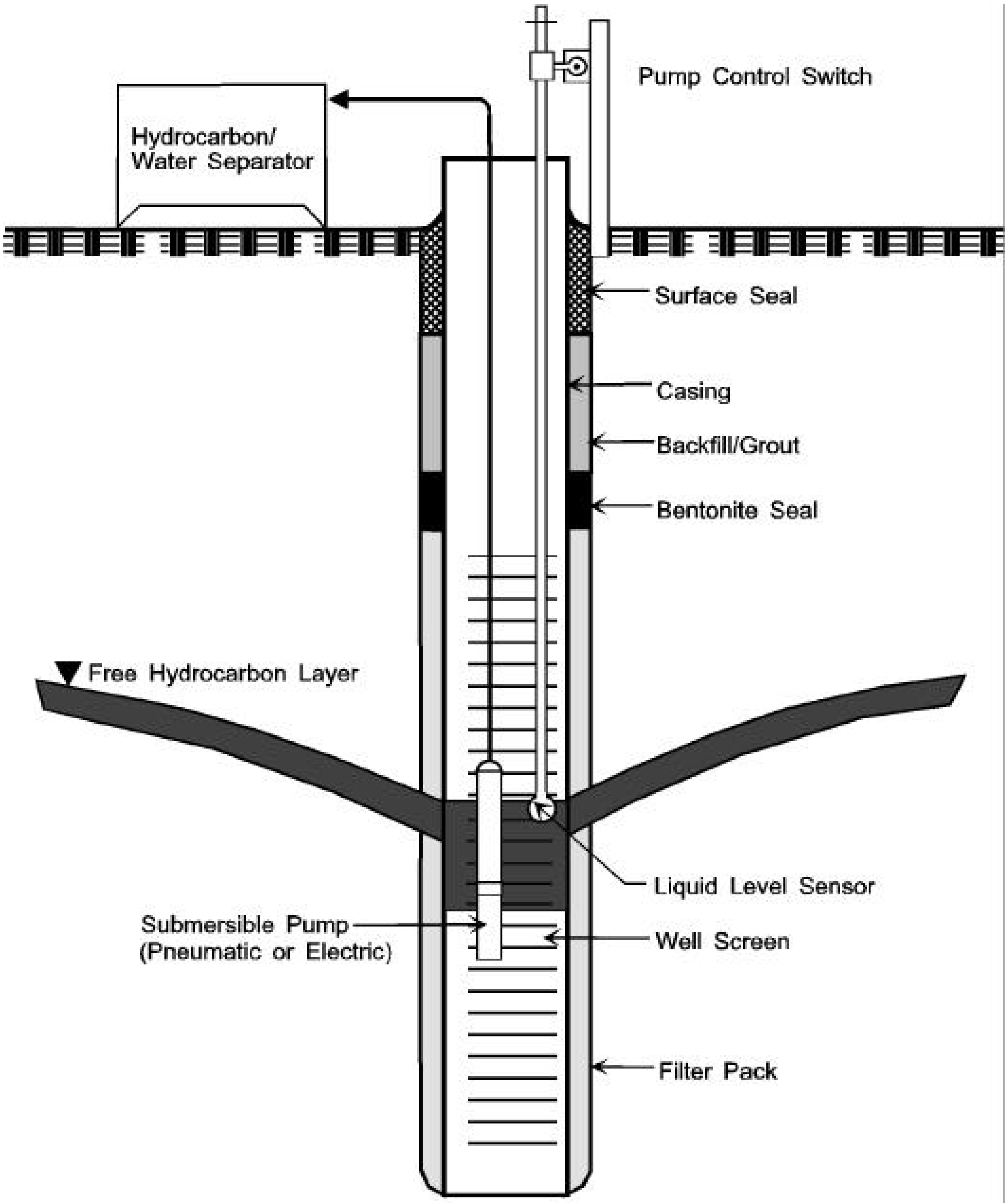
! Calibrate the characteristic drawdown of each well. A flowrate versus drawdown plot will assist in evaluating the effect on other wells.

! Determine the operational rate of the pump; select a rate that will minimize drawdown and provide control of plume movement.

! Determine a flow rate for each pump that stabilizes the fluid levels and maintains sufficient liquid hydrocarbon/water separation.

Exhibit V-10

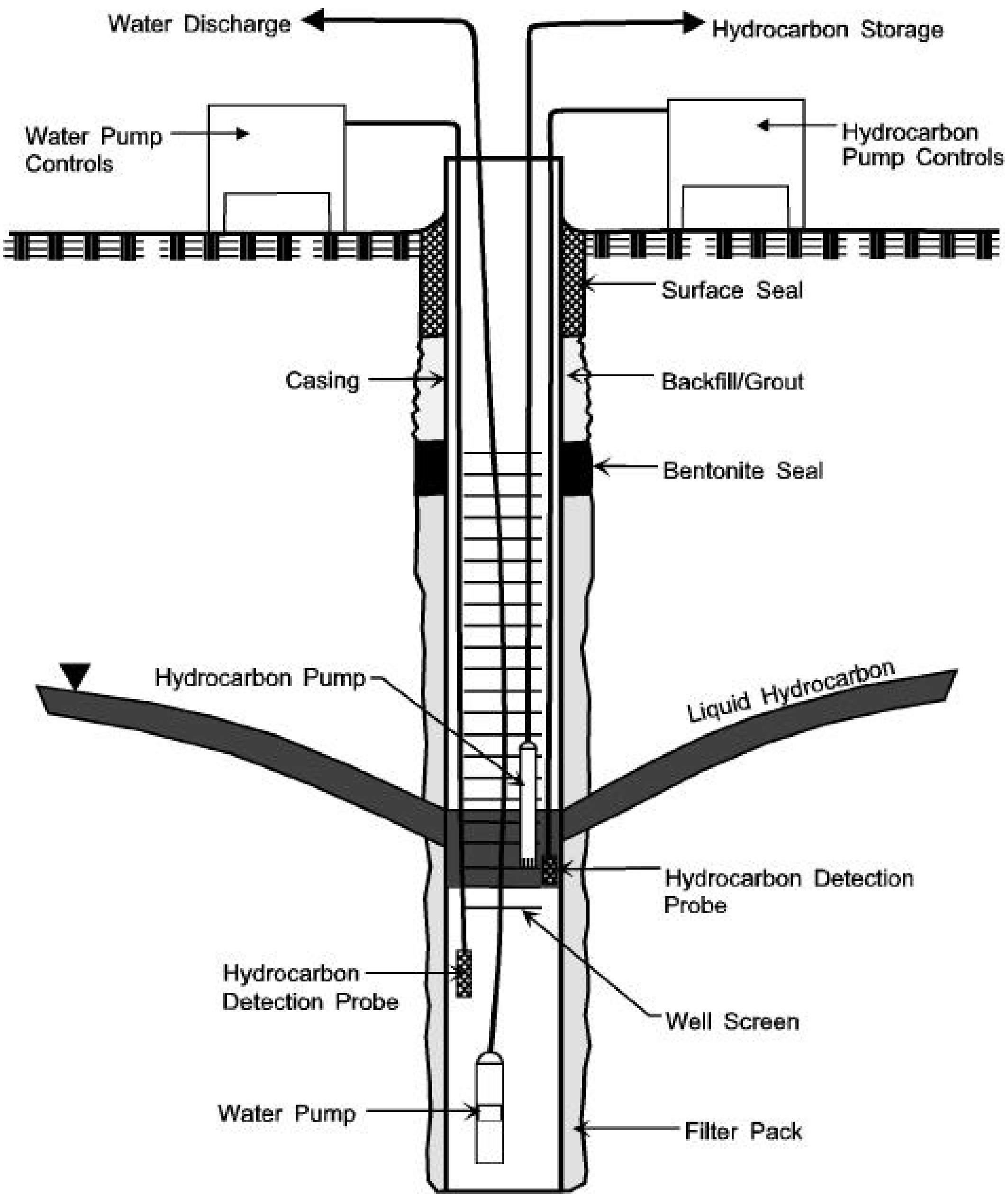
Single-Pump System For Free Product Recovery
And Water Table Depression



Source: API, 1996. A Guide to the Assessment and Remediation of Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted courtesy of the American Petroleum Institute.

Exhibit V-11

Two-Pump System For Free Product Recovery
And Water Table Depression



Source: API, 1996. A Guide to the Assessment and Remediation of Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted courtesy of the American Petroleum Institute.

- Adjust pump rates to meet fluid level and plume containment goals. Set sumps at elevations appropriate for expected drawdowns.

The initial setup, operation, and maintenance are more difficult and time-consuming for two-pump systems. Permits for well installation, discharge, reinjection, and treatment system operation should be secured prior to start-up and full operation of a pumping system.

Operation And Maintenance

Normal O&M activities begin after startup and include:

- Measure groundwater elevations and product thicknesses in monitoring wells within the plume.
- Calculate amount of free product and water recovered at each well in the pumping network and sample emulsified fluids for total petroleum hydrocarbons (TPH).
- Determine the volume of water that separates from the recovered product (or the water to oil ratio).
- Measure influent and effluent concentrations of dissolved hydrocarbons to and from the treatment system, respectively.
- Inspect all electrical and mechanical components of the recovery and treatment system.
- Perform maintenance and repair of equipment and wells when necessary.

Usually these activities are performed once every 2 weeks. Most states require reporting on a quarterly basis.

Termination Criteria/Monitoring

A free product pumping system using groundwater depression should be operated until it no longer produces significant volumes of hydrocarbons. Termination usually requires a total system product recovery at some specified rate (*e.g.*, less than 2 gallons per month or less than 0.02 percent ratio of hydrocarbon recovered to water pumped). In addition, product thicknesses less than a specified thickness at all wells in the monitoring and pumping network is a basis to terminate system operations. After the system is shut down, thicknesses should be monitored on a monthly or quarterly basis to ensure that wells do not contain hydrocarbons in significant amounts. Termination criteria should also consist of a specified period (*e.g.*, 2 years of quarterly monitoring) during which no exceedance of the threshold hydrocarbon thickness (*e.g.*, 0.1 foot) should occur. The threshold thickness should serve as an action level to restart the system if it is exceeded.

Vapor Extraction/Groundwater Extraction

Vapor extraction/groundwater extraction (VE/GE or “veggie”) systems combine conventional water table depression techniques with soil vapor extraction. The systems are designed to expose the smear zone in the capillary fringe by groundwater pumping while simultaneously volatilizing the residual petroleum hydrocarbons in the smear/vadose zone with SVE. VE/GE systems are used after other free product recovery methods have removed as much mobile product as feasible. Then, and only then, is the water table drawn down to expose the smear zone. VE/GE systems have the following favorable characteristics:

- Recovery of a larger fraction of total hydrocarbons (*i.e.*, free product and vapor) over shorter time periods.
- Increased air flow and groundwater extraction rates.
- Recovery of some residual phase hydrocarbons.

These benefits are derived from the fact that volatilization (and biodegradation) is the primary removal mechanism as opposed to the draining and dissolution that results from conventional pumping systems (Peargin, 1995). SVE is ineffective on nonvolatile hydrocarbons, but the increased flow of oxygen may aid in the stimulation of biodegradation.

Applicability

VE/GE systems may be screened on the basis of aquifer hydraulic conductivity, but they are generally most applicable to:

- Fine-grained soil types.
- Aquifers with moderate to low permeabilities (10^{-3} to 10^{-5} cm/s).
- Aquifers with thicker capillary zones (up to several feet).
- Settings in which conventional pumping approaches are too costly or ineffective.

The applicability of VE/GE systems is summarized in Exhibit V-12.

General Design Considerations

Recovery wells in VE/GE systems require additional design considerations such as:

- Air-tight well caps with an additional connection for air extraction piping.
- Well screens extending further into the unsaturated zone for air extraction.
- Solid, impermeable annular seals to prevent air short-circuiting from the ground surface to the well screen.

VE/GE well locations may be determined by the same methods used for conventional pumping wells, provided hydraulic containment of the free product plume is desired.

Equipment

The equipment used in VE/GE systems is essentially the same as that involved in conventional pumping and SVE. Exhibit V-13 depicts a VE/GE system in a monitor well. Primary equipment includes:

- Surface mounted vacuum pumps or regenerative blowers for air/vapor extraction.
- Pneumatic or electric submersible pumps for groundwater extraction.
- Air extraction piping.
- Contingent vapor treatment equipment (*e.g.*, air/water separator, GAC).
- Other equipment such as instrumentation for measuring vacuum pressure and airflow rate.

Exhibit V-12

Applicability Of Vapor Extraction/Groundwater Extraction Equipment[1]

	Recommended Minimum Well Diameter	Recommended Minimum Value for K (cm/s)	Relative Capital Costs	Relative Operating Costs	Relative Maintenance Costs	Potential For Product Removal	Advantages	Disadvantages
Pneumatic or Electric Submersible Pump Augmented with Vacuum on Well	4"	$< 10^{-3}$	H	H	M	VH	Effective on low permeability aquifers; extracts product from thick capillary fringes; recovers or remediates some residual phase hydrocarbon	Large capital investment; requires vacuum pump or blower; longer initial setup times; usually requires vapor phase and water treatment

[1] See also Exhibit V-10, Single-Pump Systems

K - Hydraulic Conductivity; L - Low; M - Moderate; H - High; VH - Very High

System Setup

The initial setup of a VE/GE system involves the following procedures:

- After readily recovered free product is removed by pumping with minimum smearing, increase pumping rate to draw water table down and expose smear zone.

- Adjust vacuum and pumping rates in the field such that the recovery of free product is maximized while the recovery of total fluids requiring treatment is minimized.

- Optimize the product recovery while maintaining static fluid levels to avoid unnecessary additional drawdown.

- Determine the optimal placement of fluids pump in each well.

Setup times for VE/GE systems are significantly longer than conventional pumping approaches. Adjustment of vacuum pressures and airflow rates will also be necessary during periods of falling background water tables.

Operation And Maintenance

Normal O&M activities of VE/GE systems are equivalent to those of conventional pumping systems. In addition, the following activities are usually performed once every 2 weeks. Most states require quarterly reporting.

- Monitor the vacuum applied to each recovery well.

- Monitor the vacuum readings at sealed monitoring wells in the vadose zone.

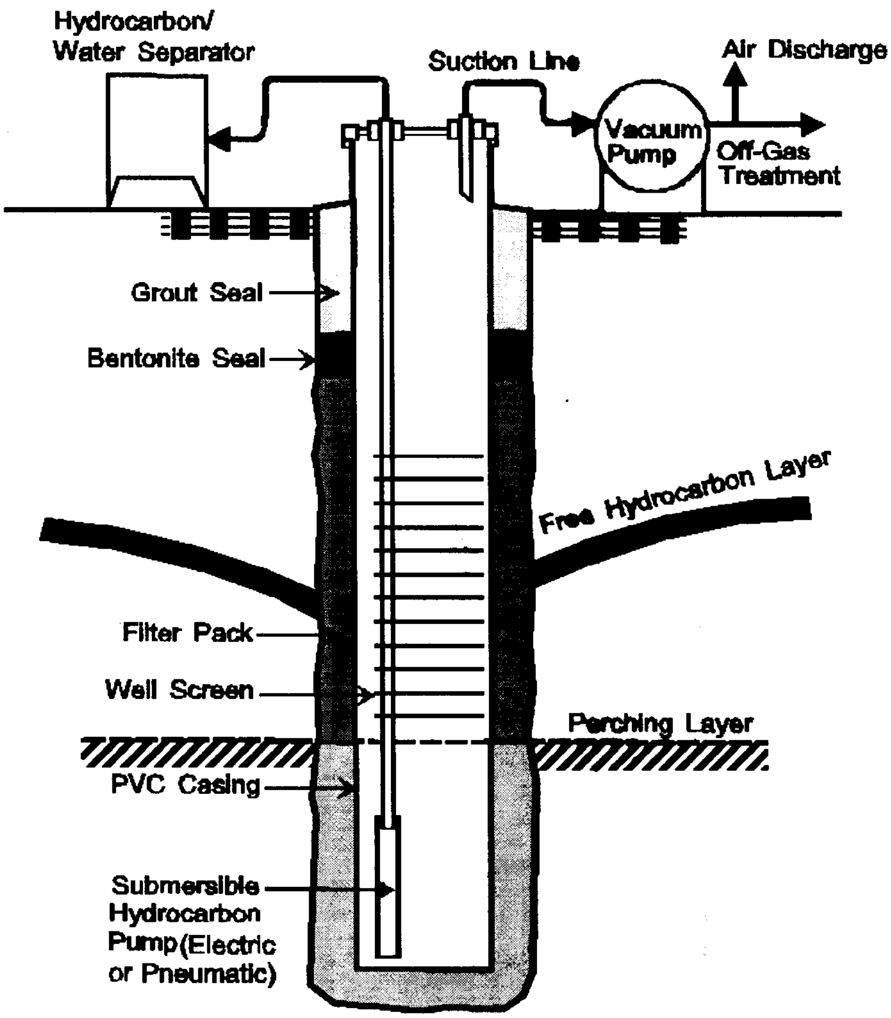
- Record the airflow rates, vacuum, and temperature readings at the vacuum pump and air/water separator (if present).

- Lubricate and maintain the vacuum pump and check all seals and connections for leaks.

- Determine the total volumes of recovered phases and calculate fraction of product recovered from extracted groundwater.

Exhibit V-13

Vapor Extraction/Groundwater Extraction (VE/GE) Recovery System



Separate Vacuum and Liquids Pump (VE/GE)

Source: API, 1996. A Guide to the Assessment and Remediation to Underground Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted Courtesy of the American Petroleum Institute.

Termination Criteria/Monitoring

A VE/GE may be operated until significant volumes of petroleum hydrocarbons are no longer recovered. Termination criteria are a total free product recovery of less than 2 gallons per month and a free product thickness of less than 0.01 foot at all recovery and monitoring wells. Product thicknesses in wells should be monitored on a monthly or quarterly basis. The free product recovery plan should specify an acceptable time frame (*e.g.*, 2 years of quarterly monitoring) in which no exceedance of the threshold thickness value (*e.g.* 0.1 foot) should occur. The system should be restarted if the threshold thickness value is exceeded within the specified time frame.

Dual-Phase Recovery

The approach of dual-phase recovery is to extract free product, vapor, and groundwater by vacuum enhanced pumping techniques. In contrast to VE/GE systems, dual-phase systems have a single well point that accomplishes dewatering while also facilitating vapor-based unsaturated zone cleanup (Baker and Bierschenk, 1995). This approach has several benefits relative to other free product recovery methods:

- A cone of depression is not formed at the air/oil interface or the air/water interface.
- Smearing of the free product zone is minimized.
- Aquifer transmissivity near the well is maintained because of the vacuum enhancement even when the water level is drawn down.
- Vapor-phase hydrocarbons and mobile free product are collected simultaneously.

There are two main conceptual approaches to dual-phase recovery, although they differ only in the vertical positioning of the pump intake (Exhibit V-14).

- Recovery of free product and water by a single vacuum/liquids pump.
- Extraction of free product, air, and water with a single pump and a vacuum extraction point set at the air/product interface. This technology is commonly referred to as “bioslurping” (Kittel *et al.,* 1994).

Dual-phase recovery systems may be designed to obtain hydraulic control of the free product plume, depending on the amount of groundwater removed and/or the number and placement of well points.

Applicability

As shown in Exhibit V-15, dual-phase recovery systems are most applicable to:

- Medium to low permeable media ($\leq 10^{-3}$ cm/s) or thin (less than 0.5 foot) saturated thicknesses.
- Water table depths of 5 to 20 feet (deeper for some designs).
- Settings in which conventional pumping approaches or trenches are inappropriate or ineffective (API, 1996).
- Free product plumes located under paved or sealed surfaces.

Equipment

The equipment used in dual-phase recovery systems includes:

- Surface-mounted vacuum pumps for air, water, and product extraction.
- Vapor and liquid treatment equipment (*e.g.*, phase separators, granular activated carbon [GAC])
- Other equipment such as manifolds, suction lines, and drop tubes.
- Gauges and other instrumentation for measuring vacuum pressures and airflow rates.

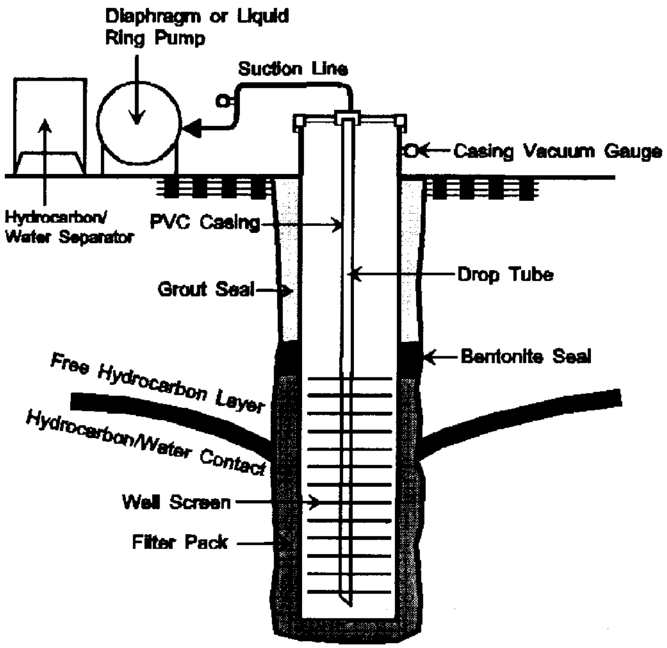
System Setup

The initial setup of a dual-phase recovery system involves the following procedures:

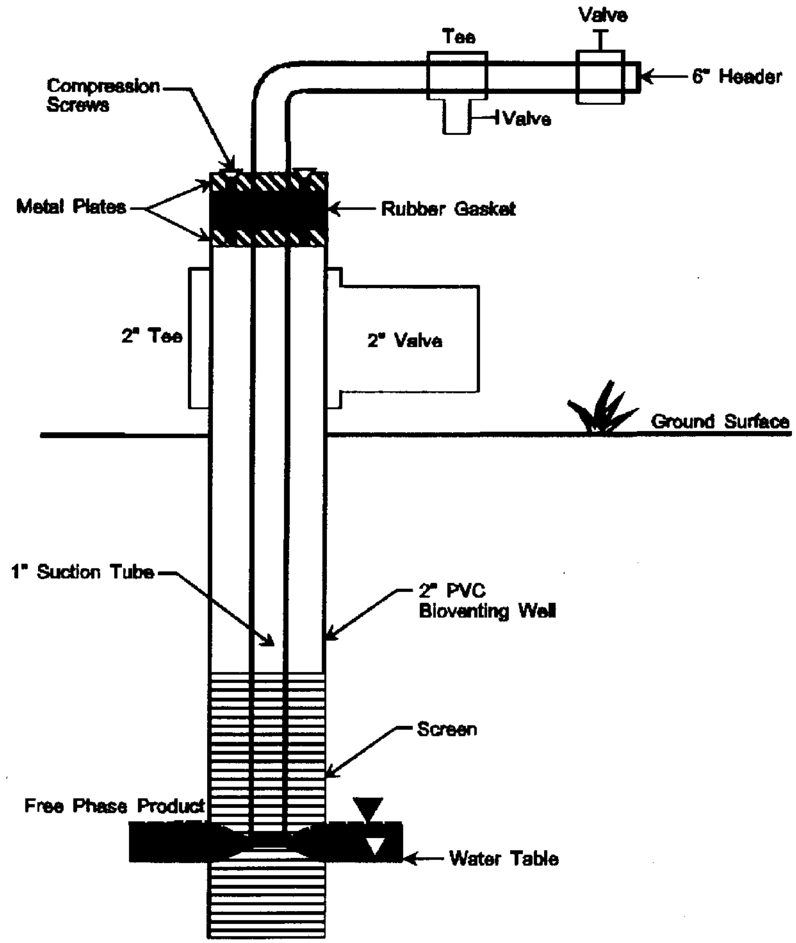
- Place wells sufficiently close to achieve measurable pressure drops (*e.g.*, 0.1 psi) at one-half the distance between adjacent wells.
- Set well screen intervals at a minimum of 5 feet above and 2 feet below the water table.

Exhibit V-14

Dual-Phase Extraction Recovery Systems



(A) Single Vacuum/Liquids Pump



(B) Bioslurping

Source: API, 1996. A Guide to the Assessment and Remediation to Underground Petroleum Releases, 3rd edition. API Publication 1628, Washington, DC. Reprinted Courtesy of the American Petroleum Institute.

Source: Kittel, et al., 1994

- Place vacuum extraction points at an elevation just above the air/product interface.

- Adjust vacuum and pumping rates in the field such that the recovery of free product is maximized while minimizing the total fluid requiring treatment.

- Optimize and control the vacuum applied to each well point.

- Seal recovery and monitoring well systems.

Setup times are significantly longer than other recovery alternatives. Adjustments may be necessary to maintain product/water suction for periods when background water tables are falling.

Operation And Maintenance

Normal O&M activities of dual-phase recovery systems include the following activities:

- Visually inspect clear tubes for the production of water and product.

- Monitor the total system vacuum.

- Frequently monitor the vacuum applied at each well point.

- Adjust the gate valves on lines at well heads (balance system).

- Operate the vacuum pump properly.

- Take vacuum and temperature readings at the vacuum pump and air/water separator.

- Record airflow rates.

- Lubricate vacuum pump.

- Check all seals and connections (for leaks).

- Monitor vacuum readings at sealed monitoring wells in the vadose zone.

- Determine the total volumes of product, water, and air produced as well as the fraction of product recovered from extracted air.

Exhibit V-15

Applicability Of Dual-Phase Recovery Equipment

	Recommended Minimum Well Diameter	Recommended Minimum Value for K (cm/s)	Relative Capital Costs	Relative Operating Costs	Relative Maintenance Costs	Potential For Product Removal	Advantages	Disadvantages
Single Vacuum Pump	2"	> 10^{-5}	M	H	M	VH	Effective for medium to low permeability soils; potentially large radius of influence; increases water and product flow by 3 to 10 times while minimizing drawdown; no reduction of transmissivity at the well; extracts product (liquid and vapor) from capillary fringe; significantly reduces remediation time	Large capital investment; requires high vacuum pump or blower; generally limited to applications of less than 20 ft.; requires phase separation and treatment; longer initial startup and adjustment periods
Bioslurping	2"	> 10^{-5}	H	H	M	VH		

K - Hydraulic Conductivity; L - Low; M - Moderate; H - High; VH - Very High

Termination Criteria/Monitoring

Operation of a dual-phase recovery system is complete when it ceases to produce significant volumes of hydrocarbons. Termination criteria may include total free product recovery rates (*e.g.*, less than 2 gallons per month or ratio of hydrocarbons recovered to groundwater pumped of 0.1 percent) and free product thickness in monitoring or extraction wells (*e.g.*, less than 0.01 foot). Thicknesses should be monitored on a monthly or quarterly basis to ensure that wells do not contain hydrocarbons. A time period should be specified in which no exceedance of a threshold hydrocarbon thickness (0.1 foot) should occur (*e.g.*, 2 years of quarterly monitoring). The threshold thickness may also serve as an action level to restart the system if it is exceeded.

A summary of the advantages and limitations of free product recovery systems is provided in Exhibit V-16.

Exhibit V-16

Summary of Advantages and Limitations of Free Product Recovery Systems

SKIMMING

	Advantages	Limitations
Floating/Floating Inlet	• Removes product to a sheen • Minimizes water recovery • Requires minimal adjustment since unit moves with fluctuating water table • Capable of recovery of up to 5 gpm	• Membranes and screens are prone to clogging and failure and require cleaning • Large-diameter units perform better than small-diameter versions • Limited radius of influence
Direct Pumping of Product Layer	• High recovery rates (>5gpm) are possible	• Removal of product to a sheen requires pumping of some water • Requires a minimum product thickness of 1 - 4 inches (~0.08 - 0.30 ft) • Frequent adjustment of pump intake required
Absorbent	• No water produced • Skims product to a thin layer (0.01 ft) • Low cost and simple operation and maintenance	• Low recovery rates and limited influence • Frequent media replacement/ change-out required • Requires manual adjustment

WATER TABLE DEPRESSION

	Advantages	Limitations
	• Capture zone is created which enables hydraulic control of groundwater and product • Product recovery rates are enhanced by water table depression, especially in high permeability formations • Recovered groundwater can be oxygenated and reinjected for bioremediation	• Recovered fluids usually require treatment • Lower permeability formations can require numerous well points • Product can be “smeared” across area of depression resulting in greater formation storage • Higher permeability formations may require high pumping rates • Well network design requires capture zone analysis

Exhibit V-16

Summary of Advantages and Limitations
of Free Product Recovery Systems
(continued)

	Advantages	Limitations
VE/GE	• Increases free product recovery rates in low permeability settings • Recovers product from thick capillary fringes • Decreased residual phase formation or "smearing" • May be used to recover or remediate residual phase hydrocarbons	• Initial startup times are longer than other, conventional methods • Phase separation is required • Water and vapor treatment is typically required • Higher capital costs
DUAL PHASE RECOVERY	• Effective for lower permeability formations • High vacuum increases groundwater and product recovery • Minimizes drawdown and "smearing" of product • Expedites site cleanup by recovering all hydrocarbon phases	• Usually requires vapor and groundwater treatment • Phase separation is required • Longer initial startup time • Higher capital costs

Primary References

API, 1989. *A Guide to the Assessment and Remediation of Underground Petroleum Releases*, Second Edition, API Publication 1628, Washington, D.C.

Baker, R.S., and J. Bierschenk, 1995. Vacuum-enhanced recovery of water and NAPL: Concept and field test, *Journal of Soil Contamination*, 4(1):57-76.

EPA, 1992. Filter canisters: A new method for recovering free product, EPA-510-8-92-002, Office of Solid Waste and Emergency Response, Washington, D.C.

EPA, 1995. *How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers*,EPA 510-B-95-007, Office of Underground Storage Tanks, Washinton, D.C.

Kittel, J.A., R.E. Hinchee, R. Hoeppel, and R. Miller, 1994. Bioslurping - vacuum enhanced free product recovery coupled with bioventing: A case study, *Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Remediation*, 1994 NGWA Conference Proceedings, Houston, TX.

Peargin, T., 1995. Vacuum-enhanced recovery: theory, *Underground Tank Technology Update*, 9(4):2-7.