CHAPTER 5

DESIGN OF FULL-SCALE MPE SYSTEMS

5-1. Introduction.

a. As with conventional SVE systems, the main objective in designing an MPE system is to achieve the greatest removal of contaminant mass in the most efficient and timely manner. To accomplish this objective, the design team must understand the nature of the contamination (e.g., composition and physical and chemical characteristics) and the soil characteristics (e.g., permeability and water table elevation). A good understanding of the site allows the designer to determine the rate-limiting step(s) for contaminant removal and thus the areas in which to focus the design effort. Collection of the data necessary to make these determinations is described in Chapter 3.

b. The process of designing an MPE system is similar to that of an SVE system. The subsurface design is based on pilot test results (always required) and the extrapolation of these results to air and liquid flows in the entire treatment zone. Pilot testing is crucial to proper design and the pilot test can function as the first phase of construction at the site. Long-term operation of the pilot testing system may give useful information for the design of additional parts of the system. Subsurface design consists of establishing a network of wells, their screened intervals and construction details, and appropriate subsurface monitoring locations.

c. The aboveground design is based on the flow rates associated with the subsurface design. Aboveground equipment design generally begins with development of a process flow diagram (PFD) identifying mass flows, selection of major equipment, development of system operation and control philosophy, and preparation of a preliminary piping and instrumentation diagram (P&ID) and site layout.

d. A complete MPE system design includes, at a minimum:

- A site layout plan showing locations of MPE wells, monitoring points, aboveground equipment, and buried utilities.
- Specifications and design analysis.
- A PFD that describes the entire system, including material and energy balances, tanks, pumps, blowers, wells, conveyance piping, valves, flow rates, temperatures, pressures, and composition of each "stream."
- A P&ID identifying equipment and components that determine the operation of the system, system controls, interlocks, and automatic shutdown logic.
- A piping drawing displaying the locations of conveyance piping and construction details.
- Well construction drawings, including well head design.

- A system control logic diagram that can be used to design and build a system control panel.

- Requirements for a system enclosure and foundations for system components including storage tanks and treatment equipment.

- An operation, maintenance and monitoring plan.

e. The elements noted above form the basis for a conceptual design. Prior to completion, more detail will be required and the design will need to proceed through a series of reviews and iterations.

5-2. MPE Design Strategy.

a. General Considerations.

(1) A typical MPE system is somewhat similar to an SVE system. A typical MPE system consists of extraction wells, conveyance piping from each well to a vacuum pump, gas/liquid separator, NAPL/water separator, transfer pump, controls, and gas and/or water treatment equipment. The piping to wells may be in trenches or aboveground in regions where there is little potential of frost. In colder regions, piping should only be installed aboveground if heat tape and insulation are applied for freeze protection. An additional requirement for aboveground installation is adequate site security. Figures 5-1 and 5-2 show examples of P&IDs describing TPE and DPE systems, respectively.

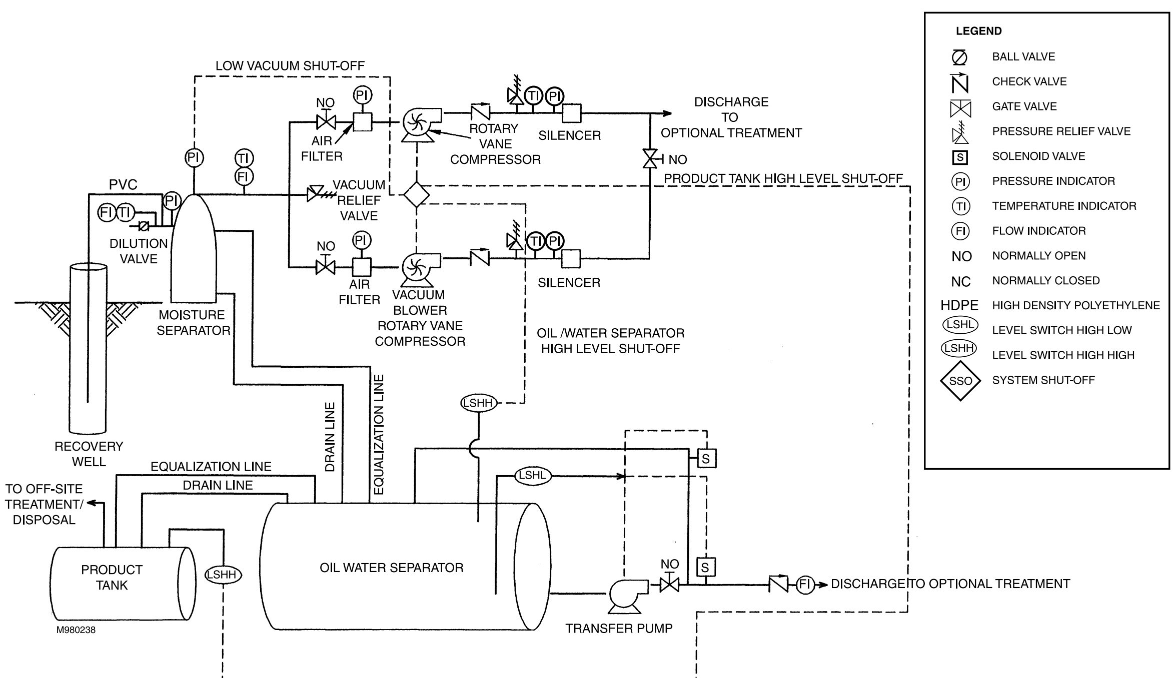

Figure 5-1. Piping and Instrumentation Diagram of Two-Phase Extraction System.

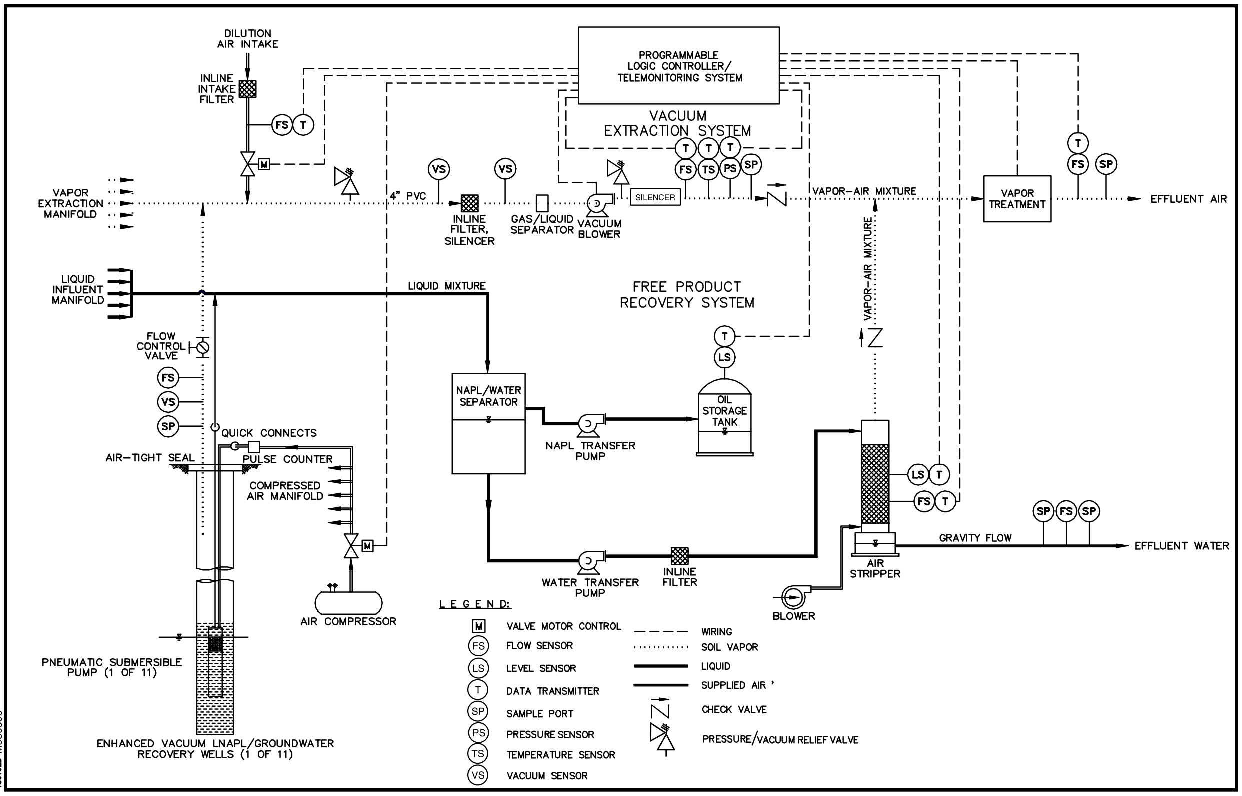

Figure 5-2. Piping and Instrumentation Diagram of a Dual-Phase Extraction System.

(2) To do a thorough and proper job of designing an effective full-scale MPE system, a comprehensive multi-disciplinary design team must first be assembled. This design team may include:

- Environmental/chemical/mechanical engineer.
- Electrical engineer.
- Geologist/geotechnical engineer/hydrogeologist.
- Chemist/geochemist.
- Cost engineer.
- Civil/structural engineer.
- Architect.
- Soil scientist/soil physicist.

- Regulatory specialist.

- Health and safety specialist.

(3) Interaction among these disciplines is critical for appropriate design development. As with other in-situ remediation approaches, it is very important that designers of above-ground components and subsurface components work together throughout the design process. Similarly, a proper design must incorporate sufficient above-ground and subsurface monitoring components to provide the feedback necessary to modify system operating parameters during normal operation and maintenance.

b. Remedial Objectives. The ultimate objective of an MPE system is to achieve the remediation goals in a cost-effective and timely fashion. However, as discussed in paragraphs 2-2b and 3-8d to 3-8f, MPE can be implemented in a variety of ways, depending on whether the goal of remediation is to address soil, groundwater, or NAPL. For example, a remediation system that is intended to remove perched water, and then subsequently remove contaminant mass through SVE will require a different system design than a remediation system that is intended to remove LNAPL to a specified thickness.

c. Subsurface Strategy.

(1) Two main MPE approaches are MPE with drawdown (i.e., dewatering) and MPE without drawdown. As a basis for the design strategy for either of these approaches, the subsurface designers must:

(a) Understand subsurface flow characteristics of gas, water, and NAPL, potential preferential flow pathways, soil permeability, and NAPL physical characteristics.

(b) Develop a conceptual model for mass removal, that is, determine the treatment mechanisms and the extent to which the system is to remove mass via the gas phase, dissolved phase, as NAPL, and through biodegradation.

(c) Optional: use flow models to predict liquid and gas flow throughout the treatment area and from MPE wells to:

- Ensure adequate well coverage in the treatment area.

- Allow specification the sizes and capacities of pumps and above-ground treatment equipment.

(2) In many ways, MPE subsurface design is very similar to SVE subsurface design, as described in EM 1110-1-4001, Chapter 5. The most critical design parameter is permeability. This parameter governs the flow rates of gas and liquids to MPE wells and therefore determines the number of wells that will be required to achieve remedial goals, as well as the capacity required for above-ground components. Soil heterogeneity also affects the number and placement of wells to be used in an MPE system. The designer should try to anticipate locations of flow short-circuiting and minimize their impact by positioning well screen intervals away from these locations.

(3) Notable differences between MPE systems with and without drawdown include: changes in the gas and liquid pathways to the well as desaturation proceeds, and different requirements for aboveground water treatment and disposal.

(a) Initially, the screen interval that is exposed to unsaturated soil will be relatively small. As MPE desaturates the surrounding saturated soil, additional air pathways will open, some of which may be more permeable than the initial pathways. Airflow patterns and extraction rates will thus change over time, along with concomitant changes in water and NAPL pathways and flow rates. The subsurface designer may use well packers or multi-level or nested wells to attempt to control the depths from which extraction is occurring. Changing flow paths and rates will also affect above-ground design.

(b) Requirements for aboveground water treatment and disposal. An MPE system that does not draw down the surrounding water table may not extract significant volumes of water. Cost-effective options for managing and treating small quantities of water may entail containment and subsequent off-site disposal or batch treatment through activated carbon. MPE with drawdown will most likely require more elaborate and costly water treatment processes.

d. Pneumatic Considerations.

(1) Pneumatic considerations for MPE are very similar to those for SVE as described in EM 1110-1-4001, Chapter 5. The primary differences in these considerations arise from the need to extract multiple phases from the subsurface. When this is accomplished using DPE (i.e., separate pumping for liquid and air phase), the air-phase pneumatic considerations are the same as for SVE, though typically the applied vacuums are significantly higher in the former case. Pneumatic considerations for TPE are complicated by the presence of multiple phases within a single pipe from the extraction well to the air-liquid separator. As discussed in Chapter 2, the flow of liquid up the extraction tube within a TPE well takes several forms. Each of these forms will engender different vacuum/pressure losses. However, once the air-liquid stream arrives in the conveyance piping to the air-liquid separator, liquid in excess of entrained droplets generally flows along the bottom of the conveyance pipe, with minimal effect on the air flow. In most TPE applications, the liquid discharge is small compared to the air discharge, and liquid does not occupy a significant amount of the cross-sectional area of the pipe. Therefore, provided piping runs are relatively short, pneumatic considerations for MPE are not substantially different from those for SVE. If the liquid flow through the conveyance piping is expected to be significant (e.g., when TPE is applied in moderate to high permeability soil) then the pipe size should be increased accordingly (or DPE should be considered as a more appropriate alternative).

(2) One pneumatic consideration that is unique to TPE is the drop tube size. As described in Chapter 3, entrainment of liquid droplets in a gas stream and subsequent extraction from a well requires linear gas velocities in excess of 275 m/min. The designer should choose a design velocity of 500 m/min or greater. The drop tube diameter will depend upon this velocity and the extracted airflow rate achievable in a given well. A 2.5 cm (1-inch) drop tube will require at least 0.25 m^3/min gas flow to provide the requisite linear velocity up the drop tube.

5-3. <u>Design Guidance – Subsurface</u>. This section discusses the considerations necessary for appropriate extraction well and wellfield design. Different applications of MPE (e.g., MPE to enhance SVE vs. MPE to enhance free-product recovery (FPR)) have different goals and thus require different design approaches. However, all MPE applications have a common set of important design parameters. The common design parameters that will be developed during the subsurface design include:

- Applied vacuum – The designer must select a target vacuum to apply in the MPE wells that will best suit the remediation objectives. The desired applied vacuum and associated fluid extraction rates dictate the type and size of the aboveground vacuum generator.

- Fluid extraction rates – The designer must determine the desired and/or expected extraction rates of each fluid (gas, water, NAPL). For some applications, the designer sets the extraction rate as a design parameter (e.g., airflow rate to achieve a desired pore volume exchange rate [PVER]). In other circumstances, the design parameter for the extraction of one fluid will generate a collateral fluid stream that requires aboveground management. For example, by imposing a vacuum to enhance the recovery rate of NAPL, an extracted gas stream is generated that must be managed and treated above ground.

- Well spacing within a well field – The designer must determine a well field configuration that will achieve the extraction rate(s) necessary to meet the remediation objectives. Well spacing has substantial impact on the cost of the MPE system.

- Well screen placement – In all cases, the factors that affect selection of well screen length and depth include the depth to contamination and the thickness of the contaminated zone. The designer must also consider the effects that will arise (e.g., short-circuiting) from changes in permeability due to stratification of the soil within the contaminated zone.

Each of the different MPE applications has specific design criteria that are associated with the different goals of these applications. Development of these design criteria for each MPE application is described in the following sections.

a. MPE with Drawdown to Enhance SVE/Bioventing.

(1) For the case of MPE with drawdown (i.e., lowering of the water table), where the primary remediation objective is to remove mass by venting or bioventing, it is critical to reduce saturation in the soil within the treatment zone to allow gas to flow through it. This is accomplished by drawing down the water table in the conventional sense, i.e., by gravity drainage. Vacuum applied to the extraction well increases gravity drainage of liquid by increasing the groundwater flow rate to the well. However, the applied vacuum impedes liquid drainage by lowering the air pressure in the capillary zone and causing the groundwater to "upwell". The vacuum applied at the MPE well should be as high as required to achieve the groundwater flow rates necessary to reduce saturation in the surrounding soil, but not so high as to overwhelm the drawdown caused by groundwater depression. In addition, in medium- and fine-textured soils, it will be necessary to achieve a distribution of vacuums in the surrounding soil that is able of overcoming the capillary pressures exerted by the soil. That is, the MPE wellfield must propagate enough vacuum in the remediation area to drain soils that will often have moderate to high air-entry capillary pressures. Paragraphs 2-4a(3) and 3-4g(3)

discuss the relationship between capillary pressure and saturation. It is important for the designer to realize that, within the lower permeability range (i.e., 10^{-4} to 10^{-5} cm/s), it may be very difficult to achieve the requisite vacuum in the formation with a reasonable number of wells.

(2) An exception to this guideline is the case where there are conduits within the soil that have higher permeability and lower capillary pressures to overcome. The presence of such conduits may only be observable during pilot testing or through a substantial number of soil cores collected from the treatment area.

(3) Achievable MPE gas and liquid extraction rates are primarily a function of the permeability and the applied well vacuum. The effective intrinsic permeability of the soil will be governed by the nature of preferential flow paths encountered by a well. Baker and Groher (1998) reported that permeabilities obtained at the laboratory scale are typically two orders-of-magnitude less than at the field scale. This may be an indication of the importance of preferential flow paths at the field scale. It may also be explained by the fact that lab permeability tests measure the vertical hydraulic conductivity, while field measurements reflect a combination of vertical and horizontal hydraulic conductivity values. MPE design rates for air and liquid extraction are dependent on the objectives of the system. As described in paragraph 5-2c, the air and liquid flow rates will change during operation of the MPE system. It is necessary to design for the highest air extraction rate expected (extraction rate expected after pores are opened/desaturated). Similarly, it is necessary to design for the highest water flow rate expected, typically the water flow rate achieved at system startup. It may be beneficial to use modular rental treatment units that allow the flexibility to handle initially higher flow rates and concentrations.

(4) When applying MPE for dewatering and enhancing SVE, the designer, within the constraints of the permeability limitations, will set the groundwater extraction rate. The ratio of extracted air to water can be adjusted by changing the elevation of the drop tube. Throughout the implementation of an MPE system, the water table (actually the top of the capillary fringe) acts as a no-flow boundary for vacuum-enhanced SVE. It may be desirable to lower the water table slowly so that vacuum-enhanced SVE can be performed in a given stratum without “exposing” potentially higher permeability soil layers and thus promoting preferential flow through them. It is also desirable to minimize capital expense for water treatment equipment; therefore, it may be prudent to lower the water table slowly to integrate the water flow rate over time and maintain a more even flow rate. Ultimately, to lower the water table, the water extraction rate must exceed the “recharge” rate. In the saturated zone, this is the true recharge rate. Within the capillary fringe (which may be several meters thick), this will be a total of the rate at which water “wicks” upward from the water table plus the rate of infiltration.

(5) One method for selecting design vacuums, well spacings and fluid extraction rates is to use an MPE model (to select an appropriate model, see paragraph 5-4). Based on information available from site investigation and pilot test data, an MPE model can be used to:

1. Predict airflow rates and determine the maximum vacuum to be applied based upon the PVER that is desirable for the site, thus determining the required well spacing and blower type and size. Typical PVERs range from 300 to 1,000 exchanges per year. For this application of MPE (vacuum dewatering to enhance SVE), it is desirable to use a PVER of at least 1,000 to account for the lower air-filled porosity of the "dewatered" soil. The MPE model can be used to estimate the air

velocities around a well or within a well field. The vacuum applied to the well(s) must be sufficient to achieve air velocities of 0.001 cm/sec throughout the treatment area (Dom Diguilio, verbal communication 1998).

2. Estimate groundwater extraction rates necessary to expose the treatment zone. In effect, the model must predict the groundwater extraction rates necessary to dewater the treatment zone and maintain the new capillary fringe at the bottom of the treatment zone. These predicted extraction rates will encompass both the maximum extraction rates (typically encountered when initiating dewatering) and the "steady-state" extraction rates. These data can then be used to determine groundwater treatment system design.

3. Evaluate various well configurations to obtain the optimum number and location of vacuum-enhanced extraction wells.

4. Estimate the concentration and mass of contaminant to be removed from the subsurface over time in both liquid and gaseous form.

(6) If an MPE model is not readily available to the designer, then another method, based on approximate solutions of one-dimensional radial flow to the MPE well can be used to select a design vacuum, approximate well spacing, and groundwater extraction rates. In this method, the designer (with assistance from a hydrogeologist) should estimate these design parameters for a single well. This will entail:

1. Calculation of an air extraction rate that will achieve the desired PVER. This will allow the designer to determine the zone of influence for the extraction well (note that the equations presented are only valid for confined conditions). This extraction rate is discussed in detail in Engineer Manual 1110-1-4001, Soil Vapor Extraction and Bioventing, Chapter 5, Design of Full-Scale SVE and BV Systems. An equation that can be used to estimate the extraction rate from a single well is:

$$Q_v^* = \frac{\pi r^2 b\, n_a}{t_{xc}} \qquad [5\text{-}1]$$

where:

Q_v^* = volumetric flow rate at atmospheric pressure [L^3 T^{-1}]

r = radius of treatment zone [L]

b = vadose zone thickness [L]

n_a = air-filled porosity of the soil [L^3 L^{-3}]

t_{xc} = the time required for one pore volume exchange (1/PVER) [T]

2. Next the pressure distribution resulting from applying a vacuum to the extraction well must be estimated. For a given vacuum, the pressure (vacuum) distribution can be estimated using the pseudo-steady solution to the one-dimensional flow equation (described in detail in Engineer Manual 1110-1-4001, Chapter 2, subsection on Fundamentals of Vapor Flow in Porous Media).

$$P_2 - P_1 = \frac{Q_v\,\mu}{4\,\pi\,b\,k_a}(\ln\frac{r_2}{r_1}) \qquad [5\text{-}2]$$

where:

r_1 and r_2 = radial distances from the well [L]

P_1 and P_2 = the pressures at r_1 and r_2, respectively [$ML^{-2}\,T^{-2}$]

Q_v = volumetric flow rate estimated above [$L^3\,T^{-1}$]

μ = dynamic air viscosity, ~ 1.83×10^{-5} N·s/m^2 [$ML^{-1}\,T^{-1}$]

b = thickness of the zone of air flow [L]

k_a = air permeability [L^2]

Analyses based on the above equation assume a 100% efficient extraction well. Note that per EM 1110-1-4001, the Chapter 4 discussion on vent well efficiency, one should incorporate flow loss due to borehole smearing that is not accounted for in this equation. Figure 5-3 shows vacuum distributions estimated using this equation for three homogeneous, isotropic soils with intrinsic permeabilities of 10^{-8}, 10^{-9}, and 10^{-10} cm^2, bracketing the range of soil conditions suitable for MPE. Each vacuum distribution was developed assuming that P_1 observed directly adjacent to the well is equal to the vacuum applied to the well. A different applied vacuum is presented for each soil type in order to achieve vacuum greater than zero at the edge of the treatment zone (set at 5.5 m for each example). It is interesting to note, that Equation 5-2 estimates negative vacuums (i.e., positive pressure) beyond 0.7 m using the Q_v estimated using Equation 5-1, indicating that the soil is too impermeable to treat to 5.5 m, even applying a vacuum of 684 mm Hg. Caution should be taken when using these equations as they may produce negative vacuum values. Estimates of negative vacuum should be interpreted as zero vacuum. These estimates can be made iteratively to determine a consistent applied vacuum, air extraction rate and treatment zone radius. In this analysis, wellhead vacuum will be higher than the values used due to well efficiency.

3. Once the airflow rate, design vacuum, and treatment zone radius are estimated, the groundwater extraction rate necessary to dewater the treatment zone can be estimated using a Cooper and Jacob (1946) modification of the Theis solution to the well equation. This solution is presented in Equation 5-3.

$$h - h_o = \frac{2.3 Q_w}{4 \pi T} \log \frac{2.25 T\, t}{r^2\, S_y} \qquad [5\text{-}3]$$

where:

r = the radial distance to the well [L]

h_o - h = the drawdown at distance r from the well [L]

Q_w = extracted water flow rate [L3 T -1]

T = transmissivity of the saturated zone [$L^3 T^{-1}$] = *K* x *b*

K = hydraulic conductivity [L T -1]

t = pumping time [T]

S_y = specific yield of the saturated zone [-]

This modification of the Theis equation is only valid when the Boltzmann variable, u = (r2·Sy)/(4·T·t) is less than 0.01.

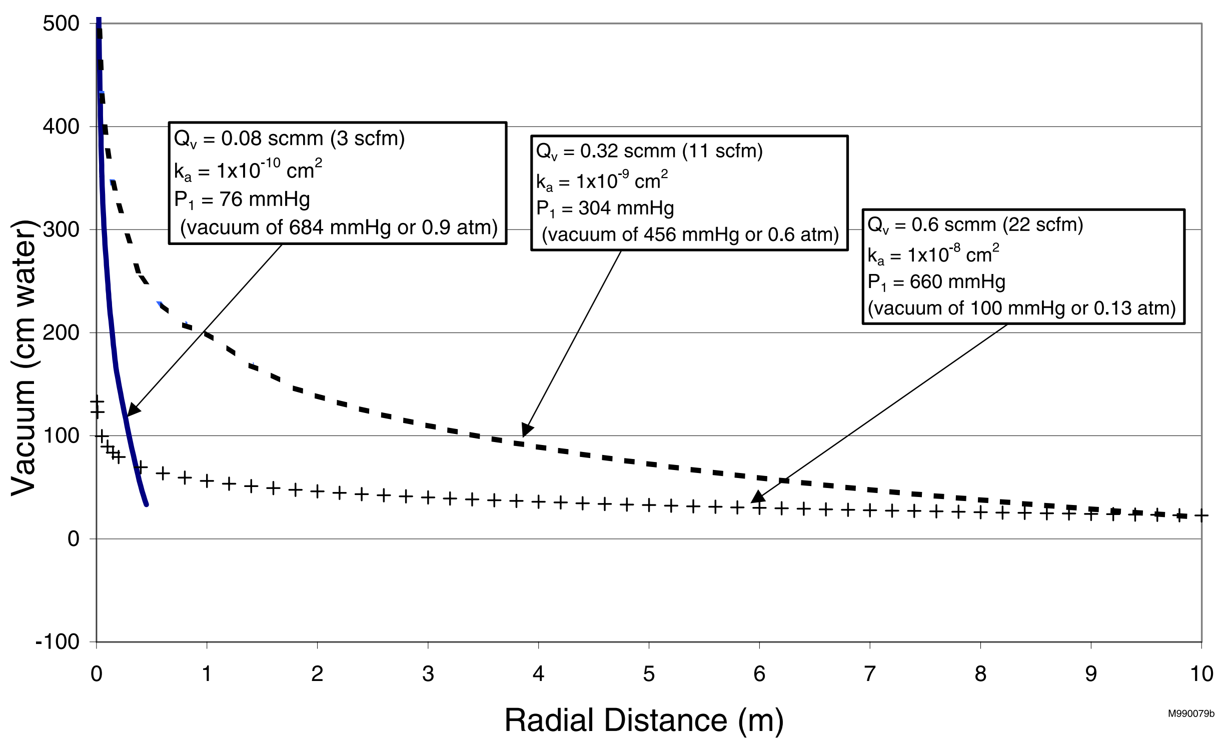

Figure 5-3. Example vacuum distribution curves using the pseudo steady-state solution to the 1-D flow equation.

Figure 5-4 shows typical drawdown curves estimated using this equation for the same three homogeneous, isotropic soils discussed above. The hydraulic conductivities of these soils are 10^{-3}, 10^{-4}, and 10^{-5} cm/sec, bracketing the range of soil conditions suitable for MPE. Each drawdown curve was developed for a given pumping time (35, 69, and 69 days, respectively). The saturated thickness, *b*, is 20 m and the specific yield, S_y, is 0.1 for each case. The curve for the low permeability, 10^{-5} cm/sec, soil appears somewhat different than the other two curves, indicating that 69 days is not sufficient to reach "steady state" in this soil.

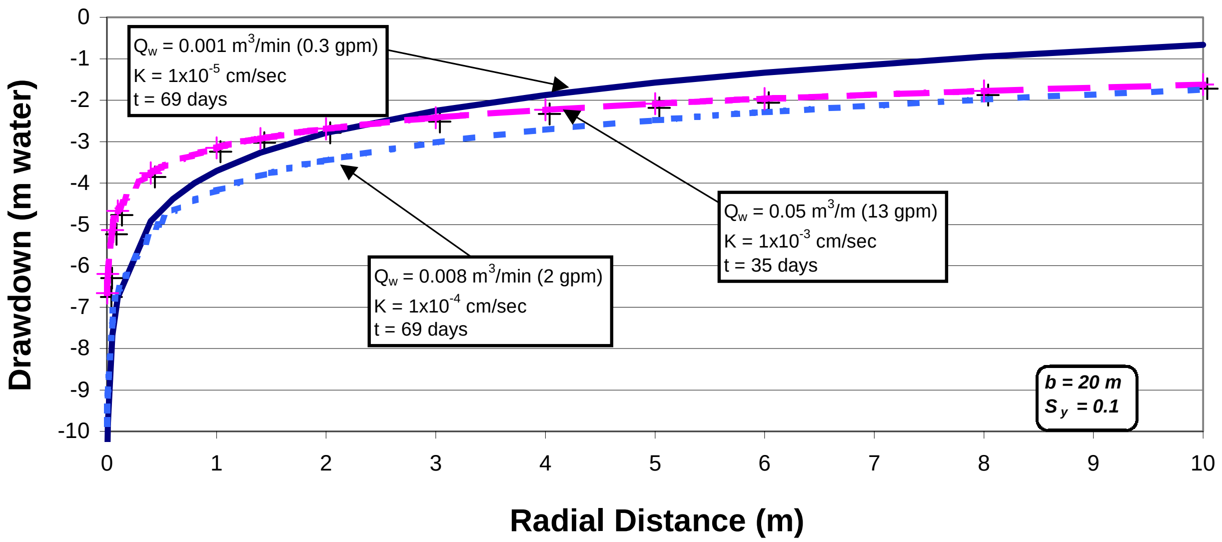

Figure 5-4. Example drawdown curves using the Cooper and Jacob approximation to the Well Equation.

4. The zone of desaturation (i.e. the lowered top of the capillary fringe) around the MPE well can then be estimated by superimposing the vacuum distribution and drawdown curves, as shown in Figure 5-5a, b, and c. This figure shows the results of this superposition for the three example soils in which a hypothetical treatment zone of 1 meter was desired (e.g., corresponding to a 1 meter smear zone). In each of these examples, a combination of applied vacuums and predicted drawdowns produces a desaturation zone greater than 1 meter at a reasonable distance from the well. It is important to note that, though this criterion is met for all the soils, the vacuum distribution for the lowest permeability soil, $k_a = 10^{-10}$ cm^2, indicates that the enhanced SVE/bioventing zone would be limited to very close to the well, thus in low permeability settings, close well spacing may be necessary to achieve the desired flow rates.

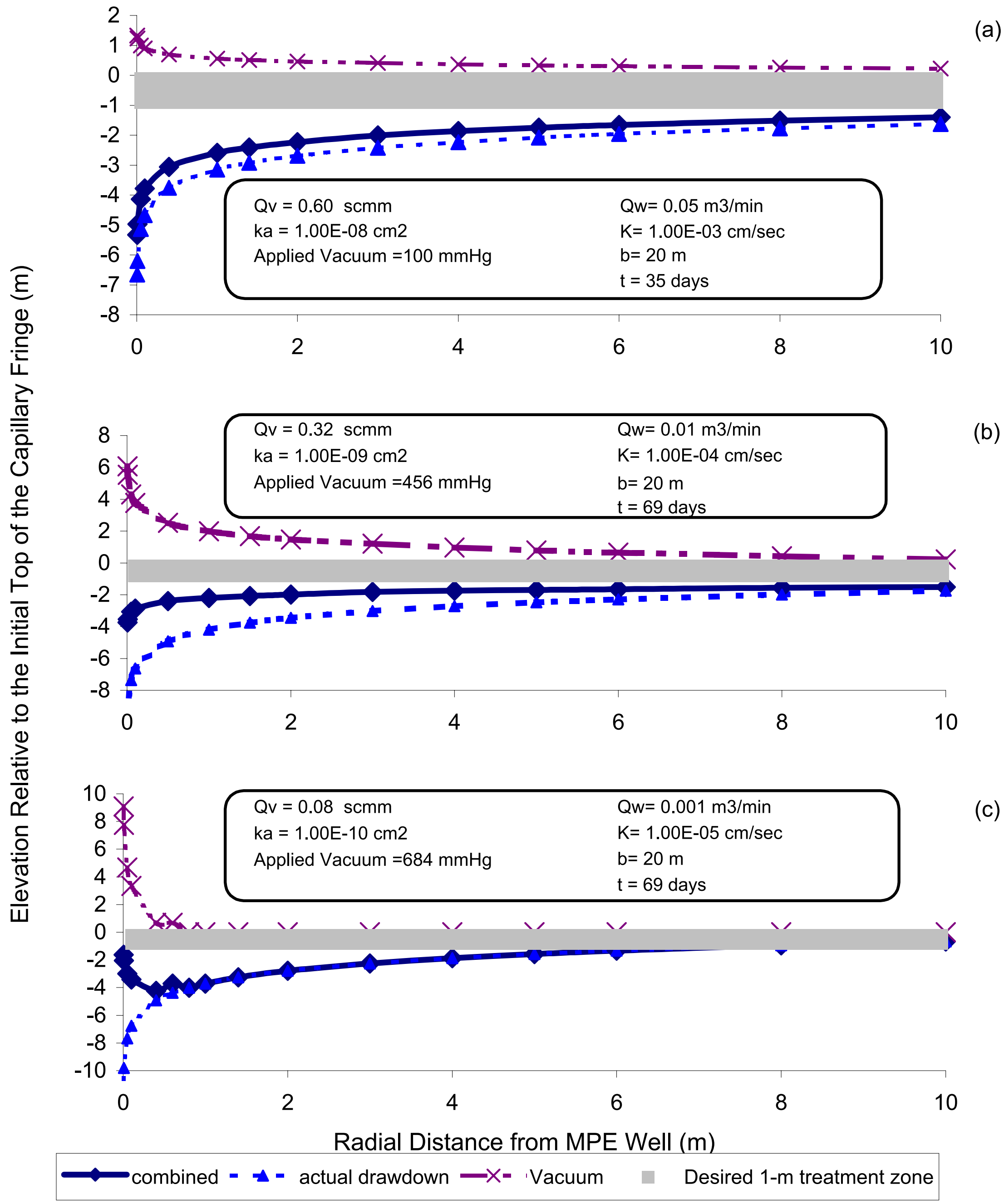

Figure 5-5. Example of a changing capillary fringe during MPE as described by the superposition of vacuum distribution and drawdowns curves for a) moderate; b) low; and c) very low permeability soils. For each, the predicted dewatered zone is >1m thick within 6m of the well; however, for c), SVE is limited to ~1m from the well.

b. MPE with Limited Drawdown to Recover LNAPL.

(1) For the case of MPE with limited drawdown, the vacuum applied at an MPE well must be sufficient to overcome the capillary forces of the surrounding soil so as to "encourage" LNAPL flow toward the well. Again, the wellfield design must create a vacuum distribution within the treatment zone such that the capillary forces holding the NAPL within the soil pores are overcome. However, it is important not to induce too high a vacuum near a well that may cause the LNAPL to flow faster than it can be "replenished" by other LNAPL within the interconnected NAPL-filled pores. "Snap-off" of the interconnected LNAPL-filled pores may occur and water may be induced to flow into the resulting void space. Under these conditions, a well may become "isolated" from the surrounding LNAPL-filled pores (Barker et al. 1997). The LNAPL interconnections may re-establish slowly after snap-off occurs. The appropriate design vacuum can only be determined based on pilot testing results, or developed over time during system operation based on careful monitoring. As described above, the optimum design vacuum for MPE for LNAPL recovery will also be dependent on the extent to which there are conduits within the soil that have higher permeability and lower capillary pressures to overcome. This may only be observable during pilot testing or through a substantial number of soil cores collected from the treatment area.

(2) MPE systems that are intended primarily as vacuum-enhanced LNAPL recovery systems will typically be designed to manage as little water as possible. Therefore, the groundwater extraction rate for such systems will be low, typically less than 7.5 liter/min (2 gpm) per well. The rate of groundwater extraction will be a function of the vacuum applied to the well and the actual drawdown imposed by setting the water pumping inlet at some depth below the water table. LNAPL extraction rates for such systems must be based on the same considerations described for design vacuum, i.e., extraction rates must be low enough to prevent snap-off.

(3) Well spacing is primarily determined by the vacuum and/or flow distribution that is desired throughout the treatment area. For the case where the objective of the MPE system is to remove mass through vacuum-enhanced free product recovery, the spacing of wells within an MPE well network should be based on pilot test results and subsurface flow modeling using a multiphase flow model. At the outset of a typical MPE project, screening level models such as, OILVOL, SPILLCAD, and BIOVENTING^{PLUS} can be used to answer questions such as:

- How much LNAPL is present?
- About how many (order-of-magnitude number of) wells will be needed for a MPE system?
- Approximately what concentrations of contaminants are expected in the extracted gas and water and therefore what type of treatment system should be contemplated?

(4) If a multi-phase flow model is unavailable, then the designer may use prior experience, designs for similar projects, published modeling results, or published MPE results as guides for order-of-magnitude estimates of MPE design parameters. For example, Figure 5-6 presents published computer simulated LNAPL recovery rates over time in SM soil that initially had 3 m (10 feet) of LNAPL. The SM soil was a sandy loam containing approximately 9% clay and 26% silt, with the remainder fine- to very-coarse-grained sand (Beckett and Huntley

1998). These simulations were performed for LNAPL recovery with groundwater drawdowns set at 0.76, 1.5, 2.3, and 4.6 m (2.5, 5, 7.5, and 15 feet). A fifth simulation was performed with a vacuum applied to the 2.3-m (7.5-foot) drawdown case. These data can be used as guidance for estimating LNAPL recovery rates under similar conditions.

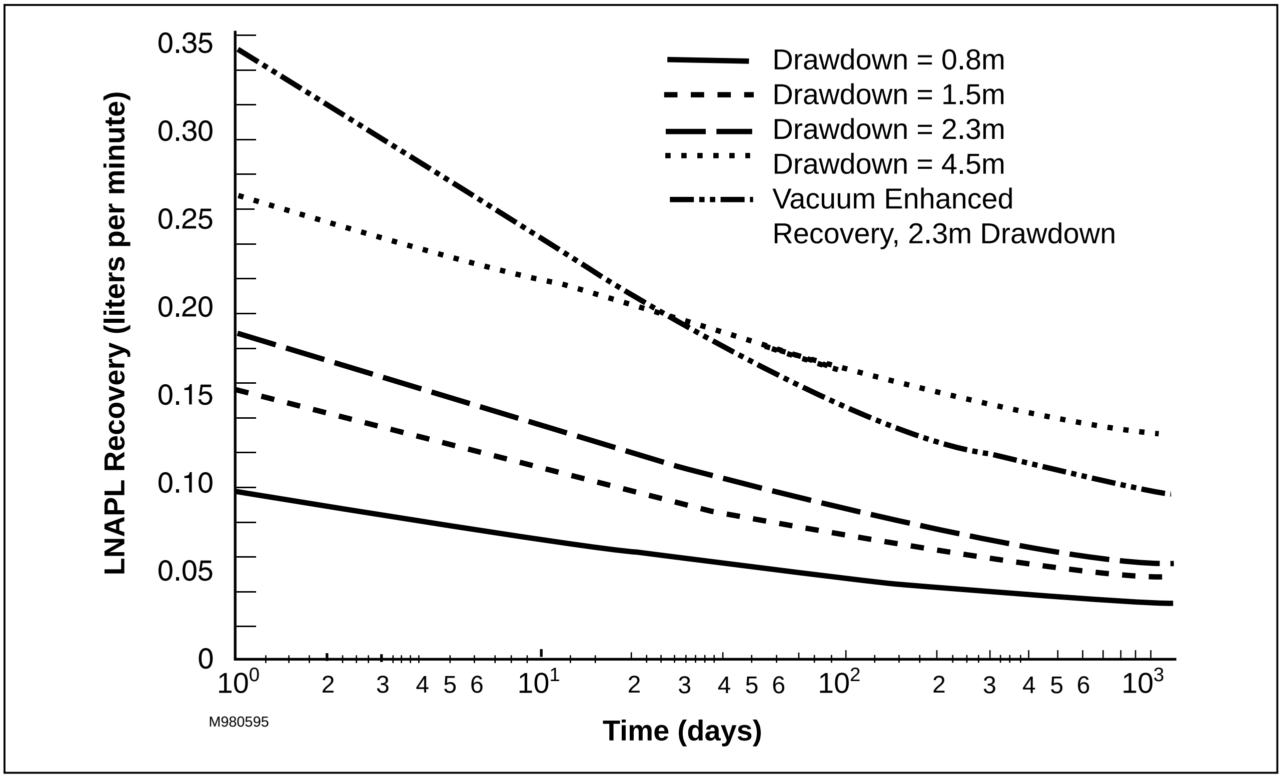

Figure 5-6. LNAPL Recovery versus Time for Various Drawdowns and for Vacuum-Enhanced Recovery with Drawdown. (After Beckett and Huntley 1998. Reprinted by permission of Environmental Science & Technology.

(5) Figures 5-7a and 5-7b present some example model simulations of MPE for NAPL recovery under a variety of scenarios. The figures illustrate remediation times for different pairs of soil. The simulations are for a hypothetical site with 1.5 m (5 feet) of LNAPL (apparent thickness) and were performed to aid estimation of the number of wells and vacuums required to recover LNAPL at this site. The model estimates the period of time required to recover the LNAPL from within a cylinder of a given radius of a well, assuming no additional LNAPL could flow into the cylinder from beyond it. In effect, this estimates the performance of one well in a multi-well field. If the time to recover the LNAPL seems reasonable to the designer for his/her site, then the total number of wells can be estimated by determining the number of wells necessary to cover the site, applying a suitable overlap or safety factor. Each of the simulations had a set of common conditions, as described in Table 5-1.

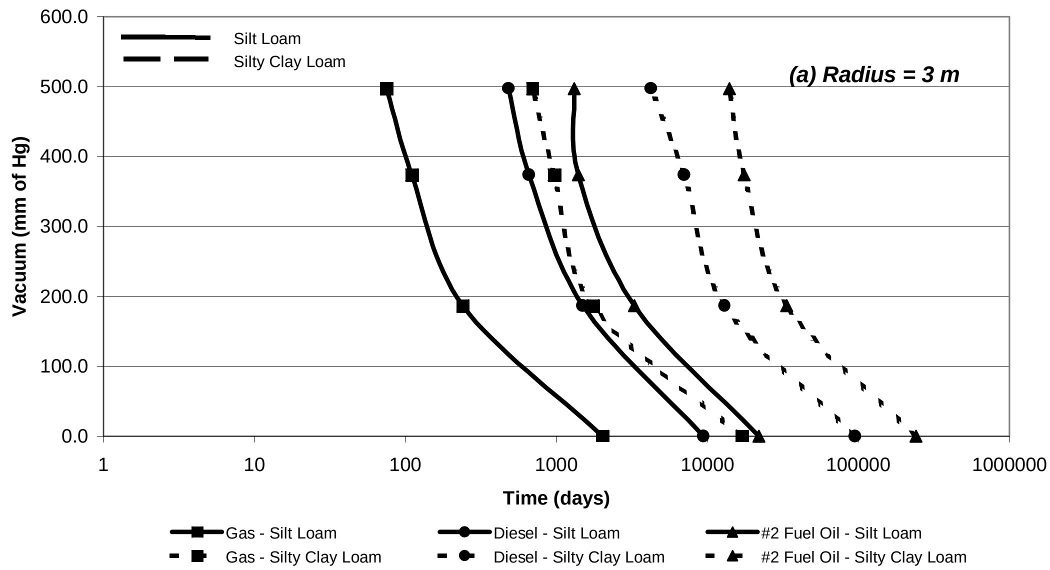

Figure 5-7a. Predicted time to 0.3 meter (1-foot) LNAPL remediation vs. applied vacuum head for various LNAPL and soil types defined by a 1.5 meter (5-foot) apparent thickness LNAPL plume with (a) 3.0 meter (10-feet) radius; and (b) 6.1 meter (20 foot) radius

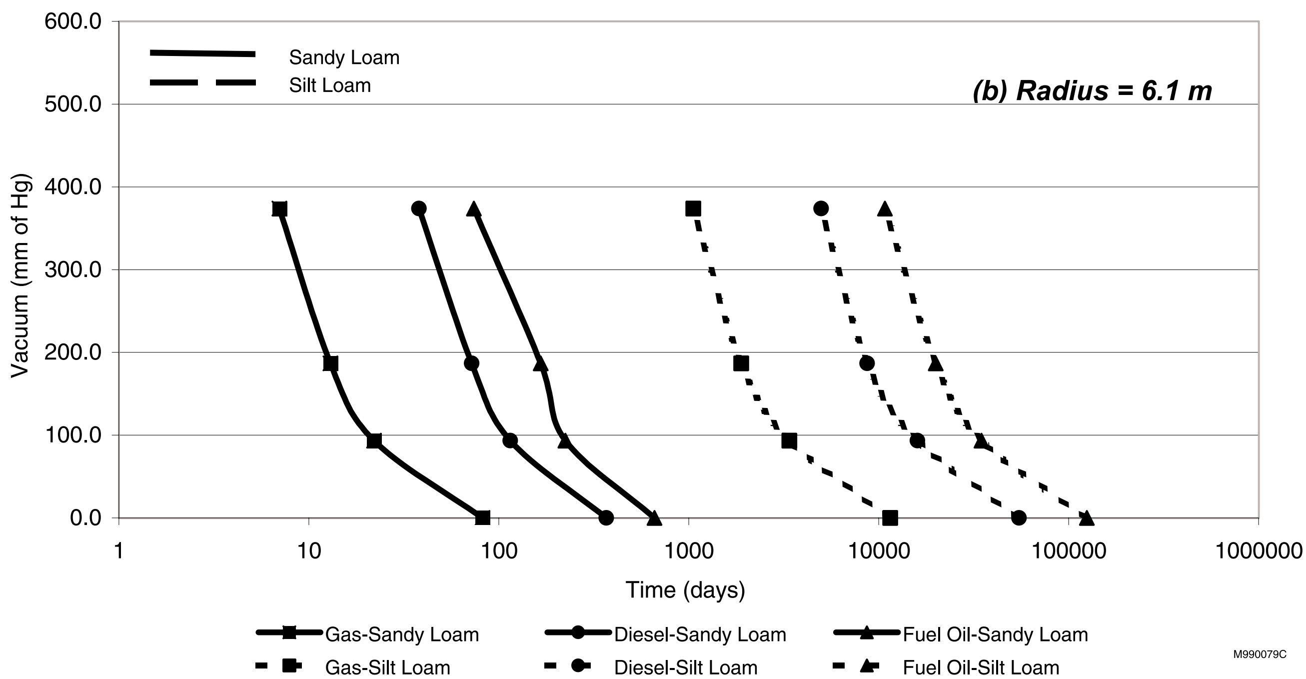

Figure 5-7b

TABLE 5-1

Model* Simulation of LNAPL Recovery by MPE: Parameters Common to Each Simulation

Parameter	**Value**
LNAPL thickness	1.5 m (5 ft)
Vadose zone thickness	4.5 m (15 ft)
Saturated zone thickness	15 m (50 ft)
Porosity	35%
Specific storage	0.2%
Unsaturated zone residual LNAPL	2.5%
Saturated zone residual LNAPL	7.5%
Drawdown in well	1 m (3 ft)
***TIMES (Trihydro 1997)**	

(6) Parameters that were varied in the example model simulations were soil type, applied vacuum, NAPL type, and recovery radius (see Table 5-2). For example, 12 LNAPL recovery simulations were performed for a 6.1-m radius from an MPE well placed in loamy sand, one for each LNAPL type (gasoline, diesel fuel and #2 fuel), applying four different vacuums to the recovery well (0, 93, 187, and 374 mm Hg, or 0, 50, 100, and 200 inches H_2O). Similarly, 12 simulations were performed for recovery from a 6.1-m radius to an MPE well placed in silt loam; 12 simulations of recovery from a 3-m radius in silt loam; and 12 simulations of recovery from a 3-m radius in silty clay loam. The results of these simulations are presented in Figure 5-7a and 5-7b. Each simulation was run until the LNAPL thickness present in the specified radius from the well (3 or 6.1m) drained to less than 0.3m (1 foot) of apparent thickness. (As described in Chapter 2 and displayed in Figure 2-17, NAPL conductivity diminishes dramatically as NAPL thickness drops to below 1 ft (0.3 m). This changing NAPL conductivity must be accounted for on a site-specific basis.) These figures can be used as guides for screening the feasibility of applying MPE at similar sites. For example, if a site has a 30 m by 30 m area with 2 m of diesel fuel in loamy sand, then the remediation designer can expect that a grid of 3 by 3 MPE wells spaced approximately 10 m apart with a vacuum of 100 mm Hg applied to the wells can expect to remove most of the LNAPL in less than one year. This is probably a reasonable remediation scenario, though the designer may want to perform a more rigorous design using MPE flow models. For the same scenario at a site with silt loam, then the designer should expect to need approximately 25 MPE wells (a grid of 5 by 5 spaced 6 m apart), with a much higher vacuum (e.g., 400 mm Hg) to remove the LNAPL within several years. Figure 5-8 presents average groundwater extraction rates that can be expected under the various LNAPL recovery scenarios presented in Figures 5-7 a and b. By examining the flow rate associated with a pumping scenario, the designer can evaluate likely groundwater treatment requirements. For the first example above, the designer can expect around 100 m^3/day of water per well to manage and treat. In the second example, the designer can expect less than 10 m^3/day of water per well. By using these figures as screening guides the designer can determine:

TABLE 5-2

Model* Simulation of LNAPL Recovery by MPE: Parameters Varied

Soil Parameters		**Soil Type**		
		Loamy Sand	**Silt Loam**	**Silty Clay Loam**
Hydraulic Conductivity (cm/sec)		4.06E-03	1.27E-04	1.98E-05
Air Conductivity (cm/sec)		2.77E-04	8.66E-06	1.35E-06
van Genuchten (alpha)		3.8	0.67	0.37
van Genuchten (n)		2.4	1.7	1.9
Applied Vacuums for "Drained Radius" (mmHg)	3 m (10 ft)		0 187 374 497	0 187 374 497
	6.1 m (20 ft)	0 93 187 374	0 93 187 374	
NAPL Parameters		**Type of NAPL**		
		Gasoline	**Diesel**	**#2 Fuel Oil**
Air-NAPL Scaling Parameters		3.3	2.8	2.8
NAPL-Water Scaling Parameters		1.4	1.4	1.4
NAPL/Water Density Ratio		0.73	0.83	0.87
NAPL/Water viscosity Ratio		0.62	2.7	5.3
***TIMES (Trihydro 1997)**				

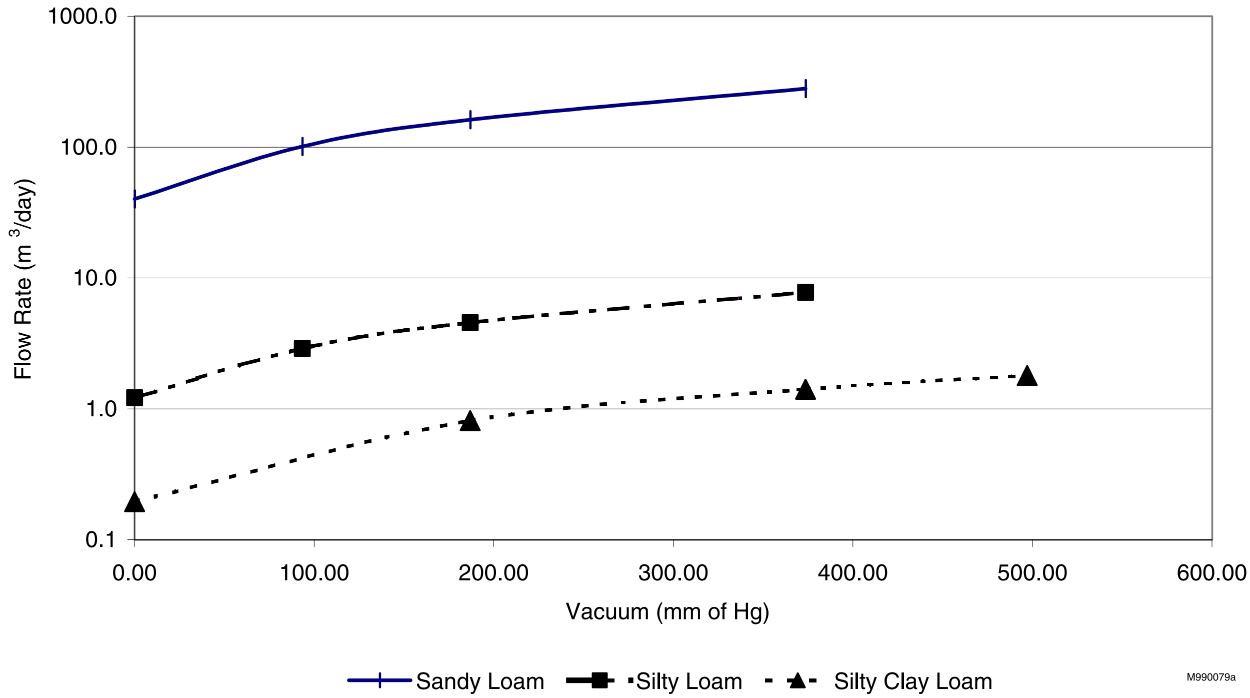

Figure 5-8. Predicted long-term average flow rates from a single well at various applied vacuums and a drawdown of 1 meter (3 feet).

- Whether to proceed in considering MPE as an applicable remediation approach for a specific site.

- Whether more rigorous modeling is desirable (i.e., cost-effective) to develop a site-specific subsurface design.

- The aboveground equipment that will likely be required for the site.

(7) After screening MPE by pilot testing, and preliminary design calculations, more sophisticated computer models can be used to establish the critical design parameters. The model is calibrated to pilot test results by iteratively running the model and making adjustments of parameters within reasonable ranges, beginning with those parameters having the most uncertainty. After achieving calibration to within acceptable criteria, the model is ready to simulate various configurations of extraction point locations and flow rates, zeroing in on an efficient system design that fulfills design criteria, e.g., sufficient contaminant removal within an acceptable time frame. A sensitivity analysis is then performed in which parameters are varied within plausible ranges to determine the effects on predicted flow rates and pressure distributions. The model is used to:

- Estimate water flow rates for the groundwater treatment system design.

- Estimate airflow rate and determine the maximum vacuum to be applied, thus determining the required blower size.

- Evaluate various well configurations to obtain the optimum number and location of vacuum-enhanced extraction wells.
- Estimate the number of pore volumes of air that will be flushed through the system during a given length of time.
- Estimate the mass of contaminant to be removed from the subsurface over time.

c. Vacuum-Enhanced Groundwater Extraction.

(1) As described in paragraph 2-3e, it is sometimes desirable to increase groundwater withdrawal rates by applying a vacuum to an extraction well. The goal for such a system is to enhance the rate of pumping and treating contaminated groundwater compared to conventional pumping systems. The approach toward design of a vacuum-enhanced groundwater extraction system is similar to that for a system designed to accomplish MPE with drawdown to enhance SVE/Bioventing (paragraph 5-3a). The important differences for vacuum-enhanced groundwater extraction are:

- There is no requirement for pore-volume exchange, therefore the zone of influence for an extraction well is not dependent on a PVER.
- The system design does not have to ensure that a specific degree of dewatering is achieved.
- The vacuums and drawdowns applied to each extraction well will generally be optimized to achieve the optimal groundwater extraction rates while minimizing soil gas extraction rates.

However, as with other MPE approaches, it will be necessary to: select a well network that yields sufficient groundwater flow to achieve the remediation goals; estimate groundwater and soil gas extraction rates for the design of aboveground fluid pumping and treatment equipment; and determine extraction fluid flows to properly size conveyance piping.

(2) As with the previous MPE approaches, the designer can develop a design using simple solutions to the one-dimensional flow equations or by using more sophisticated multi-phase flow models, as described in paragraph 5-3a.

d. Well Screen Length and Depth.

(1) A cluster of different depth MPE wells should be considered in situations where there are notable stratigraphic layers or discontinuities that might cause preferential flow to the extraction well. For example, if there is a 3-m thick contaminated zone that requires remediation, with a discernible difference in permeability between the top 1.5 m and the lower 1.5 m, then it may be desirable to use two wells with 1.5-m screen intervals to extract from the two zones separately. In this way, it may be possible to extract from the lower permeability strata without all of the air or water flowing through the more permeable zone. Caution should be used in cases of low permeability layers as extraction wells screened in such layers may have minimal effect.

(2) The likelihood of experiencing preferential flow increases as the length of the well screen increases. As a rule, MPE well screen intervals should be configured to expose no more than 3 m of screen during extraction. The well screen should extend some distance below the depth of the smear zone and be open to enough of the water-bearing zone to allow development of an adequate cone of depression if groundwater table depression is desired to enhance LNAPL recovery. The well screen must extend into the vadose zone over an adequate interval to allow airflow into the well and to initially draw air from above the capillary fringe. The well screen interval in the vadose zone should not be so large that unwanted air is induced to flow into the well from above the target remediation zone.

(3) For DPE systems that use submersible pumps to extract liquids entering the well, there is a second important factor in determining well depth and screen interval. The DPE well must include a sump that will both accommodate the body of the pump (typically at least 60 cm long below the water level) and the amount of net positive suction head necessary to prevent cavitation in the pump. Net positive suction head (NPSH) is discussed in detail in paragraph 5-6i.

5-4. Modeling. Numerical modeling is an important part of the design, development, and operation of MPE systems by allowing simulation of conditions in the subsurface around the system for different system configurations and for system evaluation. Models vary from simple, order-of-magnitude tools for estimating quantities such as the volume of oil present, to more complex models simulating various well and pressure configurations and their impact on system radius of influence and performance. The models discussed here are intended to simulate flow and transport processes over scales of meters to tens-of-meters; as such they are generally not appropriate for simulating details of multiphase flow occurring within the extraction wells themselves.

a. Currently Available Models. Numerous mathematical models have been developed and computer codes written to simulate subsurface liquid pressure distributions, airflow, transport of water and gas, and extraction. The discussion in this manual is limited to those models which have been developed for more than a specific project, are maintained as practical programs for remedial design, and are usable on IBM-compatible personal computers. Table 5-3 presents an overview of these multi-phase flow models.

TABLE 5-3
Multi-Phase Flow Models

Model Name	Model Type and Use	Developer	Computer Requirements	Input Parameters / Assumptions	Output Parameters	Ease of use
ARMOS	2D FE free-phase hydrocarbon migration and recovery	Environmental Systems and Technologies, Inc.	80486 or higher with 8 MB RAM, 10MB free disk space, DOS 3.3 or higher or MS Windows, math coprocessor, VGA graphic adapter and monitor, MS compatible mouse, not compatible with some AST computers or Macintosh computers	Mesh discretization data, water & oil pressure distribution, boundary conditions, soil hydraulic properties, species concentrations, dispersivities, mass transfer rate coefficient between oil and water, distribution coefficient, bulk density, diffusion coefficient, biodegradation parameters	Distribution of fluid pressure with time, distribution of fluid saturation with time, fluid velocity distribution with time, fluid pumping/injection rates and volume vs. time, distribution of concentration, mass dissolved in water or air vs. time, mass remaining in NAPL phase vs. time, mass adsorbed on the solid phase vs. time	moderate
BIOVENTING[PLUS]	Windows 95 based program for air injection and extraction remediation design	Environmental Systems & Technologies, Inc.	Intel 80486 based computer, math coprocessor, 8 MB RAM, 12 MB fee hard disk space, VGA graphics, Windows 95. A copy of SPILLCAD (standard version) is included with purchase from IGWMC	Airflow model requires ground surface parameters to calculate leakage across it and the mass balance model considers multiphase, multicomponent partitioning and requires appropriate parameters.	Air flow rate and pressure radius of influence, composition and mass recovery vs. number of wells, time to meet cleanup criteria, total cost vs. number of wells,	easy
HSSM	Hydrocarbon Spill Screening Model for LNAPL's in soils, capillary fringe, and ground water (analytical model)	USEPA	Intel 8086 or higher microprocessor, at least 640 KB (low) RAM (preferably 1 MB RAM to run MS Windows in enhanced mode), DOS 5.1 or higher, hard disk with at least 2 MB free disk space, EGA/VGA graphics, MS Windows 3.0 or later, and Microsoft compatible mouse	Includes a soil property regression utility for estimating soil hydraulic properties and a utility for calculating the NAPL/water partition coefficient based on Raoult's law.	Saturation profiles, NAPL lens contaminant mass balance, receptor concentration histories.	moderate
MOTRANS	Finite element LNAPL/DNAPL/water/air flow in cross-sections through saturated/unsaturated zone	Environmental Systems & Technologies, Inc.	IBM PC 386/486 with 8 Mb extended memory, math coprocessor, VGA graphics; SURFER/GRAPHER is required to view or print	NAPL viscosity, porosity, hydraulic conductivity, air-water capillary pressure, water/NAPL surface tension ratio, NAPL characteristics	System pressure, saturations, velocities, concentrations in each phase, total phase volume and total component mass	difficult
RITZ	Regulatory and Investigative Treatment Zone Model. Screening level model for transport of oily waste in soils (analytical model)	USEPA	Intel 80i86 based computer, 640 KB RAM, about 1 MB free disk space, DOS 2.0 or higher, CGA graphics, math coprocessor recommended	Assumes oily waste is uniformly mixed in the plow zone, soil properties are uniform and water flow is steady. Degradation is described as a first-order process.. Requires hydraulic conductivity and a water retention curve parameter.	Estimates of the movement and fate of hazardous chemicals during land treatment of oily wastes and evaluates fate of residual oil from leaks and spills.	easy
SPILLCAD	Oil spill volume estimation and remedial design evaluation	Environmental Systems & Technologies, Inc.	Intel 80486 based computer with math coprocessor, 8 MB RAM, about 10MB free disk space, DOS 3.3 or higher, or Microsoft Windows 3.1, VGA graphics	Monitoring well fluid level data and soil sampling data. soil concentration data, soil TPH data, domain geometry, soil hydraulic parameters.	Free product volume, and soil product thickness. Volumes of soil above a threshold, estimates of total mass of a species and estimates of residual hydrocarbon volume, capture zone analysis, estimates of recoverable product from recovery wells, compute water and oil streamlines for steady state water pumping/recharge, determinations of well placement and operation for control of free product or dissolved plumes, estimates of asymptotic recoverable and residual product for different recovery systems	easy

TABLE 5-3
Multi-Phase Flow Models (continued)

Model Name	Model Type and Use	Developer	Computer Requirements	Input Parameters / Assumptions	Output Parameters	Ease of use
SWANFLOW	3D FD research code for simulating flow of water and a NAPL in saturated/unsaturated systems	GeoTrans, Inc.	Intel 80386/80486 based computer, 4 MB RAM, hard drive with about 3 MB free disk space, DOS 3.0 or higher, math coprocessor	Pressure gradients in the gas phase (air) are assumed negligible, water and NAPL viscosity and density are pressure independent, relative permeability and capillary pressure are functions of water saturations, air saturation if a function of NAPL pressure	Flow, pressure and concentration variations through the model domain	very difficult
VLEACH	1D finite difference model for hydrocarbon leaching in soils	CH2M Hill and Dynamac Corp.	Intel 80i86 based computer, 640 KB conventional RAM, DOS 2.0 or higher, CGA graphics	One-dimensional, can simulate leaching in distinct polygons during each run; polygons may differ in soil properties, recharge rate, depth to water, or initial conditions; assumes a homogeneous soil with uniform, steady-state downward water flow; dispersion is neglected and there is no in-situ segregation or production	Groundwater impact as a function of time and soil concentration profiles (text files)	moderate
MARS 2D/3D	Multi-Phase (Water and Oil) Areal Remediation Simulator	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 4 MB RAM. With Transport requires Windows95/NT and 16 MB RAM	Mesh discretization data, water & oil pressure distribution, boundary conditions, soil hydraulic properties, species concentrations, dispersivities, mass transfer rate coefficient between oil and water, distribution coefficient, bulk density, diffusion coefficient, biodegradation parameters	Distribution of fluid pressure with time, distribution of fluid saturation with time, fluid velocity distribution with time, fluid pumping/injection rates and volume vs. time, distribution of concentration, mass dissolved in water vs. time, mass remaining in NAPL phase vs. time, mass adsorbed on the solid phase vs. time	difficult
MOFAT for Windows	Multiphase (Water, Oil, Gas) Flow and Multicomponent Transport	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 8 MB RAM	Mesh discretization data, water & oil pressure distribution, boundary conditions, soil hydraulic properties (may be estimated using DAEM's SOILPARA), species concentrations, dispersivities, mass transfer rate coefficient between oil and water, distribution coefficient, bulk density, diffusion coefficient, biodegradation parameters	Distribution of fluid pressure with time, distribution of fluid saturation with time, fluid velocity distribution with time, fluid pumping/injection rates and volume vs. time, distribution of concentration, mass dissolved in water or air vs. time, mass remaining in NAPL phase vs. time, mass adsorbed on the solid phase vs. time	difficult
MOVER	Multiphase (Water, Oil, Gas) Areal Flow with Vacuum Enhanced Recovery	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 8 MB RAM	Mesh discretization data, water and oil pressure distributions, specified head and flux boundaries, source/sink boundary: soil hydraulic properties include van Genuchten parameters, hydraulic conductivity distribution and porosity	Distributions of fluid pressure and saturation with time, fluid velocity distribution with time, pumping/injection rates and volume with time, output can be used to simulate multicomponent aqueous phase transport using BIOF&T 2D/3D	difficult

TABLE 5-3

Multi-Phase Flow Models (continued)

Model Name	Model Type and Use	Developer	Computer Requirements	Input Parameters / Assumptions	Output Parameters	Ease of use
BioSVE	Incorporates soil vapor extraction, vacuum enhanced recovery and biodegradation into one screening model	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 4 MB RAM	Air pumping rate, total mass of the spill, maximum simulation time, time increment parameters, soil air temperature, venting efficiency, bio efficiency, volume of contaminated soil, soil bulk density, fraction of organic matter in the soil, free product recovery parameters, species properties including: molecular weight, vapor pressure, mass fraction, boiling point, aqueous solubility, and Kow (oil-water partition coefficient)	Species mass in water, oil, gas, and solid phases versus cleanup time, total species mass versus cleanup time, total contaminant mass versus cleanup time	moderate
BIOSLURP	Areal finite-element model to simulate three-phase (water, oil, and gas) flow and multicomponent transport in ground water in the unsaturated zone gas phase	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 8 MB RAM	Initial fluid pressures, species concentration distribution, and free oil volume are estimated internally from monitoring well data	Distribution of fluid pressure, distribution of fluid saturation, fluid velocity distribution, distribution of concentration	moderate
AIRFLOW/SVE	A radial-symmetric model for simulating soil vapor flow and multi-component vapor transport in the unsaturated zone	Waterloo Hydrogeologic Software	IBM PC 386/486 with minimum of 4 Mb RAM, EGA or VGA display, and a math coprocessor	Permeability, initial pressures, gas characteristics, temperature	Soil pressure distribution, total system flow	easy
TIMES 2.0	Visual and interactive groundwater modeling system that integrates numerical groundwater models with data visualization	TriHydro Corporation	Windows95/NT and 16 MB RAM	Mesh discretization data, water & oil pressure distribution, boundary conditions, soil hydraulic properties, species concentrations, dispersivities, mass transfer rate coefficient between oil and water, distribution coefficient, bulk density, diffusion coefficient, biodegradation parameters	Distribution of fluid pressure with time, distribution of fluid saturation with time, fluid velocity distribution with time, fluid pumping/injection rates and volume vs. time, distribution of concentration, mass dissolved in water or air vs. time, mass remaining in NAPL phase vs. time, mass adsorbed on the solid phase vs. time	moderate
OILVOL	Estimates the free hydrocarbon volume in a soil and computes the volume of residual NAPL in the saturated and unsaturated zones	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 4 MB RAM	Depth to air-oil and oil-water interfaces measured in monitoring wells, van Genuchten soil moisture retention parameters (can be estimated with SOILPARA), and fluid properties	Free product (true product) volume, and residual oil volume after skimming	easy
SOILPARA	Estimates hydraulic parameters in the van Genuchten constitutive model (Brooks-Corey parameters can be estimated from these) for variably saturated soils	Draper Aden Environmental Modeling	Windows 3.x/95/NT and 4 MB RAM	Retention data and/or conductivity or diffusivity data (K or D vs. soil water content/pressure), or soil texture (pecentage sand/silt/clay, or USDA-recommended typical parameter values for various texture classes	Hydraulic parameters in the van Genuchten constitutive model (Brooks-Corey parameters can be estimated from these)	easy
MAGNAS	2-D and 3-D finite element transport of water, NAPL, and air through porous media; can simulate the flow of air as a fully active phase	HydroGeologic Inc. 1165 Hernadon Parkway, Suite 900, Hernadon, VA 22079 703/478-5186	IBM PC/AT compatible computer, DOS	Heterogeneous and anisotropic media properties, capillary pressures and permeability	Breakthrough curves of concentration vs. time, flow and transport mass balances	difficult

b. Criteria for Model Selection. While a large number of MPE model codes have been written, those which are generally available can be classified into four main groups (Table 5-4) in terms of generality and complexity. Use of the simplest appropriate model for a given design objective will save time and budget (Table 5-5). A more complex and general model can be used in simpler situations, but typically at the cost of a steeper learning curve and greater difficulty in setup and calibration. More complex models may require a more detailed site characterization to obtain the input parameters necessary. Some complex models require input parameters that are typically not determined in a site investigation.

TABLE 5-4

Classification of Multi-phase Flow Models

Model Class	Phases in Model[1]	Spatial Dimension	Flow	Aqueous Transport	Vapor Transport	Bio	Ease of Use	Representative Model Codes
A	Water, Oil	2D Areal	Yes	No	No	No	High	ARMOS, MARS[2]
B	Water, Oil, Air	2D Areal	Yes	TIMES only	No	No	High	TIMES, MOVER, ARMOS/AIR
C	Water, Oil, Air	2D Areal	Yes	Yes	Yes	Yes	Mode-rate	BIOSLURP, BIOVENTING
D	Water, Oil, Air	2D planar, 2D vertical, 3D	Yes	Yes	Yes	No	Low	MOFAT, MOTRANS, MAGNAS, T2VOC

[1] Phases explicitly determined in each cell, i.e. 2-phase (oil, water) models only account for a static, uniform vapor phase with no applied vacuum effects.

[2] MARS can be linked to the 2D/3D aqueous transport model BIOF&T to add aqueous transport and biodegradation reactions capabilities

TABLE 5-5

Multi-Phase Model Classifications Applicable to Specific Remedial Scenarios

Pumping Scenarios	Remediation / Design Objectives[†]					
	Determine Area of Pumping Well Influence	Optimize De-watered Zone Volume	Optimize Product Recovery	Optimize Mass Removal	Optimize Contaminant Concentration Reduction	Simulate Smear Zone Development
Groundwater Recovery	A	A	A	B[2]	A[1],C	D
Product Skimming	A	A	A	B[2]	A[1],C	D
Total Liquid Recovery (Oil + Water)	A	A	A	B[2]	A[1],C	D
Multi-phase (TPE or DPE) Recovery (Oil + Water + Air) (e.g. Slurping)	B[2]	B[2]	B[2]	B[2]	C	D

TABLE 5-5

Multi-Phase Model Classifications Applicable to Specific Remedial Scenarios (Continued)

Pumping Scenarios	Remediation / Design Objectives[†]					
	Determine Area of Pumping Well Influence	Optimize De-watered Zone Volume	Optimize Product Recovery	Optimize Mass Removal	Optimize Contaminant Concentration Reduction	Simulate Smear Zone Development
Vacuum-enhanced Groundwater Recovery	B[2]	B[2]	B[2]	B[2]	C	D
Vacuum-enhanced Product Skimming	B[2]	B[2]	B[2]	B[2]	C	D
Vacuum-enhanced Total Liquid Recovery	B[2]	B[2]	B[2]	B[2]	C	D
Vacuum-enhanced Soil Vapor Extraction	B[2]	B[2]	B[2]	B[2]	C	D

[†] **Model Classes A, B, C and D refer to Table 5-4.**

[1] **Inclusion of aqueous contaminant transport +/- biodegradation would require use of MARS + BIOF&T**

[2] **Class C models would generally be easier to apply here, unless peculiarities in the vertical profile or significant departures from sharp oil-water and oil-air interfaces require a class D (true 3D or vertical radial 2D) model.**

(1) The first group of models simulates the two-dimensional areal flow of an oil phase and a water phase. Air is not considered explicitly, so that variations in air pressure from such mechanisms as vacuum enhancement cannot be calculated at the same time as variations in pressure in co-existing NAPL and water. These simpler models also do not generally include transport of dissolved or vaporized contaminants, but are relatively simple and fast to calibrate and run. The next step up in complexity adds explicit calculation of an air phase to those of NAPL and water. This is necessary to fully consider the effects of vacuum enhancement, where air pressure must vary from a vacuum extraction well towards its surroundings. This class of models still consists of 2D areal models in which the properties of each phase are integrated vertically from one sharp inter-phase boundary to another. While sharp oil-air or oil-water boundaries, for example, are not realistic in detail, this assumption can be a reasonable simplification in many cases and greatly improves model performance. This class of models may or may not include aqueous transport of contaminants along with multi-phase flow. In the third class of models, the previous areal 3-phase models are augmented with a number of species transport and reaction options, including aqueous and vapor-phase transport as well as biodegradation reactions from simple first-order decay to higher-order decay rates. These options can be important when total reduction in contaminant concentrations needs to be simulated, rather than just radius of MPE influence or extraction rate of product.

(2) When the assumption of sharp inter-phase boundaries made by the areal models is inappropriate, a fourth class of models is necessary in which 2D cross-sectional (assuming radial symmetry) or fully 3D model domains are possible. While such models allow for mixed-phase model zones and other vertical heterogeneities to be accurately simulated, the model codes are

generally more difficult to calibrate and run. Fully 3D multi-phase model codes are generally considered not to be of practical use on personal computers for more than a quite limited model domain (e.g. 3 to 9 m).

c. Methodology for Model Development.

(1) Once the objectives of an MPE model have been specified, the appropriate modeling tool can be selected and a model developed. A screening level tool to estimate LNAPL volumes or order-of-magnitude well and flow information can be used quickly with gross generalizations about the site.

(2) More refined multiphase models are generally finite element, two-dimensional models that assume vertical homogeneity within each phase. These models employ complex numerical methods, thus requiring the skills of experienced modelers.

(3) At a minimum, the same kinds of data must be known or assumed about an area as would be required for a groundwater flow model. Groundwater modeling is discussed in detail in Anderson and Woessner (1992). When modeling more than one phase, however, additional information must be known or estimated:

- The ratio of the density of LNAPL to the density of water.
- The ratio of the viscosity of LNAPL to the viscosity of water.
- The LNAPL-water scaling parameter (USEPA 1996b).
- The LNAPL-air scaling parameter (USEPA 1996b).
- The extent and thickness of the LNAPL plume.

(4) If the objectives of the model warrant modeling of dissolved transport then the solubilities of the separate phase components in water must also be known.

(5) The designer of an MPE system is encouraged to make use of airflow in addition to water flow modeling. Several models on the market include air as a third phase in the multiphase model. This is especially important for MPE systems as the changes in air pressure that result from application of a vacuum affect the water and LNAPL heads in the vicinity of the extraction wells. The information required to handle the air phase in most models includes:

- The horizontal and vertical air conductivity.
- The applied vacuum.

(6) Air (also termed pneumatic) conductivity may be calculated from hydraulic conductivity by first calculating the intrinsic soil permeability (a soil parameter independent of fluid that can be calculated from hydraulic conductivity using the density and viscosity of water). The air conductivity can then be calculated by using the same equation relating permeability to conductivity but substituting in the density and viscosity of air. Moisture content must also be considered in determining air conductivity.

(7) If a groundwater model is selected because it is on hand and because users are familiar with it, it may be possible to apply it to model airflow as the primary phase. If the maximum pressure difference between any two points in the flow field is less than approximately 0.2 atmospheres, the differential equations developed to model groundwater flow provide good approximations to gas transport. Vapor extraction and MPE systems generally operate under pressure differences in the formation on the order of 0.2 atmospheres or less. Even at differences of 0.5 atmospheres, the error may only be on the order of 10 percent. Analytical and numerical groundwater flow models can therefore be used to model vapor and gas transport if the proper set of input variables is defined (Massmann 1989). The conceptualization of airflow, however, is significantly different than it is for water flow in a numerical model, and care must be taken to ensure that parameter values and boundary conditions are appropriate.

(8) When developing a model with the primary phase being air, the lower boundary of the model domain is assumed the same as the water/oil potentiometric surface. The model is generally set up to be a semi-confined system, with the upper boundary of the model set to be a head-dependent flow boundary. The conductance of that boundary is equal to the vertical air conductivity of the surface seal divided by the thickness of that seal (often 5 cm of pavement). The head associated with the upper boundary must be specified to be significantly higher than the elevation of that boundary to ensure the model cells do not "go dry." The vertical and horizontal conductivities in the model must be equal to the air rather than the hydraulic conductivities. The extraction wells may be simulated with constant head cells where head is specified to be equal to the head at the bottom of the unsaturated zone model, minus the vacuum pressure. A model set up in this fashion may be used to predict air pressure and flow rates through the model domain.

(9) Numerical models may also be applied to simulating the behavior of DNAPL, either as a single contiguous phase or as one of multiple phases in a multiphase model. This may be practical where DNAPL forms a thick continuous blanket over a relatively uniform confining surface. Success in modeling DNAPL is rare, however, because DNAPL rarely behaves as a single saturated contiguous phase (paragraph 3-5b). DNAPL is more likely to move through the subsurface as a complex discontinuous system of stringers, pools, and residual patches whose mobility is controlled by soil heterogeneities at a scale far below that considered by applicable multiphase models.

d. Use of Models to Evaluate System Performance. Numerical models are clearly useful in the design of MPE systems, by validating a set of assumptions and parameter estimations used in the system design and testing process. Following system startup and during system operation, there are certain system parameters such as well pressures and extraction rates that no longer need to be simulated but can be measured directly. Much of the subsurface domain undergoing remediation will nonetheless remain a black box whose characteristics cannot practically be monitored in detail. For example, the true distribution of remaining product or of soil permeability between extraction wells may be difficult or impossible to determine but clearly can have dramatic significance for future system performance.

(1) It can be of great value during system operation to continue using a model that had already been set up and calibrated for system design and testing. By maintaining a dynamic calibration of the model to current system monitoring data, it is often possible to understand the causes of presently observed trends in system performance as well as to anticipate future ones such as decreases in mass recovery rates. Other uses for a dynamically calibrated model include predicting the effects of unanticipated events such as system

shutdowns, evaluating the effects of system refinements, and updating estimates of time to cleanup.

(2) One way to look at such a numerical model is as an operating representation of the site conceptual model that is the basis for MPE system design. An on-going comparison between model behavior and actual system behavior may be the quickest way of detecting when assumptions underlying MPE system behavior, such as airflow paths or product viscosity, may no longer be valid. A good indication of this may be when certain model parameters are frequently changed to maintain dynamic model calibration. If this occurs, the model then becomes a ready-to-use tool for investigating whether modifications to the site conceptual model are warranted and how best to modify system operation in response. The model codes listed in Table 5-3 are grouped here into four broad classifications according to the phases they explicitly consider, the number of spatial dimensions, and what types of contaminant transport/reaction are considered. Table 5-5 presents multi-phase model classifications applicable to specific remedial scenarios. For each combination of pumping scenario and remediation / design objective, the model class with the minimum required complexity is indicated.

5-5. Multi-Phase Extraction System Well Construction and Specifications.

a. Introduction. This section provides guidance on design and specification of proper well/trench construction for multi-phase fluid extraction and system monitoring. This guidance is not comprehensive and must be adapted as necessary for site-specific conditions and objectives. Specific requirements for design of soil vapor extraction wells are provided in EM 1110-1-4001, Soil Vapor Extraction and Bioventing. Detailed guidance on monitoring well construction is provided in EM 1110-1-4000, Monitor Well Design, Installation, and Documentation at Hazardous and/or Toxic Waste Sites. Guide specifications for well construction are available through the U.S. Army Corps of Engineers Guide Specification (CEGS) system, including CEGS 02671 Wells for Monitoring Ground Water and CEGS 02670 Water Wells. These can be modified for typical multi-phase fluid recovery applications.

b. Applicable Standards. The guide specifications reference the appropriate industry standards for materials and testing procedures. The designer should assure that these references are appropriate for specific projects. The designer must assure that appropriate state and local well construction regulations are referenced in the specifications.

c. Contractor Qualifications. Competent professionals, drillers, and installers are required for successful installation of wells and trenches. Minimum criteria for these personnel must be identified in the specification.

(1) Well Installation. The level of experience of the contractor's well driller and hydrogeologist (or engineer) directing the well installation should be specified. It may be necessary to specify state registration or certification where required.

(2) Horizontal Well/Trench Installer Qualifications. There may be special requirements for the operators of the trenching machine or horizontal drilling rig, such as a minimum number of months or years experience. A registered or licensed driller may be necessary.

d. Multi-phase Fluid Recovery Well Design. Multi-phase fluid recovery wells are intended to capture any combination of groundwater, free product, and air. This section provides a checklist of topics to be covered in design and specification for such wells. Typical requirements are discussed under each topic. The typical construction of vertical multi-phase extraction wells is illustrated in Figure 5-9.

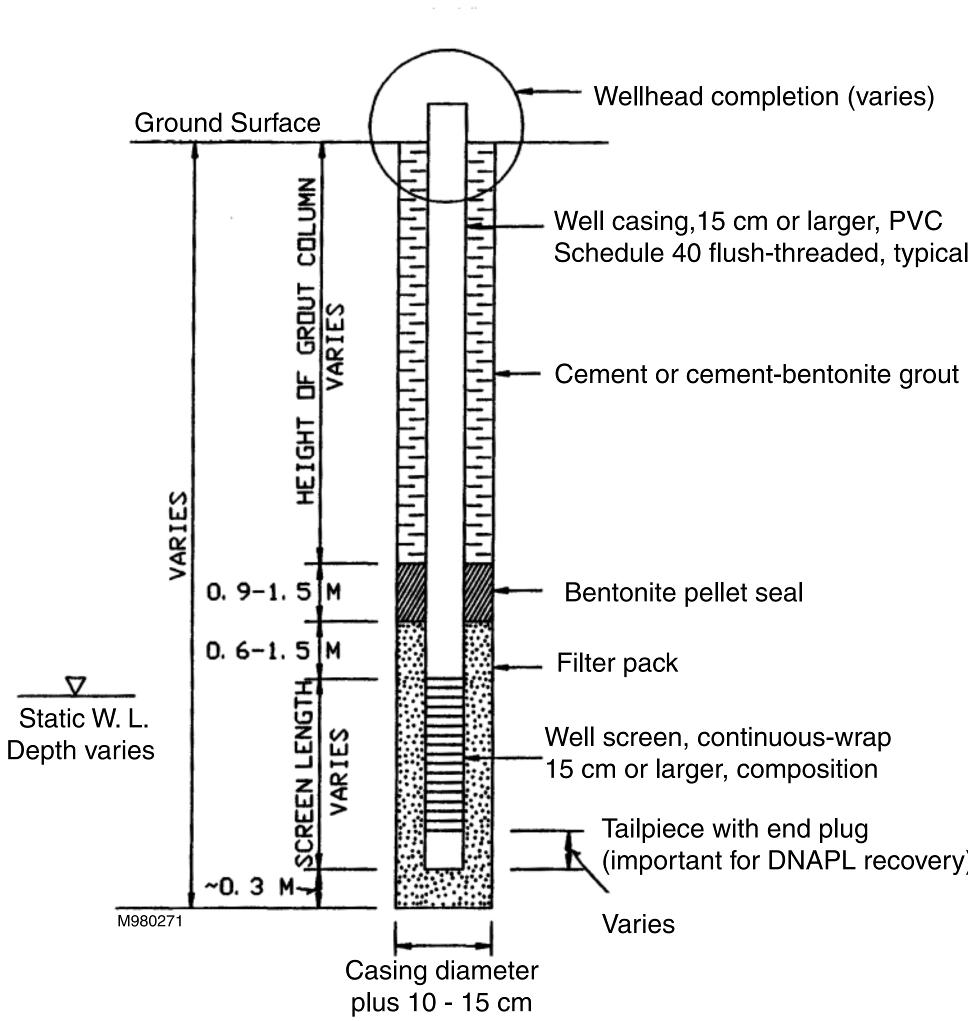

Figure 5-9. Multi-phase Extraction Well Detail.

(1) Materials. The materials used for multi-phase fluid recovery wells will generally depend on site conditions and project objectives. Composition of the materials will depend on the subsurface geochemistry including the natural constituents and contaminants.

(a) Casing. For many applications, schedule 40 PVC well casing is adequate. A reference to ASTM D 1785, Standard Specification for Polyvinyl Chloride (PVC) Plastic Pipe, Schedule 40, 80, 120 or ASTM F 480, Standard Specification for Thermoplastic Water Well Casing Pipe and Couplings Made in Standard Dimension Ratio (SDR), is appropriate. If high levels of liquid organics are to be encountered by the casing, the compatibility of the casing material with the fluids must be considered. Require stainless steel (generally schedule 5S or 10S, type 304) if PVC will be degraded by the product. A reference to ASTM A 312, Standard Specification for Seamless and Welded Austenitic Stainless Steel Pipe, is recommended. Alternatively, PVC may be preferred in an environment that is highly corrosive to metals. The well can be a "hybrid" of PVC casing and stainless steel screen. PVC casing exposed to sunlight should be protected or treated to withstand ultraviolet radiation without becoming brittle. Casing diameter is generally dependent on pump space requirements. Dual-phase pumps usually require a minimum of 15 cm (6 in) inside diameter; larger pipe diameters allow easier pump installation. If only groundwater and air are to be removed, groundwater pumps as small as 5 cm (2 in) in diameter capable of pumping 0.04 m^3/min (10 gpm) are available. Wells in which small diameter groundwater recovery pumps or drop tubes are installed should be at least 10 cm (4 in) in diameter to provide higher well efficiency. Generally, 15 cm (6 in) diameter or larger wells are recommended. The specifications should require casing with flush-threaded joints and o-ring seals. A well sump, 0.6 to 3 m (2-10 ft) long and constructed of the same casing materials, should be incorporated in wells designed for DNAPL recovery. It should be noted however, that regulatory agencies may not approve of installation of a sump in a DNAPL recovery well where drilling into an aquitard that is preventing DNAPL from migrating further vertically is required. In such a case, it may be possible to modify submersible pumps to make them bottom-loading, enabling DNAPL recovery in a well without a sump.

(b) Screen. Well screen is usually PVC, but as noted above, other materials may be more appropriate. The use of continuous-wrap "v-wire" screen is strongly recommended. Screen slot size is designed based on the formation material and filter pack gradation according to methods outlined in Driscoll (1986) or similar reference. Different slot sizes can be used in different portions of the screened interval if the producing formation varies in soil gradation. The screen slot-size selection for the portion of the well likely to be placed above the typical location of the capillary fringe can be selected based on guidance given in EM 1110-1-4001, Soil Vapor Extraction and Bioventing. If the gradations of the producing formation have not been determined during design, the contractor should obtain samples during drilling. Require the contractor to run gradations according to an appropriate method (e.g., ASTM D 422 Standard Method for Particle-Size Analysis of Soils) and size the screen slot (and filter pack, discussed below) accordingly. Screens with flush-threaded joints and o-ring seals are preferred.

(c) Filter pack. The requirements for filter pack for this application are generally more critical than for SVE wells because the filter pack plays a more significant role in reducing entrainment of fine sands, silts, and clays in the produced fluid. As described above, the filter pack gradation should be chosen based on the gradation of the producing formation. Design should follow methods outlined in Driscoll (1986) or similar reference. If only groundwater and air are to be recovered, require the chosen filter pack to have a uniformity coefficient of 2.5 or less. A less uniform filter pack may be appropriate if non-wetting fluids, such as hydrocarbons, are to be recovered or in those cases involving fine grained, low-yield soils, where the formation may yield significant amounts of fine material through a uniform filter pack. In this case, a uniformity coefficient greater than 2.5 may be specified; however, the uniformity coefficient must not exceed the uniformity coefficient of the typical formation. Require rounded to subrounded siliceous particles, free from organic matter and calcareous or elongated particles. If free product recovery is of primary concern, a special filter pack that includes hydrophobic materials, such as ground high density polyethylene (HDPE) or polytetrafluoroethylene (PTFE, Teflon®), may improve the early rates of product (LNAPL and DNAPL) recovery (Hampton et al. 1993). In certain (relatively rare) circumstances, a well can be designed that does not include filter pack, but develops a natural filter pack. Thorough well development can selectively remove fines from the native formation material and leave coarser native sands and gravel around the well as a natural pack.

(d) Seal and grout. A well seal is necessary to prevent entry of grout into the filter pack and well screen. Unamended sodium bentonite, as pellets, granules, or a high-solids bentonite grout, is normally specified for the seal material. The use of bentonite chips is not acceptable for most applications. Since most applications will involve the extraction of groundwater and either floating product or soil gas, the well seal will be above the water table and pellets or granules must be hydrated with clean water added to the annulus. A cement grout is normally required above the bentonite well seal. The mixture of the grout should be specified and is normally one 43-kg (94-lb) bag of cement, (optionally with up to 2.3 kg (5 lb) of bentonite powder to further resist cracking), with less than 0.03 m^3 (8 gal) of clean water. Reference ASTM Standard C150, Standard Specification for Portland Cement, as appropriate. In the event that the seal will be placed below the water table, the use of bentonite pellets is preferred.

(e) End caps and centralizers. Flush-threaded end caps, consistent with the casing and screen in size and material, should be specified. Centralizers center the well in the borehole and must be a size appropriate for the casing and borehole. Select centralizers made of material that will not lead to galvanic corrosion of the casing. For DNAPL recovery wells, a funnel-shaped “basket” can be placed outside the bottom of the well screen at the base of the filter pack that directs product flowing downward within the filter pack into the well (Niemeyer et al. 1993).

(2) Installation.

(a) Test holes. Careful design of the filter pack, screen slot size, and screen location needs to be based on site-specific conditions. It may be necessary for the contractor to drill test holes at the proposed well locations to obtain boring logs and samples for gradation analyses.

(b) Drilling methods. There are many methods for drilling. Drilling methods can be proposed by the contractor or specified. Avoid mud-based drilling fluids if possible because of the difficulty in developing the zone containing floating product. The use of water-based fluids can also impede product recovery because the water can displace the hydrocarbon near the well and disrupt continuous hydrocarbon flow pathways. Auger, air-rotary, dual-wall air casing-hammer, rotosonic, or cable tool drilling may be acceptable, depending on site conditions. Choose drilling methods that minimize smearing of fines on the air- or product-bearing interval. Require that all equipment be decontaminated and disinfected before drilling at each location.

(c) Soil sampling and logging. Sampling of soils encountered during drilling increases understanding of the subsurface and allows better decisions to be made about well construction, including screen placement. Require sampling of soils at regular intervals, at least every 1.5 m (5 ft); sometimes, continuous sampling is appropriate. Samples should be obtained by appropriate method such by as split spoon sampler or thin-walled tube according to ASTM D1586, Standard Method for Penetration test and Split-Barrel Sampling of Soils, or D1587, Thin-Walled Tube Sampling of Soils, respectively. Consider sample volume requirements when specifying the sampling method. Require that sampling for chemical and physical analyses be done according to an approved sampling and analysis plan. Strongly recommend a drilling log be prepared by a geologist or geotechnical engineer. Materials encountered should be described according to a standard such as ASTM D2488, Standard Practice for Description and Identification of Soil (Visual-Manual Procedure). Geophysical logging may be appropriate for borings that extend into the water table. Electrical and gamma ray logs can help identify coarser materials for screen placement and can supplement or reduce soil sampling. This can reduce the time needed to drill and sample the hole. Refer to EM 1110-1-1802, Geophysical Exploration for Engineering and Environmental Investigations, for further information on geophysical logging.

(d) Borehole diameter and depth. Specify the dimensions of the borehole for well installation. The diameter must be approximately 10 to 15 cm (4 to 6 in) greater than the diameter of the casing and screen to allow placement of the filter pack. If the well is to be naturally developed, a smaller borehole diameter is acceptable. Note that in fine-grained formations, natural development is problematic. The depth of the borehole should be based on the screen depth. The borehole should only extend to a foot below the projected bottom of the screen (or DNAPL sump, if part of the well design, paragraphs 3-8g(4) and 5-5d(1)(a).

(e) Screen and casing placement. Casing and screen must be cleaned and decontaminated before placement. Disinfection of materials may also be desirable. Screen and casing should be joined by flush-threaded joints and suspended in the center of the borehole. To maintain plumbness and alignment, the string should not be allowed to rest on the bottom of the hole. Centralizers should be placed on the casing at regular intervals if the depth of the well exceeds some minimum value such as 6 m (20 feet).

(f) Filter pack placement. The specification should require the filter pack to be placed using a decontaminated tremie pipe. Since much, if not most, of the filter pack is placed below the water table, the tremie pipe should be kept within 0.6 to 3.0 m (2 to 5 feet) of the surface of the placed filter pack. This prevents the pack material from bridging or segregating by size while falling through the water column. Measure the level of the pack material following placement. Approximately 0.3 m (1 ft) of filter pack should be placed in the borehole below the bottom of the screen to act as a cushion for the screen and casing. Filter pack material should extend 0.6 to 3.0 m (2 to 5 feet) above the top of screen to allow for settlement so native material will not collapse around the screen. Gentle agitation of the water within the well during or after filter pack placement can help ensure full settlement before grouting. Store and handle the pack material carefully to avoid contamination from undesirable materials.

(g) Seal and grout placement. The grouting of the well is critical to preventing vertical migration of contaminants along the wellbore and short circuiting due to air leakage from the ground surface if vacuum is applied. Normally 0.9 to 1.5 m (3 to 5 ft) of a bentonite well seal are placed above the filter pack. If the well seal is to be placed above the water table, the specification should include a requirement for hydrating the bentonite before placement of the grout. The specification should require the addition of a volume of distilled or potable water for every 15-cm (6-inch) lift of bentonite pellets or granules. The bentonite should hydrate for at least three to four hours before placing the grout. This can be avoided by specifying the use of a bentonite high-solids grout as the seal. Place the high-solids bentonite grout by tremie pipe. Cement grout should also be pumped into annular space via a side-discharge tremie pipe and the pipe should be kept submerged in the grout during grout placement. If the grout is to be placed to a depth of less than 4.6 m (15 ft), the grout may be poured into place directly from the surface. If the well seal is to be placed below the water table, allow the bentonite pellets to hydrate in place for three to four hours before grouting the well. Fine sand can be placed above the bentonite pellets to further prevent grout intrusion.

(h) Surface completion. The extraction of multiple phases from a single well will require specification of a suitable wellhead. Provisions may be needed in the wellhead for multiple discharge pipes, electrical leads, compressed air or vacuum lines, control leads, and sampling ports. Compression grommets with rubber or viton seals that squeeze around electrical conduit, drop tubes, etc. when the compression fitting is tightened are used to seal the well penetrations. If finished above grade, the well may require suitable protection, such as a small wellhouse and bollards, to avoid damage to the well and equipment from vandalism, traffic, etc. A well vault may be required.

(i) Well development. Well development is critical to the ultimate performance of the well. A careful specification of the acceptable development methods and development criteria is strongly recommended. Require the water-bearing interval of the well be developed by surging and bailing using a suitably sized surge block or jetting at appropriate water velocities. The development of the water-bearing zone should continue until the well is producing clear water with less than 2 to 5 ppm by weight sand and/or other suspended solids. A turbidity criterion defined as less than 5 Nephelometric Turbidity Units (NTUs) determined by a nephelometric turbidity measurement method can be used. Such criteria may not be appropriate or feasible in fine-grained formations. Establishing some required level of effort (e.g., development time) may be an acceptable option in those cases. Sometimes, the use of dispersing agents such as phosphates can help develop wells by breaking down clay smears on the borehole walls. The regulatory authorities may need to approve dispersing agents or other additives such as acids. Note that jetting or other development techniques that use water can dramatically affect product recovery by disrupting floating hydrocarbon flow pathways. Do not use jetting (or surging) in the product-bearing zone. The use of surfactants in development of the product-bearing zone may also improve product recovery by reducing pore-scale NAPL/water interfacial tension barriers to product flow. In rare cases, and only with regulatory agency approval, introduction of previously recovered product into the well may improve product recovery by increasing product saturation in the filter pack and surrounding formation. Development is conducted after placement of the filter pack and before or after grouting the well. Development before the grouting of the well will ensure that the filter pack is fully settled before grout placement, thus assuring no voids would be created; however, the potential exists for cross-contamination while the well annulus is open above the pack. Normally, conduct development after grouting.

(j) Disinfection. In some cases, biological encrustation has caused severe degradation of performance of extraction wells. Contaminated sites often provide ample food for microorganisms that can plug well screens. Disinfection of the drilling tools and the well itself can help prevent or slow these problems. Disinfection can be done by various means (refer to Driscoll 1986; AWWA A100, Section A1-A10), including creating a specified concentration of a strong oxidizing agent, such as sodium hypochlorite, in the well. Consider the chemical ramifications of any additives. Consult with the project chemist to evaluate possible dangerous or undesirable reactions that may occur between the groundwater constituents and the disinfecting reagents.

(k) Surveys. Establish the horizontal coordinates of the well by survey. Survey the elevation of the top of the casing to provide accurate groundwater elevations. The accuracy of the surveys depends on the project needs, but generally is to the nearest 0.3m (1.0 ft) for the horizontal coordinates and the nearest 0.003 m (0.01 ft) for elevation.

(3) Permits. Identify the well and construction permits needed from local agencies. These are usually obtained by the contractor. Utility clearances are also typically required.

e. Soil Gas/Vacuum Monitoring Points and Monitoring Wells. Refer to EM 1110-1-4001 for guidance on the design and construction of soil gas/vacuum monitoring points. Refer to EM 1110-1-4000 for guidance on the design and construction of groundwater monitoring wells.

f. Horizontal Wells. Horizontal wells or drains can be used for multi-phase recovery provided adequate steps are taken to assure proper depth. Horizontal wells can be used for the simultaneous recovery of water and product if the well can be installed near the NAPL/water interface. The well acts as a drain for both product and water. Provided the liquids can be removed at an adequate rate to result in open-channel flow in the well, air could also be extracted at the same time. Horizontal wells can be used to recover product under structures (provided adequate steps are taken to avoid damage to foundations) or as an alternative to trenches if the creation of contaminated trench spoil is problematic. Depth control is critical for multi-phase extraction. Poor depth control can cause inconsistent product, air, or water production due to high and low spots in the screened interval. Refer to USEPA (1994) and other USACE guidance on horizontal wells for additional design and installation information.

(1) Materials. Differences between horizontal and vertical applications are discussed below.

(a) Casing. Although PVC casing is commonly used, flexible or rigid polyethylene pipe may be more efficient for certain placement methods. Reference appropriate ASTM standards for PVC pipe or ASTM D3350 for polyethylene plastics pipe and fittings materials. The casing can be joined by threaded coupling or thermowelds, as appropriate for the material. Pipe sizes of 50 to 200 mm (2 to 8 inches) are typically used. Larger diameters than typically used in vertical wells may be required because of the potentially larger flow rates and better recovery of multiple phases. Larger pipe sizes allow easier access for development, surveys, and maintenance.

(b) Screen. Avoid using drainpipe wrapped with geotextile or other filter-like material because of the potential for fine material to plug the openings. Perforated piping is more difficult to develop and rehabilitate that continuous slot screen. Prepacked well continuous-slot screens have been successfully used in recovery applications. Prepacked screens are really two screens enclosing preselected filter pack material. The use of prepacked screen can overcome the difficulties of installing filter pack within a horizontal well. Stainless steel prepacked well screen is typically used instead of PVC because its greater strength allows it to withstand the stresses of placement. There are porous materials, including porous sintered polyethylene, that have also been used very successfully as screen and filter pack in horizontal wells.

(c) Bedding material/filter pack. If a filter pack is to be placed around the horizontal well screen, it should be sized according to the formation, as it is for vertical wells. Filter pack is difficult to place uniformly in horizontal wells.

(d) Development. Horizontal wells are more difficult to develop than vertical wells. Jetting has been most commonly used. As discussed for vertical recovery wells, jetting should not be used in the product-bearing zone. If the horizontal well is to be used for LNAPL recovery, any development should be done before the product in drawn to the level of the well. Development of a DNAPL recovery trench is problematic. Best results may be obtained without any development.

(2) Installation. Installation methods vary significantly depending on drilling method. Refer to EPA (1994) for additional information. The use of bentonite-based drilling fluids is discouraged. Degradable additives, such as guar-based products are preferred.

g. Recovery trench. Recovery trenches can be used effectively at sites with shallow product and groundwater. The placement of a recovery trench can be accomplished by several methods including normal excavation or trenching machines (which excavate and place pipe and filter pack in one pass).

(1) Materials. Materials specified for recovery trench construction are often similar to those specified for horizontal wells. Different materials may be needed if specialized trenching methods or machines are used. Differences between trench and vertical/horizontal well applications are discussed below.

(a) Casing. Although PVC casing is commonly used, flexible or rigid polyethylene pipe may be more efficient for certain excavation methods such as trenching machines. The pipe must resist the crushing pressures of the backfill and compaction equipment.

(b) Screen. Screen can consist of slotted pipe, continuous slot screen, or porous material.

(c) Bedding material/filter pack. The guidance for specifying filter pack in vertical multi-phase extraction wells may be applied for trenches, but somewhat coarser material may be needed for a secure bedding and cover for the pipe and screen. Coarse material (uniform coarse sand and gravel) also provides a high hydraulic conductivity during pumping.

(d) Backfill material. Native material may be used as backfill above the filter pack in an excavated recovery trench. Coarse filter pack material may extend into the unsaturated zone especially if there are seasonal variations in the water table.

(e) Geotextile. A geotextile may be needed to separate the filter pack from native material or clay backfill in an excavated trench.

(f) Marking tape and locator strips. Specify a locator strip specifically manufactured for marking underground utilities. This tape is made of colored polyethylene backed with foil or containing embedded wire that allows others to locate the trench at later dates.

(2) Installation. Installation methods vary significantly depending on excavation method.

(a) Excavation methods. Methods used to install recovery trenches include many standard earth-excavating equipment (e.g., backhoe) and trenching machines. Given this wide variety, it may be desirable to specify only the pipe, screen, pack materials, and an ultimate pipe alignment and depth. This would allow the contractor the option to propose what might be the most cost-effective method; however, the trenching technique used by the contractor must provide an adequate filter placement around the collector pipe and avoid to the extent possible smearing of fines along the trench wall in any product bearing zone. Dewatering or shoring will be required in most cases. Dewatering generates contaminated water that requires storage or treatment. Shoring with trench boxes or sheet piles, for example, maintains wall stability while bedding material and piping is placed. Compliance with Occupation Safety and Health Administration and USACE safety requirements is mandatory.

(b) Soil sampling and logging. If open excavation techniques are used, a graphical log of the materials encountered in the trench should be prepared, including the description of the materials according to ASTM D2488.

(c) Trench dimensions. The trench dimension should be wide enough to allow preparation of the bottom of the trench and placement of the pipe. Normally, the trench width is limited to the pipe diameter plus 600 mm. If the material to be trenched is contaminated, a smaller trench reduces the volume of material to be disposed or treated as waste. The trench depth must exceed the depth of the bottom of the mobile NAPL if product recovery is a goal. A deep trench may be useful for providing more certain capture of a dissolved plume, though it may increase water yield for product recovery. If the recovery of soil gas is desired, the filter pack must extend some height above the projected water levels, but should not extend to depths less than 1 to 1.5 m (3 to 5 ft) below the surface if no surface cover is provided. Trench length is selected based on the objective of the system. If the trench is meant to capture a migrating plume of NAPL and groundwater, the trench width should span the width of the plume. If the trench is designed to capture an area of NAPL, the trench length must be adequate to assure that all product flow lines extend to the trench. Modeling may be required. Excessive trench length may make operational modification difficult. For example, if the plume shrinks during operation, a long trench extending well past the limits of the plume may recover undesirable volumes of clean water.

(d) Trench bottom preparation and pipe placement. The bottoms of the excavated trenches must be prepared before placement of pipe and screen. Unstable materials should be removed. A bedding layer of filter pack material approximately 100 mm thick should be placed before pipe and screen placement. The trench bedding must be leveled to the required grade to provide uniform bearing for the pipe and to assure somewhat uniform hydrostatic head along its length. Pipe depth must consider the objectives of the system. If both air and liquid recovery is desired, two pipes set at different depths, one shallow (in vadose zone) and one deep (at depth of desired groundwater or product depth), may be appropriate. Place pipe near the depth of maximum hydrocarbon saturation for product recovery with minimal water production. Pipe should be placed no more than a few feet below the product smear zone for simultaneous groundwater and LNAPL recovery. The pipe and screen should be placed in a way that prevents entrapment of filter pack or native material inside the pipe. The joining of sections of the pipe and screen must be done in a manner consistent with the material and manufacturer's recommendations. A clean out or access port for the pipe should be provided to allow for later surveys and maintenance of the screen and casing.

(e) Filter pack placement. Compaction of the filter pack material should not be done within 150 mm to 300 mm of the pipe and screen. Some trenching machines place the pipe and filter pack material as it progresses. In these cases, it is important to verify that the machine is placing adequate filter pack around the screen.

(f) Backfilling and compaction. The remainder of an excavated trench is backfilled with the appropriate material. Placement of a geotextile between the filter pack and backfill may be appropriate if there is a significant difference in grain size between the two materials. Backfill above the filter material should be placed in 150- to 200-mm lifts and compacted to approximately 90 percent optimum standard density, determined by ASTM D 698, if cohesive materials are used. Compaction should not occur closer than 0.3 m (1 ft) above the pipe. A locator strip should be placed within 0.5 meter of the surface.

5-6. Piping and Above-Ground Equipment. Selection of piping and system hardware will depend on site and contaminant specific factors. Configuration of the various extraction and treatment system components will depend on whether the MPE system is simultaneously extracting total fluids (air, NAPL and water) with a common intake line or whether the system is recovering air and liquids separately. Designers of above-ground piping and components must coordinate with designers of underground portions of the MPE system to ensure compatibility in materials and flow capacity.

a. Piping.

(1) It is important to select piping materials of appropriate size and materials of construction to allow proper and efficient operation of the MPE system. Undersized piping system components could lead to inefficient operation of the MPE system or damage to the system blowers/pumps, while oversized components may add unnecessary capital costs and result in inefficient operating conditions. Selection of piping materials that are incompatible with the recovered fluids or the system operating parameters may result in failure of the piping system, while improper or unnecessary specification of exotic or expensive piping materials will add an unwarranted burden to the system capital cost.

(2)Piping for an MPE system generally includes one or more intake (suction) lines, influent manifold(s), interconnecting piping between the phase separation and treatment system components, sampling lines, recovered NAPL transfer lines, and pressurized discharge lines. Certain types of MPE pumps will have oil or water seal circulation lines. Natural gas, propane or diesel fuel lines may also be required for thermal off-gas treatment systems (e.g., catalytic or thermal oxidizers, internal combustion engines, etc.). MPE piping systems may employ polyvinyl chloride (PVC), coated black (carbon) steel, stainless steel or copper pipe, as appropriate for the intended use. In addition, flexible reinforced hose (PVC, HDPE, rubber, etc.) or flexible tubing (HDPE) may also be used to incorporate a degree of flexibility into the system.

(3) Refer to CEGS-02500 (Pipelines, Liquid Process Piping) and CEGS-02150 (Piping, Off-Gas) for specific guidance on process piping requirements. EM 1110-1-4008 on Liquid Process Piping is also available to supplement CEGS-

02500. Refer to the process piping EM 1110-1-4008 and the applicable CEGS sections when designing or installing process piping.

(4) The following major issues must be considered when designing an MPE piping system: pneumatics and/or hydraulics, pressure/vacuum limitations, temperature limitations, material compatibility and mechanical constraints. When metallic components are used, corrosion of some type may occur. USACE policy requires that all underground ferrous piping be cathodically protected. In addition, corrosion may occur when dissimilar metals are immersed in a conductive medium. Use of dielectric bushings to prevent corrosion should be used when dissimilar metals are joined together (e.g., copper tubing connecting to a steel pipe or tank). Additional information may be found in EM 1110-1-4008, Liquid Process Piping. Table 5-6 provides a summary of the physical property limitations of the various types of piping materials typically used in MPE systems. These considerations are discussed in the following paragraphs.

TABLE 5-6

Physical Properties of Common MPE Piping Materials

			Chemical Resistance[2]			
Material	**Max. Presure[1] PSI**	**Max. Temp. °C (°F)**	**Non-Halogenated VOCs[3]**	**Halogenated VOCs[4]**	**Oils**	**Acids[5]**
Sch. 80 PVC	400[6]	60(140)	Good-poor	Poor	Excellent	Good to excellent
Sch. 40 Galv. Steel	2500		Good-poor	Good	Good	Fair to poor
Sch. 40 Coated Steel	2500		Fair	Excellent	Good	Poor
Sch. 40 Type 304 S.S.		204 (400)	Excellent	Good	Excellent	Fair to poor
Type K Copper Tubing	450	Varies	Good-poor	Excellent	Good	Poor
Reinforced PVC Hose	Varies, typ. <200	27-93(80-200)	Good to poor	Poor	Excellent	Good
HDPE Tubing	55-140		Good to poor	Poor	Poor	Good to fair

Notes:
1) Max. Pressure rating for 50 mm (2 in.) diameter pipe at approx. 38°C(100°F). If operating temperature is over 38°C (100°F), working pressure must be de-rated. Maximum allowable pressure will vary for pipe sizes other than 50 mm (2 in.)
2) This table is intended as a general guideline for various classes of contaminants. Always consult with the manufacturer to determine chemical compatibility with site-specific contaminant suite.
3) e.g., pure benzene, toluene.
4) e.g., pure trichloroethylene.
5) e.g., sulfuric acid. Different acids will have different chemical compatibility.
6) PVC pipe manufacturers do not typically recommend their products for use in above-ground air/gas, pressure/vacuum applications. Pressure rating is for water service.

Source:
Pressure, Vacuum, Temperature Limits:
F.W. Webb Company. 1995. General Catalog. Wallace Press. Hillside, IL.
Chemical Compatibility Data:
Omega Engineering, Inc. 1995. Flow and Level Handbook. Omega Engineering, Inc. Stamford, CT. pp. Z46-Z57.

(5) Pneumatics and/or Hydraulics.

(a) The piping system (intake and discharge) components must be sized to accommodate the design flow without excessive frictional losses. Frictional loss calculations for liquids flowing through piping typically use the Darcy-Weisbach equation:

$$h_f = f\ (L/D)(v^2/2g) \qquad [5\text{-}4]$$

where:

h_f = friction loss

f = friction factor (dimensionless)

L = Length of pipe

D = inside diameter of pipe

v = average fluid velocity

g = gravitational constant (9.8 m/s^2, 32.2 ft/sec^2)

(b) The friction factor is a dimensionless number that has been determined experimentally, and is based on the pipe's interior roughness and the Reynolds number. The Reynolds number is a function of the fluid velocity, pipe diameter and fluid viscosity. From this, it can be seen that friction loss (or head loss as it is often termed) is related to the volumetric flow rate and fluid viscosity (which is a function of temperature), as well as the pipe material, diameter, and length. Any one or a combination of these items can be manipulated to maintain frictional losses through the piping system within acceptable limits. A detailed discussion of pneumatic analysis for determining head loss through extraction system piping is presented in EM-1110-1-4001, Chapter 5, and as such will not be discussed here. In addition, most elementary fluid mechanics texts (e.g., Gerhart and Gross 1985) or engineering handbooks (Perry and Green 1984; Marks 1987; Ingersoll-Rand 1987) provide detailed discussions on this subject.

(c) In addition to the Darcy-Weisbach equation, many empirical formulas have been developed for evaluating frictional losses under turbulent flow conditions. Turbulent flow is believed to be common in MPE applications, especially in TPE where fluid is moving at high velocities through a small diameter drop tube. Turbulent flow is a function of the Reynolds number, which indicates flow is turbulent at values greater than approximately 4,000 (Munson et al. 1990). The Reynolds number is proportional to fluid density, velocity, and pipe diameter and will therefore increase as any of these values increase. The Hazen and Williams formula is a commonly used empirical solution for determining frictional losses through pipes, with inputs of length, diameter, flow rate and the Hazen and Williams friction factor (C), which is based on the material type and condition of the pipe. The Hazen and Williams "C" factor is different than the Darcy-Weisbach "*f*" factor. As engineering handbooks (Ingersoll Rand 1988; Crane 1988) provide a discussion of this method of friction loss calculation, it is not discussed in detail here; however, the designer should note that this empirical formula was developed for water at 15°C (60°F). Significant variation in results can occur at different temperatures.

(d) Many handbooks present the concept of "equivalent lengths" for fittings, where the friction loss through a fitting (e.g., elbow, tee, valve, etc.) is represented as an equivalent length of straight pipe of the same nominal diameter as the fitting. Various nomographs have been developed to speed the friction loss calculation procedure (Crane 1988; Driscoll 1986). In addition to these nomographs, several suppliers offer computer programs to calculate piping system friction losses and to aid in optimizing pipe size (e.g., Crane 1997; Costello 1996).

(6) Pressure/Vacuum Limitations. Pressure and vacuum limitations of the various types of piping typically used in MPE systems vary, depending upon the material of construction and the method used to join pipe sections and fittings (i.e., threaded, flanged, or glued). The type of joint specified and the care with which the joint is installed in the field should be given careful consideration to minimize air leakage into (or out of) the MPE system under operating conditions. Where polyvinyl chloride (PVC) pipe is used, PVC pipe joints depend on internal pressure forcing the seal into the joint (for larger diameter PVC pipe where compression joints are required). Thermoplastic piping or tubing (e.g., PVC, high-density polyethylene [HDPE], etc.) is typically limited to lower positive pressure applications than metallic piping systems. Reinforced flexible hose or tubing may be used on the intake (suction) side of the vacuum blower provided that the hose or tubing is rated for the maximum applied vacuum anticipated for the MPE system. Thermoplastic pipe or flexible tubing may not be suitable for high vacuum applications (>88 kPa [>26" Hg] vacuum). Consult with the manufacturer to determine pressure and vacuum ratings for the type of pipe or tubing proposed for use. Remember that the manufacturer's specified vacuum or pressure rating may change with fluid temperature. In some cases, testing performed by manufacturers may not reach the pressure or vacuum limits required for a particular MPE system. In these cases, additional research and/or testing should be performed in order to ensure proper material specification.

(7) Temperature Limitations. The temperatures typically encountered in MPE system operation generally do not significantly affect metallic piping components. However, it is often desirable to use thermoplastic piping or flexible hoses to join certain components of an MPE system to reduce piping costs, to allow flexibility for system adjustments (e.g., raising/lowering the drop tube), or to facilitate treatment component change out. Thermoplastic piping or tubing (PVC, HDPE, etc) may weaken or melt at elevated temperatures. It is not uncommon to encounter temperatures in excess of 93 °C (200 °F) in the vapor exhaust stream of a MPE blower. Typical Schedule 40 PVC can deform or melt at temperatures in excess of approximately 60 °C (140 °F), and it is therefore not applicable for use in locations where the temperature is expected to approach or exceed this value. To be conservative, a temperature lower than the typical manufacturer rating of approximately 43 °C (110 °F) is a reasonable limit to avoid deformation. In many cases, a segment of metallic pipe can be utilized at the blower exhaust to radiate heat to the atmosphere, after which PVC, CPVC, or other thermoplastic materials can be used to complete the remainder of the plumbing through the treatment train. Insulate or cover piping sections and employ appropriate warning signs to protect workers from pipes carrying high temperature (>38 °C [>100 °F]) fluids, and also to prevent condensation and freezing in above grade pipelines. Thermal expansion and contraction of plastic pipe exposed to ambient conditions weakens and occasionally destroys the joints. Refer to Plastic Pipe Institute publications AW-132 TR-22 Thermal Expansion and Contraction of Plastic Pipe and AW-129 TR-18 Weatherability of Thermoplastic Pipe for more information.

(8) Material Compatibility. Careful consideration must be given to the materials of construction employed in MPE piping systems that will be in contact with contaminated fluid streams. In many cases, PVC piping will

suffice; however, there are circumstances where PVC is not appropriate. For example, chlorinated solvents when present as pure product will degrade PVC, however in most MPE applications where chlorinated hydrocarbons are present in the ppb to ppm range, PVC piping should suffice. Contact with NAPL or high dissolved concentrations may cause some plastic or rubber materials to degrade, become brittle, or crack, resulting in a mechanical failure and a potential release to the environment. Consult the manufacturer's chemical compatibility chart before specifying pipe materials, particularly in cases where NAPL or high dissolved concentrations are present.

(9) Mechanical Constraints. Piping for an MPE system must be supported and protected from damage. The cyclic action of vacuum application and suction breaking that can be encountered in an operating TPE system results in an effect somewhat similar to a water-hammer, which can damage improperly restrained or unsupported pipes. Pipe supports should conform to MSS SP-58, MSS-SP-69 and MSS-SP-89.

b. Design and Installation of MPE Manifold.

(1) The intake manifold system connects the extraction wells to common header pipe(s) and combines the extracted fluids into a common flow network for phase separation and subsequent treatment. In the case of DPE (separate pumps for liquid and vapor recovery), the liquid and gaseous phases are withdrawn from the extraction well within separate conduits. Separate manifolds may be constructed for liquid and air streams. A typical MPE intake manifold will consist of some or all of the following components:

- Pressure/vacuum indicators.
- Temperature indicators.
- Flow control valves.
- Flow meters (air and/or water for DPE applications).
- Sample ports.
- Ambient air (dilution) inlet valve(s).
- Check valves.
- Solenoid valves or motorized valves (optional - to allow automated cycling between wells).

Vacuum applied to the subsurface and/or flow extracted from the wells may be regulated using a dilution valve (ambient air bleed-in valve) or by a variable speed drive on the vacuum pump. The variable speed drive is a more efficient means of regulating vacuum and flow.

(2) A typical MPE manifold layout is depicted in Figure 5-10. Manifolds may be constructed of PVC, HDPE, galvanized steel, or where required, stainless steel. MPE designers and installers should install segments of transparent PVC pipe or hose on the intake side of multi-phase vacuum blowers for TPE

applications (transparent pipe is normally needed for DPE). This will facilitate observation of the fluids being produced by the MPE wells and may provide useful information on the nature of the multi-phase flow into the system (i.e., slug flow, annular flow, etc.), to aid in optimizing performance.

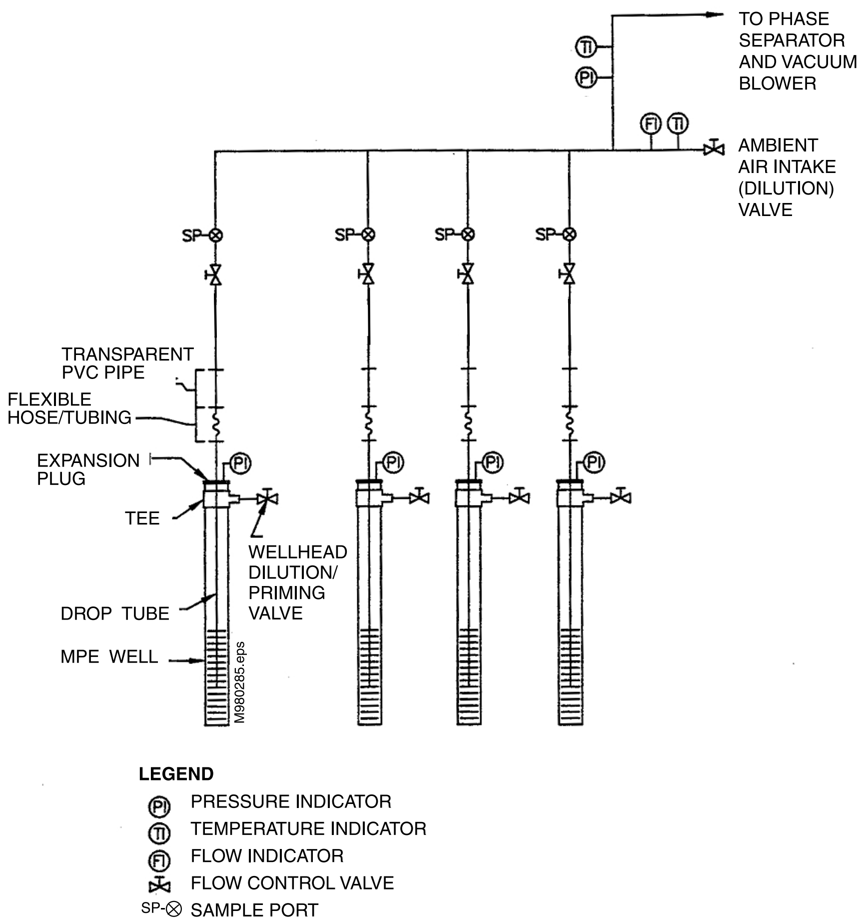

Figure 5-10. Typical Two-Phase Extraction System Piping Manifold.

(3) The MPE manifold must be designed to allow monitoring and control of individual MPE wells. This will allow the operator to observe the effectiveness of individual MPE wells and balance flows among multiple MPE wells. Control of individual wells will also allow the operator to cycle among MPE wells to vary subsurface air and water flow pathways, and to focus remediation efforts on the most contaminated areas as the remediation progresses. Preferential flow pathways may exist in the subsurface prior to the start of MPE as described in Chapter 2, or may develop as the soil moisture content is reduced during MPE operation. Varying subsurface air and water flow pathways by cycling individual MPE wells, or groups of MPE wells, on and off will change the subsurface hydraulic gradients, thus varying the flow pathways within the treatment area.

(4) Manifold piping may be located either above or below ground. For extended operating periods it is generally best to install manifold piping below ground in shallow utility trenches to protect the piping from mechanical damage, freezing and vandalism. Piping located below ground should be constructed of, or coated with, non-corroding materials, or should be mechanically protected from corrosion (e.g., cathodically). In some cases, MPE piping may be installed with as little as two feet of cover if adequate slope is provided to allow liquids to drain from the pipe. However, in colder climates, especially in cases where liquid is moving as creep flow or as droplets, frost/ice scale will build up on the pipe interior and reduce the available flow area, which will eventually cause a blockage in the pipe. If pipe is installed above the local frost line, frost heaving may damage the pipe or weaken underground joints. Where installation of MPE piping below frost depth is not feasible, the lines should be heat-traced and insulated to avoid the damage discussed above.

(5) The manifold can be installed at a central location (e.g., inside the treatment enclosure). This is convenient in that the flow/pressure/temperature monitoring, flow control devices and sample ports can be located in an easily accessible location; however, constructing the manifold in this fashion requires running separate lines to each extraction well to achieve control of the individual wells. This method, although slightly more costly to install, provides the best means for balancing flows during system operation. An alternative is to place the monitoring and control devices in the well vaults and connect the lines from the individual wells to one or more common header pipe(s), which extend back to the vacuum pump in the treatment enclosure. To monitor or adjust flows and pressures, the operator must travel between wells making incremental adjustments at each location, and checking the effect at the other wells. This small installation cost savings is likely to be far outweighed by labor costs incurred during system operation.

(6) The working pressure (not burst pressure) of the manifold piping should be able to withstand the maximum anticipated (worst-case) system pressure (USEPA 1996a, Appendix B).

(7) If an underground manifold is constructed of plastic pipe, a metallic locator strip or similar material should be installed in the trench along with the manifold piping to allow magnetic location of the buried manifold at a later date. As an added safety measure, caution tape or other marking material should be placed in the trench above the pipe bedding materials, to indicate the presence of buried lines.

c. Piping and Valves.

(1) Extraction piping for MPE systems may include a single multi-fluid (air, NAPL, water) intake line or may consist of separate fluid intake lines for air and liquids, depending on what variation of MPE is employed at the site. Piping and valves used in MPE installations should be selected and installed in accordance with CEGS 02500 Pipelines, Liquid Process Piping and CEGS 02150, Piping, Off-Gas.

(2) Valves are used to regulate flow in the MPE system, or in the case of closed valves, to isolate portions of the MPE system. Valves should be assigned unique identification numbers during the design phase and should be labeled with corresponding identification markers during installation to facilitate operation and maintenance of the MPE system.

(3) A number of different types of valves may be used to control or shut off flow in MPE systems. A list of the valve types and a brief discussion of the nature and function of these valves is provided below. A more detailed discussion of these various valves can be found in many sources, including EM 1110-1-4001 Soil Vapor Extraction and Bioventing (Chapter 5), EPA/600/R-96/042 (USEPA 1996a, Appendix B) or in Perry's Handbook (Perry and Green 1984, Sec. 6). Be aware that MPE systems frequently extract some silt with the recovered liquid stream. This may cause valves to become clogged and require frequent cleaning. Care should be taken to design piping systems that enable easy valve removal if silt clogging is a potential problem.

- Gate valves – Used for on/off service. A wedge shaped gate is moved up (for open position) or down (for closed position where the gate is seated) to allow or stop fluid flow. This valve is designed to minimize pressure drop in the open position.

- Globe (and angle) valves – Used for on/off service and clean throttling applications, this valve controls flow with a convex plug lowered onto a horizontal seat. Raising the plug off the seat allows for fluids to flow through.

- Ball valves – Used primarily for on/off control and some throttling applications, the ball valve uses a rotating ball with a hole through the center to control flow.

- Butterfly valves – Used for on/off and throttling applications, the butterfly valve controls flow with a rotating disk or vane. This valve has relatively low friction loss in the fully open position.

- Diaphragm valves – This multi-turn valve is used to control flow in clean and dirty services. The diaphragm valve controls flow with a flexible diaphragm attached to a compressor and valve stem.

- Needle valves – This multi-turn valve is used for precise flow control applications in clean services, typically on small diameter piping. Needle valves have relatively high frictional losses in the fully open position.

- Plug valves – Used for on/off service and throttling applications. Flow is controlled by a plug with a hole in the center that rotates to align with the flow path.

- Foot valves with strainer – Foot valves are located at the bottom of the suction line of a surface-mounted jet pump. The valve functions similar to a check valve to keep water in the down-well pipe or hose and contains a strainer or screen around its inlet to keep solids from clogging the valve.

(4) Check valves (swing, lift, flapper, and spring check types) should also be incorporated into the intake (immediately upstream of the air/moisture separator) and discharge piping (immediately downstream of the transfer pump that empties the water reservoir of the oil/water separator) of the MPE system to prevent back flow.

d. Condensate Controls and Fluid Separation. Successful operation of an MPE system requires good separation of the recovered contaminant phases to minimize treatment costs (e.g., due to carbon fouling and/or excessive carbon consumption) and to ensure compliance with discharge permit limits. In the case of a dual pump system, liquid (water and/or NAPL) and air are extracted from the well separately. Water and NAPL, if present, may require separation at the surface if a "total fluids" (water and NAPL) pump is employed to recover liquid from the DPE well. However, for other MPE applications, multi-phase fluids (air, NAPL, water) are all extracted simultaneously through a single intake tube and must be separated at the ground surface. The following paragraphs discuss various fluid separation techniques applicable to MPE.

(1) Gas-Liquid Separation. Typical MPE systems employ inertial gas-liquid separators equipped with water level controls/sensors similar to the moisture knockouts used in SVE systems. Because the gas-liquid separators are typically installed between the vacuum pump and the extraction well, the gas-liquid separator tank must be designed to withstand the maximum vacuum that the extraction blower is capable of producing. A brief description of inertial separators is presented in EM 1110-1-4001 Soil Vapor Extraction and Bioventing. A more detailed discussion of centrifugal separation, as well as other gas-liquid separation mechanisms, is presented in Perry's Handbook (Perry and Green 1984). Recovered liquids are typically pumped from the gas-liquid separator to the water treatment system, which may include a NAPL-water separator. If NAPL is present, the transfer pump should be selected to minimize shearing and turbulence of the pumped liquids and thereby prevent formation of oil-water emulsions.

(a) One design approach utilizes a transfer pump with a high suction-head capacity (i.e., low net positive suction head required [$NPSH_R$]). Positive displacement pumps, such as progressing cavity, diaphragm, or double diaphragm pumps, are often used in this application. It should be noted that air-operated double diaphragm pumps may require a large volume of high-pressure air to pump against the vacuum applied to the gas-liquid separator. This approach is relatively simple, is based on components that are readily available, and is particularly good for applications where NAPL is expected, since positive-displacement pumps typically do not tend to increase emulsification.

(b) An alternate approach utilizes a low suction-head transfer pump (e.g., centrifugal pump), coupled with a vacuum-relief device (e.g., vacuum-relief valve or solenoid valves) to allow the transfer pump to evacuate the accumulated liquids from the gas-liquid separator. This approach is also relatively simple; however, there are several disadvantages. Periodic vacuum relief in the phase separator allows ambient air to enter the phase separator. This has the effect of reducing the overall mass removal efficiency from the subsurface (due to discontinuous application of vacuum) and also dilutes the influent concentration to the gas treatment device, which will reduce its treatment efficiency. Also, centrifugal pumps tend to increase formation of emulsions due to the turbulent shearing action that occurs in the volute (impeller chamber).

(c) Another design approach employs multiple gas/liquid separation vessels equipped with level controls that operate under vacuum (refer to Figure 5-1). In this approach, small-diameter tubing connects the headspace of each vessel to that of the other vessels so as to equalize the pressure (vacuum) differences among the vessels. The liquids are then able to flow by gravity between the vessels. In practice, the gas/liquid separator would be located above the other vessels, so that liquids (water and NAPL) separated in it can drain by gravity to a NAPL-water separator. The NAPL-water separator may be a simple decanter for small NAPL volumes or a coalescing-type oil-water separator (see paragraph 5-6d(2) where greater NAPL recovery is expected. Recovered NAPL flows over a weir and drains by gravity to a NAPL storage tank. Accumulated water may be pumped from the NAPL-water separator using either a high-suction head transfer pump or a low suction-head transfer pump and vacuum relief device, as described in the preceding two paragraphs. Manual or automatic isolation valves can be used to allow accumulated NAPL to be pumped from the NAPL storage tank. This approach is somewhat more complex than the previously described approaches since multiple vessels are involved and NAPL-water separation is accomplished under vacuum. An advantage is that the recovered NAPL-water mixture does not have to pass through a pump, reducing the chance for additional emulsification to occur.

(d) A novel approach for multi-phase separation under vacuum combines gas/NAPL/water separation in one vessel (Rentschler 1998). This approach uses an inertial gas-liquid-solid separation tank coupled with a coalescing plate oil-water separator on the intake (negative pressure) side of the vacuum pump. Extracted fluids enter the phase separator tank through a tangential inlet, which forces liquids and entrained or suspended solids to the outer wall of the tank where they eventually settle to the bottom of the first chamber. Extracted vapors are drawn off the top of the phase separation tank by a dry vacuum pump. Liquids (NAPL, water, and condensed water vapor from the air stream) flow over a weir into a stilling chamber where a coalescing plate pack separates LNAPL and water. A pressure (vacuum) equalization line connects the multi-phase separator to a NAPL storage tank, allowing separated NAPL to flow over an adjustable weir and drain by gravity to the NAPL storage tank. Water flows under and over a set of weirs to exit the coalescing chamber. Level sensors in the final chamber control the water transfer pump. A high-suction head transfer pump is preferred for this application since water seals and weirs separate the headspace of the second and third chambers from the first (air/liquid separation) chamber.

(2) LNAPL-Water Separation.

(a) LNAPL-water separators most commonly used in MPE systems are coalescing plate or tube oil-water separators. These types of separators are readily available from a number of vendors, are relatively inexpensive and require little maintenance. Coalescing plate or tube LNAPL-water separators are sized to allow laminar flow conditions to develop based on the design water feed rate. The LNAPL-water mixture flows through a section of corrugated or chevron-shaped plates or vertical tubes, under laminar flow conditions. Small entrained LNAPL particles agglomerate to larger particles and droplets, and rise vertically through the coalescing media. The greater the difference in the specific gravity of the two liquids (LNAPL and water), the more rapid and effective the separation will be (USEPA 1996). Recovered LNAPL is retained in a chamber over the coalescing media, where it can be skimmed off and transferred to a storage tank. Most oil-water separators of this type can effectively remove non-emulsified oil to concentrations below 10 mg/l (USEPA 1996). Effluent water then flows through a series of baffles and typically discharges from the separator by gravity. A pump chamber can be incorporated into the separator or a pressurization tank/pump can follow the separator if additional water treatment is required. NAPL-water separation chambers must be vented to a safe location. Oil/water separators should be sized based on anticipated maximum fluid recovery rates. The separators should also have sufficient sediment and oil storage capacity based on site-specific information such as expected product recovery and the presence of fine sediments within the extracted liquid stream.

(b) Liquid-liquid centrifuges can be used to separate fluids of different specific gravities. Membrane separators (e.g., hydrophobic or hydrophilic membranes) can be used to separate water and hydrocarbons. Distillation can also be used to separate liquids of different boiling points and specific gravity. However, these devices are usually not warranted for LNAPL-water separation applications in MPE systems due to the added capital cost, complexity and maintenance requirements.

(c) Additional guidance on the selection and design of oil-water separators can be found in other USACE guidance on oil/water separators.

(3) Emulsions.

(a) Emulsions are stable dispersions of one liquid in another and are generally characterized by droplet diameters of 1 μm or less (Perry and Green 1984). Emulsions may be characterized as oil-in-water (i.e., organic droplets in an aqueous medium) and water-in-oil (i.e., water droplets dispersed in a continuous organic liquid phase).

(b) Emulsions may be mechanically separated using porous or fibrous solid coalescing media, centrifugal extractors, separating membranes (e.g., hydrophobic or hydrophilic membranes), or by using high-voltage electric fields to separate electrically conductive liquids from non-conductive liquids. Perry’s Handbook (Perry and Green 1984) provides a detailed discussion on liquid-liquid separation techniques. Organically activated clays have also proven to be effective in capturing oil-water emulsions to prevent fouling of activated carbon or other treatment equipment. These clays can be used as a pre-filter prior to secondary treatment equipment. Organically activated clays are especially useful in removal of heavier oils and can remove 50% of their weight in oil (Alther 1997).

(c) Numerous commercially available emulsion-breaking reagents are also available. A bench or pilot scale test should be conducted to determine the most appropriate and effective emulsion-breaking chemical for site-specific conditions. Some of these reagents may require pH adjustment or heating of the emulsion to enhance their effectiveness.

(4) DNAPL-Water Separation.

(a) DNAPL-water coalescing plate or tube separators work on the same principle as LNAPL-water separators. Coalescing plate or tube separators take advantage of the difference in specific gravity between the DNAPL and water, allowing DNAPL to separate under laminar flow conditions. DNAPL and water can be separated using a similar type of coalescing media to that used in LNAPL coalescers, although the DNAPL withdrawal outlet must obviously be on the bottom of the separator tank. More viscous DNAPLs (e.g., creosote, coal tar) may require addition of chemicals to enhance DNAPL flow through this type of device.

(b) As with LNAPL-water separation, other mechanical separation means are available for DNAPL separation, although their use is typically not warranted in MPE systems due to the added cost and complexity of the additional equipment. For operating facilities with organic solvent contamination (e.g., TCE, PCE) where a source of steam is readily available, condensation separation may be a feasible alternative.

e. Electrostatic Charge Considerations. Build-up of electrostatic charges results from the contact and separation that occurs as non-polar liquids (e.g., gasoline, jet fuel) flow through a pipe. Static charge generation increases as fluid velocities and pipe lengths increase (Curran 1997).

(1) Electrostatic Charge in Tanks and Piping Systems. Static charges in underground steel and fiberglass tanks are readily dissipated through the adjacent soil matrix. Aboveground steel and fiberglass tanks (including drums) can develop a static charge between the fluid and the tank wall (or metallic fitting in non-metallic tanks) during filling. Maintaining electrical continuity between the tank and the fill line will help prevent static accumulation and discharge. Grounding and/or bonding may also be required to prevent static discharge. Because plastic containers are not conductive, electrical continuity can not be maintained between a plastic tank and a metallic fill tube. Therefore, the use of plastic piping and containers for transport and accumulation of recovered NAPL should be avoided.

(2) Ignition of Electrostatic Charge. Once a means of generating a static charge exists, it can be a source of ignition if the following three conditions are met (Curran 1997):

- A static charge accumulates that can produce an incendiary spark.
- There is a spark gap (arc).
- There is an ignitable vapor-air mixture within the spark gap.

Thus, by the third condition, the vapor concentration must be between the lower explosive limit (LEL) and upper explosive limit (UEL) for the specific flammable liquid, assuming oxygen is present at 20% by volume. If there is a concern about the vapor concentration in the NAPL storage tank or within the treatment enclosure, LEL sensors can be deployed to detect excessive flammable vapor concentrations and shut down the recovery system at a pre-set vapor concentration (i.e., 10% to 20% of LEL). JP-4, for example, requires added precautions in handling, as its vapors above free product are naturally within their explosive range. JP-4 grade jet fuel forms explosive vapors in the vapor space of storage tanks in the range of $-23\ ^{\circ}C$ to $27\ ^{\circ}C$ ($-10\ ^{\circ}F$ to $80\ ^{\circ}F$). These are temperatures usually encountered in storage and handling of fuels. In addition, jet fuel is more subject to buildup of static charges than gasoline products (Department of the Air Force 1981).

(3) Electrostatic Charges in MPE Applications. In many MPE system applications, NAPL is not being recovered or discharged to a tank at a

significantly high velocity or piped over a very large distance, so build-up of significant electrostatic charges is generally not a problem. However, in some cases, where NAPL is pumped at a relatively high velocity or travels over a long distance, design measures must be incorporated to reduce the risk of static discharge. Grounding and/or bonding of NAPL accumulation tanks and conveyance piping may be required to prevent static discharge. Nitrogen purging or blanketing of the headspace of a tank or container can be used to eliminate the third condition (ignitable air-vapor mixture within the spark gap) discussed above, thus preventing accumulation and ignition of flammable vapors (Ebdat 1996; Curran 1997).

(4) Consult NFPA 77, Static Electricity, for further guidance on preventing build-up or discharge of electrostatic charges. Although preventing the development of potentially explosive conditions is preferred, the designer should incorporate explosion isolation and containment measures (i.e., explosion-proof vessels), explosion suppression, and/or venting measures into the design in cases where there is a high potential for explosive conditions to develop (Chatrathi and Siwek 1996). Suppression is preferred to venting, as the release of flammable vapors to the environment may be problematic. Also, release of exploding vapors may represent a risk to personnel and/or equipment in the vicinity of the relief vent. Additional guidance on explosion suppression and prevention is available in NFPA 68, Guide for Venting Deflagrations and NFPA 69, Explosion Prevention Systems. In addition, designers should review and comply with NFPA 30, Flammable and Combustible Liquids Code, when flammable liquids are expected to be present.

f. Blowers, Pumps and Motors. There is a multitude of available vacuum producing devices that can be employed in an MPE design. A wealth of information on operating principles, capabilities, design and selection of vacuum pumps has been produced throughout the chemical and food processing industries where vacuum pumps are widely used. Selection of the most appropriate vacuum producer depends mainly on the vacuum and flow requirements of the specific application; however, other site-specific factors may influence selection of the vacuum device. These factors may include, but are not limited to: hydraulic conductivity and air permeability of the soil, number and configuration of MPE wells, power availability, cooling/seal water availability, waste stream treatment/disposal costs, remoteness of site, and the skill level of on-site maintenance personnel. The following paragraphs present a summary of commonly available vacuum pumps for MPE applications. Figure 5-11 presents a graphical description of the various types of vacuum pumps and Figure 5-12 presents a comparison of the typical operating flow and vacuum ranges for these various types of vacuum pumps. Figure 5-13 presents a comparison of optimal MPE equipment (vacuum generators and pumps) for various hydraulic conductivity ranges. These ranges are approximate and selection of the MPE pump for a specific site will depend on the factors discussed in the preceding paragraph, as well as the anticipated duration of the MPE remediation and the capital and maintenance cost associated with the pump(s). More information on blowers and pumps applicable to MPE can be found in CEGS 11215 Fans/Blowers/Pumps; Off-Gas.

(1) Liquid Ring Pumps. Liquid ring pumps are the most commonly used vacuum pumps reported in the literature for MPE applications (AFCEE 1997; Hansen, et al. 1994; Suthersan 1997). Liquid ring pumps can transfer both liquids and gases through the pump casing. A rotating impeller, offset from the center of the pump casing, generates centrifugal force to drive liquid within the pump casing to the outer wall of the casing. The liquid forms a seal layer conforming to the interior shape of the pump body. The eccentric impeller causes gases trapped between the rotating vanes and the seal liquid to be compressed and forced in toward a central discharge port. Seal liquid is typically water or oil. Water-sealed liquid ring pumps may use once-through

municipal water, recirculated water, or if there is a sufficient volume, groundwater, to provide seal liquid for the pump.

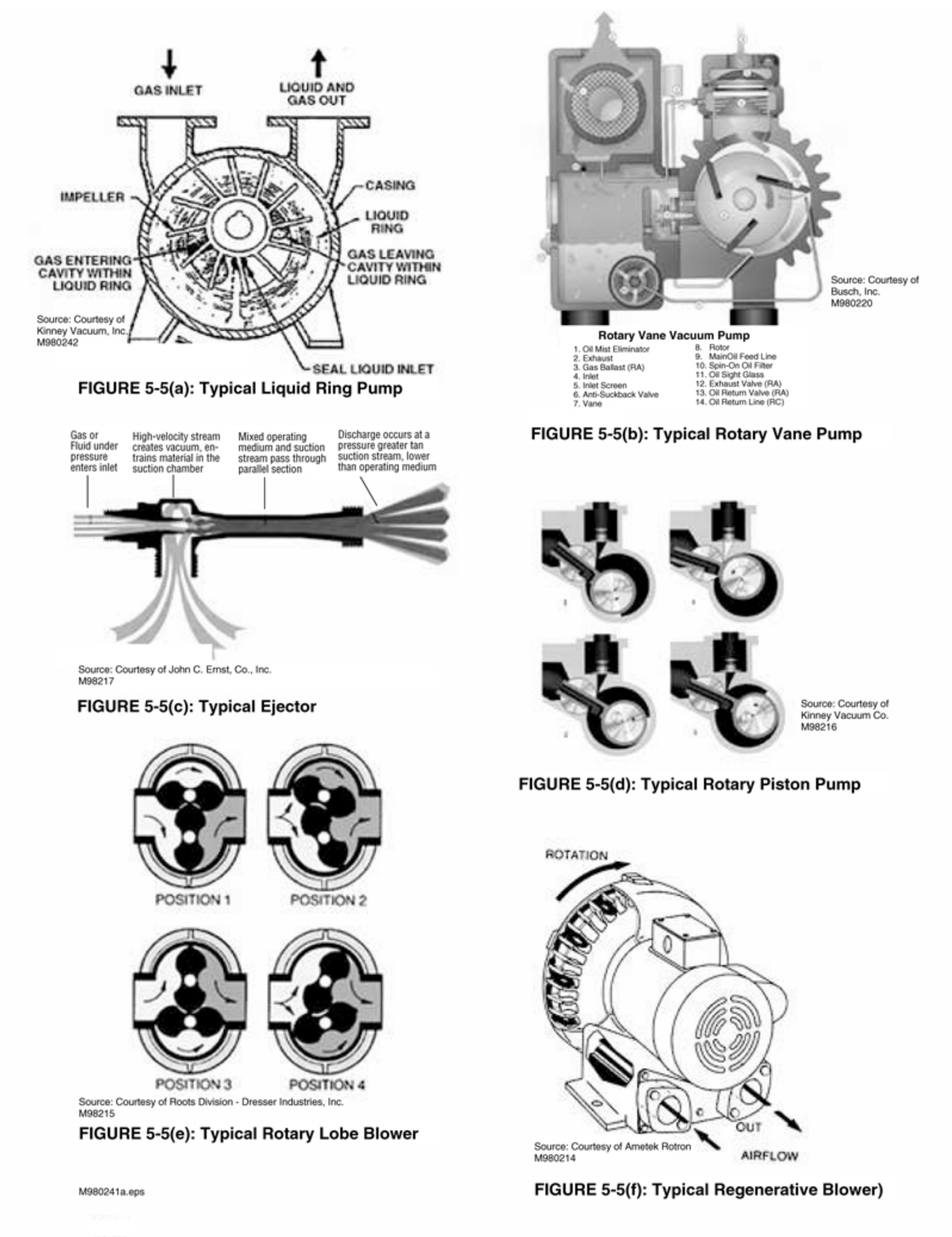

Figure 5-11. a) Typical Liquid Ring Pump b) Typical Rotary Vane Pump c) Typical Ejector d) Typical Rotary Piston Pump e) Typical Rotary Lobe Blower f) Typical Regenerative Blower. Reprinted by permission of: a) Tuthill Corporation, Kinney Vacuum Division, b) and d) Busch, Inc., c) John C. Ernst Co., Inc. e) Roots Division, Dresser Equipment Group, Inc., a Halliburton Company, f) Ametek Rotron.

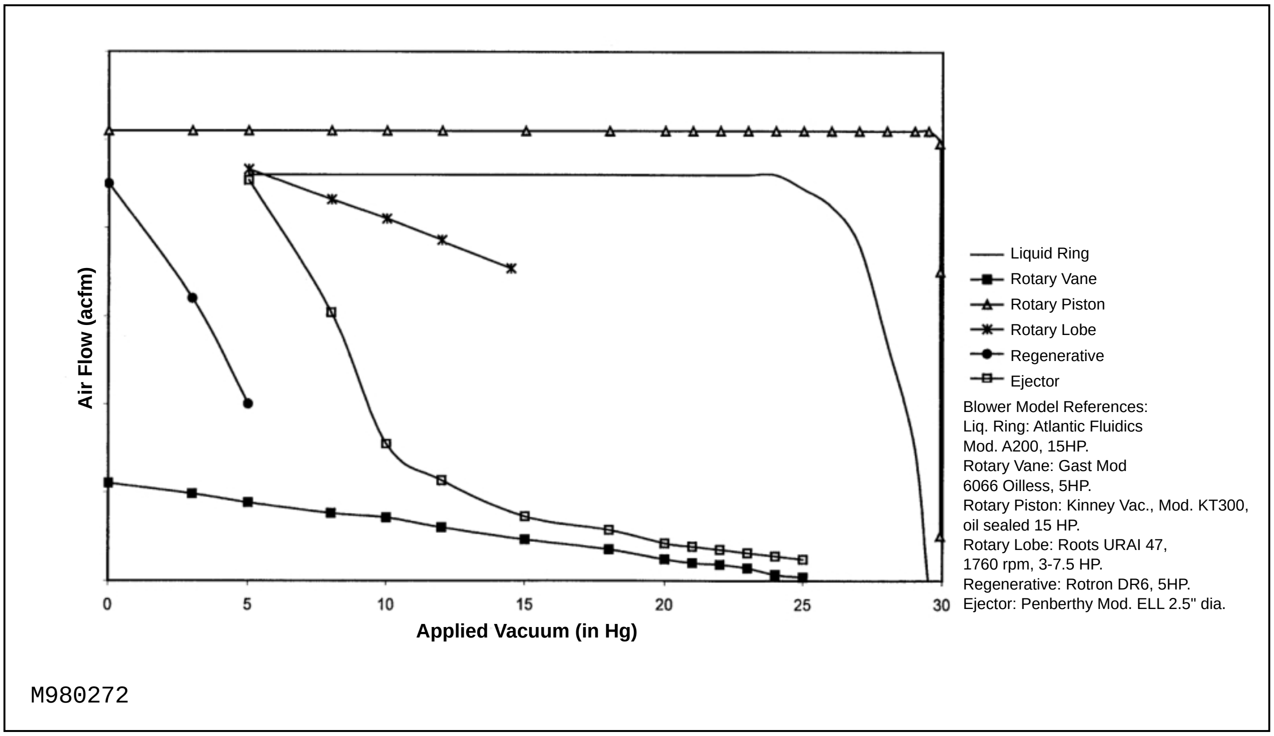

Figure 5-12. Comparison of Air Flow vs. Vacuum for Various Types of Vacuum Pumps.

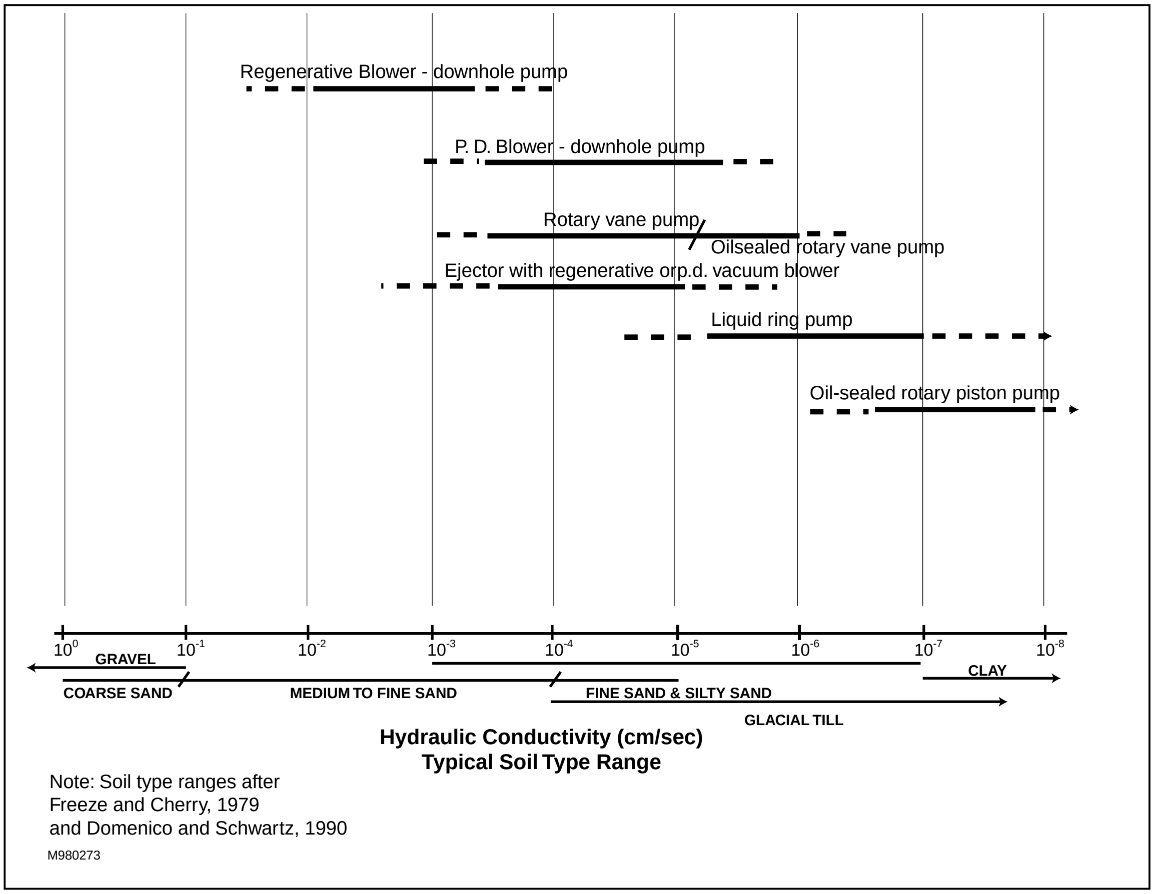

Figure 5-13. Optimal MPE Equipment for Varying Hydraulic Conductivities. (After Peargin 1998. Reprinted by permission of T.R. Peargin, Chevron Research and Technology Corp.) (Refer also to Figures 3-1a and 3-1b)

(a) Extracted groundwater is generally not preferred for the seal liquid due to the presence of inorganic impurities that tend to increase scaling on the vanes, and the often insufficient/irregular groundwater recovery rate at low-permeability sites. Due to the heat generated during compression of the extracted gas, pumping systems that used a closed-loop seal liquid system must be equipped with a heat exchanger to cool the seal liquid. Oil-sealed liquid ring pump systems, although generally more expensive than water-sealed pumps, may be preferred for remote sites since the units are essentially self-contained, typically including an oil reservoir, oil heat exchanger, and an oil mist filter and coalescer on the vapor discharge line from the pump. Vacuum in excess of 98 kPa (29 in Hg, gauge vacuum) can be generated by water sealed liquid ring pumps, while vacuum to 101 kPa (29.9 in Hg, gauge vacuum) can be generated by oil-sealed liquid ring pumps. As shown in Figure 5-12, liquid ring pumps have relatively flat performance curves over the majority of their operating range. A main disadvantage of using liquid ring pumps is that if NAPL is extracted, emulsions tend to form due to the high velocity of the extracted NAPL and groundwater, which may necessitate additional treatment to separate the emulsion (unless NAPL and groundwater is separated upstream of the pump).

(2) Rotary Vane Pumps. Rotary vane pumps are positive displacement pumps with sliding (or spring loaded) flat vanes mounted in an eccentric rotor. As the rotor turns, the vanes are flung outward against the casing wall trapping gases between the vanes, and providing a seal between the intake and exhaust ports of the blower. The offset position of the rotor within the pump housing causes compression and subsequent expansion of the compressed gases, resulting in a vacuum at the intake port of the blower. Rotary vane pumps are available in oil sealed or oil-less models, in a wide range of flow capacities. Oil-sealed rotary vane pumps are typically capable of generating vacuums up to 98 kPa (29 in Hg, gauge vacuum), while oil-less pumps are generally limited to vacuum below 85 kPa (25 in Hg, gauge vacuum). Oil-sealed rotary vane pumps are typically equipped with an oil reservoir, oil filter, air-oil heat exchanger, and an oil-mist or coalescing filter on the vapor discharge. Larger rotary vane pumps with spring loaded vanes may require special tools and skilled mechanics to perform repairs; however, smaller pumps typically use centrifugal force to fling the vanes outward and can generally be repaired in the field.

(3) Ejectors (Eductors).

(a) Ejectors are perhaps the simplest of vacuum pumps because they have no moving parts. An ejector is essentially a specially designed nozzle consisting of three sections, a pressure nozzle, a siphon body, and a discharge diffuser. Pressurized gas or liquid (e.g., for MPE applications, water or steam) used as the motive force, is injected through the pressure nozzle. The reduced diameter of the nozzle throat increases the velocity of the motive fluid and creates a suction within the chamber around the nozzle throat. The pumped fluid is drawn into the nozzle by the suction created in the chamber, and then both the motive fluid and the pumped fluid are discharged through the diffuser as a single mixed stream. Ejectors are available in a wide range of sizes and can be combined into multi-stage units for higher vacuum requirements. Vacuum and flow limitations of ejectors depend on the number of stages, the nature (water or steam) and pressure of the motive fluid, and discharge pressure. Single stage liquid-powered ejectors can typically produce 68 to 74 kPa (20 to 22 in Hg, gauge vacuum), while multiple stage steam jet ejectors frequently used in high vacuum processing can develop significantly greater vacuum. Steam jet ejectors have a low capital cost; however, they are very energy intensive to operate. It is not likely that an MPE application would require the use of a steam jet ejector but if a steam source is readily available this type of vacuum generator may be worth some consideration. Ejectors can also be combined with liquid ring pumps or rotary lobe blowers to increase the airflow and/or vacuum capacity of the MPE pumping system.

(b) A patented system (see paragraph 9-3(e) employing water-powered ejectors has been used to extract groundwater from low permeability formations. Water from a holding tank is circulated at high pressure through a manifold of small ejectors piped in parallel. The resulting vacuum generated at the ejectors is used to draw groundwater (and to a lesser extent, soil gas) from several extraction wells simultaneously. The extracted groundwater enters the holding tank and is circulated through the system. Level switches in the circulation tank maintain the water level within specified limits. Excess water from the holding tank is discharged to the treatment system. An advantage of this type of arrangement is that if one extraction well breaks suction (i.e., the water level drops below the intake tube), the other wells will not lose vacuum because each ejector operates independently. Each ejector will continue to apply vacuum to its well as long as water is pumped through the manifold.

(c) There are other methods of employing ejectors for vacuum applications. Motive water for the ejector can be from a municipal supply (although this will likely require a booster pump to increase the water pressure), from a sump well in a groundwater recovery trench, or from any other source. Motive water can be recirculated, or treated and discharged. High pressure steam, typically 690 kPa (100 psi) gauge pressure or more, if available on site, will allow development of higher vacuums.

(4) Rotary Piston Pump. Rotary piston pumps are essentially positive displacement oil-sealed compressors, and are typically available in single- or two-stage models. As the piston rotates, vapors are drawn into the pump, compressed and discharged to a treatment device or the atmosphere. Vacuum is generated during the pump intake cycle as the piston withdraws into the cylinder. The mechanical operation of the rotary piston pump is similar to an internal combustion engine. These pumps can develop vacuums in excess of 98 kPa (29 in Hg, gauge vacuum), at low to moderate flow rates (0.28 to 14m^3/min [10 to 500 cfm]). Because these types of vacuum pumps operate in an oil bath, condensation within the pump chamber can create problems and cause reduced vacuum capacity. Volatile compounds may also condense under the high pressure of the compression cycle. As such, this type of vacuum pump is not recommended for most MPE applications.

(5) Rotary Lobe Vacuum Blowers. Rotary lobe vacuum blowers are positive displacement blowers that use two interlocking rotors to trap and compress gases. The rotors are synchronized by external gears and turn in opposite directions (Ryans and Croll 1981). Although the external gears operate in an oil bath, the process air chamber is typically dry (i.e., free of oil). This type of blower can be used in MPE applications requiring moderate vacuums (up to 51 kPa [15 in Hg], gauge vacuum) and high gas flow rates. They may be applicable for use in conjunction with submersible pumps in DPE systems employed at sites with moderate to high permeability soils.

(6) Regenerative Vacuum Blower. Regenerative blowers use a multi-stage impeller to create a pressure (vacuum) differential through use of centrifugal force. Air drawn in between rotating vanes is thrust outward toward the impeller casing, then turned back to another section of the rotating impeller (Soil Vapor Extraction and Bioventing EM 1110-1-4001). Regenerative vacuum blowers generally do not produce a sufficiently high vacuum for use in MPE applications. However, regenerative blowers may provide an economical solution when used in conjunction with submersible pumps in DPE systems, or for sites

where less than 34 kPa (10 in Hg), gauge vacuum (CEGS 11215) and relatively high air flow rates are required to meet MPE design requirements.

(7) Liquid-only Pumps for Use in Dual-Phase Extraction Systems. Liquid-only pumps for DPE may be either electric or pneumatically operated submersible pumps, or surface-mounted diaphragm pumps, jet pumps, or vertical turbine pumps equipped with appropriate down-well level controls. Liquid pumps should be sized to handle the anticipated groundwater yield that will be generated by the water table drawdown created by the water pump plus the additional groundwater yield induced by the application of vacuum to the extraction well head. Consideration must be given during design and construction of the well head seal to allow water and gas transfer lines plus submersible pump control lines, to pass through the well head while maintaining a vacuum-tight seal. Refer to CEGS 11211 and 11212 for guidance on liquid-only pumps.

(8) Variable Speed Drives. Although variable speed drives (VSDs) are not pumps, their use in controlling pump motor speed can be valuable in MPE use. VSDs allow simple adjustment of motor speed to achieve the optimal applied vacuum and flow rate. This is especially useful for pilot test operations where vacuum is often applied in stepped increments. These drives allow adjustment of applied vacuum without the need for dilution or bleed-in air valves. Bleed-in air may still be required, however, in order to obtain the necessary velocity to lift fluids from the well in TPE operation. Some VSDs can be configured with a feedback control loop to maintain constant pressure (vacuum) or flow operation. See also paragraph 5-6(h)(2).

g. Selecting Vacuum Pump Sizes.

(1) In order to properly size a vacuum pump, or any pump in general, the designer should determine the flow the pump is expected to see approximately 80% of the time, the minimum anticipated flow rate and the maximum expected flow rate. The pump should be sized to operate as near as possible to the Best Efficiency Point (BEP) on the pump curve for the flow rate that is expected 80% of the time, while still having the capacity to operate at the maximum and minimum anticipated flow rates without causing damage to the pump (Monroe 1996). Since site conditions or operating configuration of the MPE system may change over time, the vacuum blower(s) selected for the system should be able to operate efficiently over the anticipated range of operating conditions.

(2) When sizing a pump, the designer must define the flow and vacuum requirements at the extraction well(s). This should be established through pilot testing during preliminary design. Then, starting from the most remote well on the line, work through the piping manifold summing flows and frictional losses associated with piping, valves, and fittings to determine the flow and vacuum requirement at the blower. Remember to include losses through manufacturer-supplied items on the blower skid (filters, mufflers, knockouts, etc.), or alternately, specify the flow and vacuum required at the suction point of manufacturer-supplied skid-mounted vacuum pumping system. Include a reasonable factor of safety (typically 10 to 25 percent; however, the exact determination is site specific and may depend on the degree of confidence in design values) to allow for future expansion, vacuum leakage, or unforeseen system losses. Include also the backpressure on the discharge side of the blower associated with off-gas treatment equipment, as this may reduce the available vacuum the pump can apply to the wells. Keep in mind that it may be beneficial to split the extraction flow between two or more smaller blowers rather than one large blower. Duplex pumps may be used at remote locations where system redundancy is desirable due to lag time for parts and maintenance. Also, if there are excessive discharge pressure requirements, which may require over-sizing the vacuum pump, consider instead employing a booster blower on the

discharge side of the vacuum system to provide the required discharge pressure. The operating point of the blower/pump is determined by developing a system head curve based on pilot test data and laying it over the pump curve. An example of this step can be found in EM 1110-1-4001, Soil Vapor Extraction and Bioventing, Chapter 4, Bench- and Pilot-Scale Testing for SVE and BV.

(3) A brief example of vacuum pump sizing procedures for MPE applications is provided in this paragraph. A detailed numerical example is presented in EM 1110-1-4001, Soil Vapor Extraction and Bioventing, Chapter 5, SVE and BV Design Strategy. Evaluating head losses through the extraction pipe network is an iterative process in which the designer must adjust the system piping configuration to ensure that the pressure at each node (junction point) will balance. The designer must also be aware that air is a compressible fluid, and as such the actual volumetric flow rate (acmm or acfm) must be used when calculating frictional (velocity) losses through the piping system. Also, designers must note that the actual volumetric flow rate will increase on the discharge side of the vacuum pump as a result of the temperature rise induced by the blower during the vacuum (compression) cycle. These calculations can be done by hand or using readily available computer software (e.g., ABZ, Inc. 1998). The effect of discharge losses due to off-gas treatment equipment must be included in the calculations before a blower can be properly sized, since backpressure on the positive-pressure side of a vacuum generator may significantly affect the vacuum pump performance.

(a) Assume that a system curve (vacuum versus flow) and appropriate regression coefficients have been developed for the pilot test data. Assume also that the pilot test results indicate the following requirements for a full-scale MPE system:

- Three parallel lines of four MPE wells each, connected to a common junction point, then piped to the vacuum pump.
- The desired extraction vacuum (design value) at the wells is 54.2 kPa (16” Hg, gauge vacuum).
- The desired extraction flow (design value) is 0.33 scmm (11.8 scfm) per well, for a total air extraction flow rate of 4.0 scmm (141 scfm).
- Line losses through the subsurface piping, header and manifold will add approximately 10.7 kPa (3.2 in Hg, gauge vacuum).
- The air/liquid separator and particulate filter will add an additional 1.3 kPa (0.4 in Hg, gauge vacuum) loss on the vacuum side of the pump at the anticipated operating flow.
- Vacuum pump discharge restrictions will be approximately 10.3 kPa (1.5 psi or 3.1 in Hg, gauge pressure) at the anticipated operating flow.
- Up to 2.3 L/min (0.6 gpm) of water may be extracted with the vapor stream.

(b) With these data in hand, the designer may now select a vacuum pump to fit the specific situation. From the specified design requirements, the vacuum pump must be capable of delivering 4.0 scmm (141 scfm). Summing vacuum requirements (well vacuum plus losses), a minimum inlet vacuum of 66.2 kPa (19.6 in Hg) is desired. The discharge pressure requirement is 10.3 kPa (3.1 in Hg). Sum the suction and pressure losses for a total of 76.5 kPa (22.7 in Hg), and add a 15% factor of safety to get a total of 88 kPa (26 in Hg) as the normal operating requirement. Head losses should also be calculated for the anticipated minimum and maximum operating flows in a similar fashion, to develop the system curve for the normal, minimum and maximum operating conditions. Search manufacturers' literature (vacuum versus flow curves) to find a vacuum pump that will operate near its optimum efficiency for the anticipated operating conditions. The system curve should be overlaid on manufacturer-supplied pump curves when determining the best vacuum pump for a specific application. Based on these data, i.e., a flow of 4 scmm (141 scfm) and total head requirement of 88 kPa (26 in Hg), a liquid ring pump or oil-sealed rotary vane pump are likely vacuum pump candidates (see Figure 5-12). Designers should also consider vacuum pump noise when determining the most appropriate pump for a given situation. In general, operating a pump or blower at a point away form its optimum efficiency will result in more noise, and operating at a higher speed (RPM) will also result in greater noise.

h. Selecting Motor Size.

(1) Once a range of vacuums and flow rates has been determined, designers frequently consult vendor-supplied performance curves to determine the required motor horsepower. An alternate method of calculating the motor power requirement for vacuum blowers based on mass flow rate, head loss and efficiency is provided in Chapter 5 of EM-1110-1-4001. For liquid pumps, the power requirement can be estimated by the following equations (Perry and Green 1984):

$$\text{Power (kilowatts)} = [\text{total dynamic head (m)}] \times [\text{pump capacity (m}^3\text{/hr)}] \times [\text{density kg/m}^3] \times \text{efficiency} \div 3.670 \times 10^5 \quad [5\text{-}5]$$

or, in customary English units,

$$\text{Power (horsepower)} = [\text{total dynamic head (ft)}] \times [\text{pump capacity (gpm)}] \times [\text{sp. gravity}] \times \text{efficiency} \div 3.96 \times 10^3 \quad [5\text{-}6]$$

(2) In some cases it may be advantageous to employ a VSD instead of a throttling device (e.g., valve, flow restrictor) to regulate vacuum pump output. VSDs (paragraph 5-6(f)(8) are the most efficient method of varying both flow and pressure in vacuum systems (CEGS 11215). Several types of VSDs are available. Mechanical gear VSDs use a handwheel to change the effective diameter of opposing drive wheels, and thus vary the rotational speed of the output drive shaft; however, these types of VSDs require manual adjustment to vary motor speed (Perry and Green 1984). In most MPE systems, electrical or electronic VSDs are more appropriate. These devices control alternating current (a.c.) motor speed by varying frequency and voltage, and can be configured to automatically and continuously vary motor speed in response to changing system vacuum and flow demands in real-time. In larger systems, the

potential cost savings afforded by automatically adjusting the load on the motor in response to vacuum and flow fluctuations may provide substantial cost savings (Revelt 1996.) However, not all motors are suitable for use with VSDs. Consult with the manufacturer to determine whether a VSD-compatible motor is available for the specific application.

i. Net Positive Suction Head Considerations for Liquid Pumps in MPE Applications. The following paragraphs provide an overview of net positive suction head (NPSH) considerations. Additional information on NPSH can be found in chapter 3 of TM 5-813-9.

(1) When selecting a pump, one must determine the required capacity of the pump and the total dynamic head (TDH) required by the specific application. TDH is equal to the total discharge head, h_d, minus the total suction head, h_s. The suction head, h_s, has a positive value when the free surface of the liquid being pumped is above the pump impeller centerline (i.e., a flooded suction condition), and has a negative value when the liquid level is below the pump centerline (a suction "lift" condition). The head equivalent to the vacuum applied above the free surface of the liquid must also be overcome when selecting a pump. Static and friction losses must be included in the calculation of h_d and h_s. Calculation of these values is discussed in paragraph 5-6a(5).

(2) Cavitation in a pump occurs when the pressure of the liquid being pumped is reduced below the vapor pressure of that liquid (at the system operating temperature). This occurs in a pump impeller as the velocity of the liquid is increased, resulting in a corresponding reduction in pressure. Gases within the liquid vaporize, forming bubbles. These gas bubbles are transported to zones of higher pressure by the rotating impeller where they collapse instantaneously and with great force. Cavitation is often observed as noise and vibration and should be avoided, as it can result in excess wear or erosion of pump internals and dramatically shorten the operating life of a pump. Cavitation can also greatly reduce the pump's efficiency resulting in insufficient throughput.

(3) The Net Positive Suction Head Required ($NPSH_R$) is the minimum suction condition required to prevent pump cavitation, and is equal to the total suction head of liquid (absolute) determined at the first stage impeller datum, minus the vapor pressure of the liquid (in head of liquid pumped), required to prevent more than 3% loss in total head from the first stage of the pump at a specific capacity (Hydraulic Institute, 1994). NPSH is generally expressed in terms of a height of a column of liquid (mm Hg, ft of water). Manufacturers typically plot $NPSH_R$ data for a given pump operating a certain speed and capacity on the pump's characteristic performance curve. $NPSH_R$ for centrifugal pumps typically ranges between 22 mm Hg (1 ft H_2O) for a high-quality progressing cavity pump, to 224 mm Hg (10 ft H_2O) for low-end flooded suction centrifugal pumps. $NPSH_R$ can be greatly influenced by flow rate.

(4) The Net Positive Suction Head Available ($NPSH_A$) depends on the system layout and, to prevent cavitation, must always be greater (by some margin of safety) than the $NPSH_R$ for the intended operating range of the pump. $NPSH_A$ is calculated according to the following equation (Driscoll 1986):

$$NPSH_A = h_a + h_s - h_{vp} - h_f \qquad [5\text{-}7]$$

where

h_a = absolute pressure on the free surface of the pumped liquid, in meters or feet of liquid. This will be equal to atmospheric pressure if the liquid is in an open tank or well, or can be less than atmospheric if the liquid is in a well or tank under vacuum.

h_s = static height (in meters or feet) of liquid surface above (positive value) or below (negative value) the centerline of the pump intake.

h_{vp} = absolute vapor pressure of the liquid at the pumping temperature, in meters or feet of liquid. In mixtures such as gasoline or NAPL/water systems, this value should be determined by the bubble point method (Karassick, et al. 1986)

h_f = suction line losses (in meters or feet of liquid) including entrance losses and friction losses due to pipe, fittings, and valves.

(5) In an MPE application, the $NPSH_A$ of a pump can be thought of according to the following expression, which is similar to the equation presented above.

$NPSH_A$ = (absolute atmospheric pressure) - (lift + line losses) – (vacuum in well or tank) - (vapor pressure of liquid) [5-8]

In other words, the limiting factor for a pump drawing liquid from a well or vessel under vacuum in an MPE application is:

(lift + line losses + vacuum in well) = (absolute atmospheric pressure) –

$NPSH_A$ - (vapor pressure) [5-9]

(6) As can be seen from the preceding expression, a dual-pump MPE system comprised of a surface-mounted liquid pump for liquid removal and vacuum blower for vapor extraction, is limited to shallow water table applications. In this configuration, the sum of lift, line losses and vacuum can not exceed the difference between absolute atmospheric pressure and the sum of the liquid's vapor pressure and the $NPSH_A$. Therefore, a pump with a lower $NPSH_A$ will allow for either greater suction lift or will be capable of overcoming a stronger applied vacuum.

(7) If a submersible liquid pump is used in conjunction with a vacuum blower for MPE, the $NPSH_A$ only limits pumping when the vacuum in the well exceeds approximately 609 to 635 mm Hg (24 to 25 in Hg). There is no limitation by depth to water (lift) because the submersible pump operates in a flooded condition. Manufacturer's specifications on $NPSH_A$ are typically not available for submersible pumps since this application is relatively rare. One can safely assume a submersible pump to have an $NPSH_R$ of approximately 112.1 mm Hg (5 ft H_2O).

(8) Another common MPE application where $NPSH_A$ must be considered is in the case of a pump used to transfer fluids from a tank under vacuum such as transfer pump on a phase separator on the intake side of a dry vacuum blower. The transfer pump $NPSH_A$ must be sufficiently low as to allow the pump to overcome the vacuum in the tank without cavitating. Frequently in this

application, a pump with a very low $NPSH_R$, such as a progressing cavity pump or a multi-stage centrifugal pump is required.

(9) Consideration must be given to prolonged application of vacuum to the volute (pump impeller chamber) of a liquid transfer pump. Pumps with low $NPSH_R$ may allow air leakage into the volute when the liquid pump is not operating. This may occur when an operating MPE system recovers very little water in the phase separator over the course of several hours, such that the liquid transfer pump does not cycle on for an extended period. Air leaked into the volute may result in the pump losing its prime and not being able to develop sufficient suction to overcome the vacuum applied to the phase separator tank by the vacuum pump. Installing a flapper check valve or solenoid valve between the vacuum source and the transfer pump intake may alleviate this problem; however, the valve will reduce the $NPSH_A$ due to the increase in frictional loss associated with the valve.

5-7. Instrumentation and Process Controls. The designer must carefully consider instrumentation and control requirements of the MPE system. A guide specification for process instrumentation and control is currently under development. Designers should refer to this guide specification to determine minimum standards during the preliminary process control design stage. A good instrumentation and control system design will assure that the individual components are coordinated and operate effectively. Presented in the following paragraphs are the typical types of instrumentation and controls normally included in an MPE system, a discussion on the degree of automation for MPE systems, and a list of minimum instrumentation and control requirements.

a. Instrumentation.

(1) Designers may specify various types of instrumentation to monitor desired system operating parameters, including flow, vacuum/pressure, level, temperature, etc. Other specialty sensors that may be required for certain MPE applications may include combustible gas indicators, organic vapor analyzers, and process gas chromatographs. Direct reading instruments and gauges are preferred to provide the on-site operator with easily obtainable information. The anticipated level, and range of levels, expected for the parameter that will be measured should govern the accuracy and scale of measuring devices. If the instrument is properly sized for the application, then an unusually high degree of accuracy should be unnecessary. Electrical or electronic sensors and switches used in hazardous areas must be designed for use in these areas. See paragraph 5-8d for a discussion of hazard classification. Note that all instrumentation that may be in contact with potentially explosive conditions should be intrinsically safe. Most of the instrumentation discussed in the following paragraphs can be obtained from manufacturers with adjustable set point switches, dry contacts, low voltage DC output, or 4-20 mA signal output that can be integrated with a central control panel or PLC for automated control or monitoring purposes.

(2) Multi-phase fluid flow measurement with a single instrument is possible; however, the instrumentation required is relatively large and expensive and is not realistically applicable to MPE projects. Flow rates of the individual phases (gas, water and NAPL) must be monitored separately (i.e., measure gas flow after the phase separator, water flow at the treatment system effluent and NAPL recovery at the inlet to the holding tank). If it is critical that gas and/or liquid flow rate from the individual wells be determined, individual phase separators may be provided for each extraction well; however, this is expensive and typically not warranted. In DPE applications, each well must have the capability to measure flow of extracted air and water. It is, however, important to measure dilution air flow rate at

the individual extraction wells and/or at the extraction blower, as this air flow must be subtracted from the total air flow rate to determine the actual flow contribution, and hence contaminant mass removal, from the subsurface.

(3) Airflow (or velocity) may be measured using rotameters, orifice meters, turbine flow meters, pitot tubes, or hot-wire anemometers. The process air flows through rotameters, orifice meters, and turbine meters, while pitot tubes and anemometers are typically placed in the flow path to measure airflow rate. As a result, pitot tubes and anemometers (which have relatively low pressure drops across them) can be either fixed or portable devices. Since pitot tubes and anemometers have portable capability, a single device can be used to measure multiple wells. Between the two, pitot tubes are generally less expensive as they contain only the appropriate piping connections to measure static and total pressure (where the difference between the two is given as the velocity head using a differential pressure gauge). Rotameters consist of a float mounted inside a tapered cylinder, which is marked with a calibrated scale. The fluid flows through annular space between the float and the cylinder wall. The higher the fluid flow/velocity, the greater the annular opening required to allow passage of the flow, and thus the higher the float will be lifted within the cylinder. Rotameters provide simple direct flow measurement, although they have a poor turndown ratio if flows are at the lower end of the scale and often result in higher pressure drop than some of the other types of meters. Orifice meters measure the pressure drop across an orifice (reduced diameter section) installed in the airflow path to determine air velocity or flow in through a pipe. Turbine flow meters typically consist of a paddlewheel sensor that is turned by the flowing air stream. The rate of revolution of the paddlewheel is converted to flow rate. Pitot tubes and differential pressure gauges can be used to measure air velocity in a pipe. Specially calibrated gauges (i.e., for a specific size pipe) are available to allow direct reading of flow rate based on differential pressure. Pitot tubes and anemometers are both sensitive to the position of the measurement device in the pipe and to moisture or liquid droplets in the air stream. Hot wire anemometers measure temperature change across a resistive element to determine air velocity. Anemometer readouts are typically provided with selectable scale ranges to provide good turndown ratio over a wide range of air velocity (flow) conditions. The best method of airflow measurement depends on the configuration of the system, location of the desired flow measurement, etc., and therefore should be selected based on the specific application. Note that the airflow measurement device should typically be located within a straight run of piping, at least 5 pipe diameters upstream and 10 pipe diameters downstream of the nearest flow interference or piping direction change.

(4) Water flow can be measured using pressure type meters similar to those used for air measurement such as orifice meters, nozzle meters, or venturi meters (Munson et al. 1990). More commonly in MPE applications, volume flow meters such as rotameters, turbine flow meters, paddle wheel, or magnetic flow meters are used. Rotameters are used to measure flow rate in a pipe. Disadvantages of rotameters include high pressure drop across the meter and potential for clogging since the float in the rotameter acts as a collection point for any suspended solids within the water stream. Turbine flow meters are used to measure flow rate or total flow (using a totalizing meter). These meters provide a wide range of flow at relatively low cost. Paddle wheel flow meters can measure flow rate or total flow. These meters provide very low pressure drop but are generally more expensive. Both turbine and paddle wheel meters can be used for remote flow sensing. Magnetic flow meters also provide very low pressure drop. These meters are also very useful for water streams where suspended solids may be present, as they are not easily fouled. Fouling may occur from precipitated metals or bacterial growth (biofouling), which can cause significant errors in flow meter accuracy. Magnetic flow meters are, however, the most expensive of those discussed here. In applications where gravity flow of water in a pipe exists, open channel flow meters that measure

partial flow in pipe are required. The volume flow meters discussed above apply only to full-flow applications.

(5) Typically it is desirable to measure vacuum applied at the individual well heads, at intermediate points in the system (i.e., at header/manifold joints), at the vacuum blower, and at the dilution air inlet. This vacuum measurement will give the operator an idea of how well balanced the vacuum/pressure is at various locations throughout the system. Vacuum or pressure sensors are available in many varieties, including manometers, diaphragm sensors, and Bourdon tube sensors. Manometers may be U-shaped or inclined, and are typically used for obtaining precise differential pressure measurements. These devices are not frequently used in field MPE applications, but field portable manometers are available. Diaphragm sensors measure the motion of a rubber or metallic diaphragm, and use a mechanical, electrical, magnetic or optical mechanism to convert this physical motion to a pressure/vacuum reading on a calibrated gauge. The widely used Magnahelic gauges manufactured by Dwyer Instruments (Michigan City, IN) are diaphragm sensors. Bourdon tube pressure gauges typically consist of a semi-circular piece of metallic tubing, fixed in position at one end, while the other end is allowed to flex or move in response to varying pressure. Bourdon tube indicating mechanisms, as with diaphragm sensors, may be mechanical, electrical, magnetic or optical. Many common dial-indicator pressure gauges use Bourdon tube sensors.

(6) Level sensors may be simple sight glasses, or may include float sensors, conductivity sensors, optical sensors, radio-frequency sensors, or proximity sensors. Typically used float sensors may be lever arms with floats, or float balls of a specific gravity that allows them to rise and fall with changes in the level of the liquid being measured. Conductivity sensors typically consist of a ground probe and one or more additional probes to detect the presence of a conductive liquid (i.e., water). Optical and radio frequency level sensors typically use an emitter and receiver to determine the position of a liquid surface relative to the position of the sensor. Proximity sensors are non-contact sensors that typically use capacitance to detect the presence or absence of a conductive liquid. Proximity sensors can be mounted on the outside of a tank to detect the level of a liquid within that tank. More information on level sensors can be found in TM 5-813-9, Chapter 3.

(7) Temperature sensors may be bi-metal thermometers, thermocouples, or infrared temperature sensors. Bi-metal thermometers typically consist of a coil comprised of two dissimilar metals with different thermal expansion properties. Bi-metal thermometers are typically used in MPE system applications. The differential expansion or contraction of the two metals is mechanically or electrically converted to a temperature reading on a calibrated scale. Thermocouples are calibrated bi-metallic elements that employ a small voltage across the dissimilar metals at the measuring end. Voltage changes as a known function of temperature. Infrared temperature sensors use a calibrated infrared detector to determine the temperature of a process stream.

(8) In certain applications it may be desired to continuously monitor for potentially explosive conditions (i.e., on the intake of a thermal or catalytic oxidizer, or within the atmosphere of a hazardous area) using a combustible gas indicator (CGI). CGIs may be used for continuous or periodic monitoring for explosive conditions; however, they may not be necessary if explosion-proof control wiring is used. It may also be desirable to continuously record influent and/or effluent vapor concentrations using a dedicated organic vapor analyzer (photoionization detector [PID], flame ionization detector [FID], etc.) or a process gas chromatograph (GC). PIDs and FIDs will record total hydrocarbons, while the GC will differentiate between individual hydrocarbon species. PIDs are the easiest to operate, requiring no external fuel or

standards; however, some compounds may not be detected or may have poor response factors. FIDs determine total hydrocarbon concentration through combustion of the sample stream, and therefore require a fuel source. Bottled hydrogen is typically used. PIDs and FIDs require regular (e.g. daily) calibration. GCs required trained chemists to prepare calibration standards and interpret results.

b. Process Controls. A description of process control design elements for a typical soil vapor extraction/bioventing system is presented in EM 1110-1-4001, Chapter 5. These same basic minimum design elements are required for an adequate and complete MPE system design. A full MPE system design should include the elements discussed in Chapter 6, Design Documentation. As discussed in Chapter 6, a full MPE design should also include a Process Flow Diagram. The process flow diagram should show the flow pathways through the extraction and treatment system for the various fluid phases, and provide mass balances and flow rates for each phase throughout the extraction and treatment system.

(1) Control Needs. In a typical MPE system, the following systems typically require control:

(a) Flow rate: Monitoring and controlling fluid (gas, water, NAPL) extraction rate is important to assess the progress and optimize the performance of the remedial activity. Contaminant concentration and extraction rate over time can be used to estimate mass removal of the MPE system. In multi-well systems, flow from the various extraction wells must be balanced or adjusted to maintain optimum mass removal and areal influence. Control of flow from individual wells is typically done with manual control valves located at the wellhead.

(b) Vacuum/pressure: Vacuum application can be controlled through the use of dilution (air inlet) valves positioned either at the extraction well head or at the extraction blower, or by adjusting the frequency of the VSD, if used. Vacuum and pressure relief valves should be installed at appropriate locations to protect blowers, pumps, tanks and other vessels from excessive vacuum or pressure, as applicable.

(c) Liquid level: MPE systems must be equipped with liquid level controls to operate transfer pumps and prevent tank over fills. Level sensors, switches and alarms should be installed at appropriate locations to control filling and discharging of tanks and vessels, and to activate an alarm in the event of a high-level condition.

(d) Temperature: The temperature of exhaust gases and lubricating or sealing fluids should be controlled to prevent operation of the MPE system outside allowable limits. Operation at excessively high temperatures may result in damage to blower or pump motors or and/or seals. Temperature of off-gas control equipment (e.g., carbon adsorbers, oxidizers) must be controlled to allow operation within a safe and efficient range.

(2) Degree of Automation.

(a) The degree of automation required for an MPE system is dependent on the size and complexity of the system, the remoteness of the system location, and upon owner or regulatory agency specified monitoring and control requirements. In general, process controls may be either local (i.e., control elements are mounted adjacent to equipment being controlled), central (i.e., control elements are mounted at a central control panel or operator station), or remote (i.e., system controls are accessed via modems or radio telemetry).

(b) Designers must recognize that there are capital and maintenance costs associated with automating system controls and should be selective as to which process items are specified for automated control. For active sites with readily available technicians to monitor process conditions and respond to potential problems, minimal automation is required. By contrast, at unattended remote sites, it may be desirable to employ a state-of-the-art supervisory control and data acquisition (SCADA) system to monitor system progress and alert operations personnel in the event of an alarm condition. SCADA systems typically comprise a programmable logic controller (PLC) with various instrumented inputs and outputs. Software specially configured to each site can provide the user with a graphical interface to observe a digital "picture" of the system operation in real time. SCADA systems can be used to monitor, adjust and record system flow, vacuum/pressure, and liquid levels, alternate operation of extraction wells, record influent and effluent concentrations for determining mass removal and verifying permit compliance, and initiate proper system shutdown procedures and notify maintenance personnel in response to an alarm condition. Installation of a full SCADA system, including the PLC, the SCADA software and customized program, plus purchasing, installing and maintaining all of the required monitoring instruments can add a significant cost to a project. Adequate consideration must be given to the availability of maintenance personnel, potential system failure conditions, and the risk associated with the various types of potential failures in comparison with the costs and benefits of employing a complete SCADA system. In most cases, a centralized control panel equipped with either a remote annunciator (light or horn) or telemetry capability to signal an alarm condition will be sufficient.

5-8. Electrical Requirements. All electrical equipment and wiring must comply with NFPA-70, the National Electrical Code (NEC), and applicable local codes and standards. EM-1110-1-4001, Chapter 5, provides a discussion of electrical systems planning, including: identification of applicable codes and standards, determining hazard area classification, electrical conduits, motor selection, heat tracing, and fire protection.

a. External Protection. Electrical conduits, enclosures and motors should be selected with the anticipated operating conditions in mind. At a minimum, designers should consider the potential for dirt and dust accumulation, water (drips, mist or spray as applicable), contact with corrosive liquids or vapors, and the hazard classification in which the item will be located. The National Electrical Manufacturer's Association (NEMA) has established standards for manufacture of enclosures to protect electrical equipment from various environmental hazards. Table 5-7 provides a description of the various NEMA enclosure numbers and their designated usage. Conduits should be specified to be resistant to external corrosion from moisture and/or exposure to acids or caustics including vapors, if neutralizing/scrubbing waste from a process treating chlorinated hydrocarbon contaminated water (e.g., air stripping) is used. Corrosion protection for electrical conduits should at a minimum include external galvanizing for metallic conduit, and if warranted may include PVC coating of metallic conduit. Where allowed by the NEC, PVC or ABS conduit may be used. For highly corrosive environments, fiberglass reinforced plastic (FRP) enclosures may be required to protect electrical devices. In highly corrosive environments, stainless steel hardware (nuts, bolts, pipe hangers, clamps, etc.) should also be specified. Protection of system operators from electricity and mechanical equipment must also be considered. Guards and shields around motors, belts and other moving parts should be installed in accordance with manufacturer specifications. Piping exposed to extreme temperatures should be insulated and labeled. Health and safety procedures (e.g., lock-out/tag-out) must be followed (see paragraph 9.4) to ensure protection from electrical equipment.

TABLE 5-7

NEMA Enclosure Classifications (Ametek Rotron 1998)

NEMA Type 1 - General Purpose - Indoor	Type 6 - Submersible, Watertight, Dusttight and Sleet Resistant-Indoor and Outdoor
Type 2 - Dripproof - Indoor	Type 7 - Class I, Group A, B, C or D Hazardous Locations; Air-break Equipment-Indoor
Type 3 - Dusttight, Raintight and Sleet (Ice) Resistant - Outdoor	Type 8 - Class I, Group A, B, C or D Hazardous Locations; Oil-immersed Equipment - Indoor
Type 3R – Rainproof and Sleet (Ice) Resistant - Outdoor	Type 9 - Class II, Group E, F or G Hazardous Locations; Air-break Equipment - Indoor
Type 3S – Dusttight, Raintight and Sleet (Ice) Proof - Outdoor	Type 10 -Bureau of Mines
Type 4 - Watertight and Dusttight – Indoor	Type 11 -Corrosion Resistant and Dripproof; Oil-immersed - Indoor
Type 4X - Watertight, Dusttight and Corrosion Resistant - Indoor	Type 12 -Industrial Use, Dusttight and Driptight - Indoor
Type 5 - Superseded by Type 12 for Control Apparatus	Type 13 -Oiltight and Dusttight - Indoor

b. Motors.

(1) Motor enclosures have been developed to protect motors from a variety of environmental hazards typically encountered. Table 5-8 presents a summary of available motor enclosures and their intended use. Commonly used motor types in MPE applications are open drip-proof (ODP), totally enclosed fan cooled (TEFC) and explosion proof (XP). Unless otherwise required based on expected environmental conditions, ODP motors should be specified. ODP motor enclosures essentially protect the motor from dripping liquids or solids. TEFC motors incorporate a sealed (but not airtight) housing with an integral shaft-mounted fan to blow cooling air across the motor frame. TEFC motors are typically used when the motor may be located in a dusty or dirty environment. XP motors are

totally enclosed motors whose casing and conduit box are designed to withstand and contain an explosion, and prevent the surrounding atmosphere from igniting due to an explosion occurring within the casing.

TABLE 5-8

Motor Enclosures & Typical Uses (Revelt 1996)

A PRIMER ON MOTOR ENCLOSURES
A broad range of electric-motor enclosures is available. Enclosures can most easily be visualized in terms of descriptions of motors that employ them. The descriptions given here present the enclosures that are most widely used.
An Open Motor is one having ventilating openings that permit passage of external cooling air over and around the windings
A Drip-proof Motor is an open motor in which the ventilating openings are so constructed that drops of liquid or solids falling on the machine at any angle not greater than 15 deg from the vertical cannot enter the machine
A Guarded Motor is an open motor in which all ventilating openings are limited to specified size and shape to prevent insertion of fingers or rods, so as to avoid accidental contact with rotating or electrical parts
A Splash-proof Motor is an open motor in which the ventilating openings are so constructed that drops of liquid or solid particles falling on the machine or coming toward the machine in a straight line at any angle not greater than 100 deg from the vertical cannot enter the machine
A Totally Enclosed Motor is a motor so enclosed as to prevent the free exchange of air between the inside and outside of the case, but without being airtight
A Totally Enclosed Nonventilated (TENV) Motor is a totally enclosed motor that is not equipped for cooling by means external to the enclosing parts
A Totally Enclosed Fan-Cooled (TEFC) Motor is a totally enclosed motor with a shaft-mounted fan to blow cooling air across the external frame. It is a popular motor for use in dusty, dirty, and corrosive atmospheres
A Totally Enclosed Blower-Cooled (TEBC) Motor is a totally enclosed motor equipped with an independently powered fan to blow cooling air across the external frame. A TEBC motor is commonly used in constant-torque, variable-speed applications
An Encapsulated Motor is an open motor in which the windings are covered with a heavy coating of material to protect them from moisture, dirt, abrasion, and other difficult environments. Some encapsulated motors have only the coil noses coated. In others, the encapsulation material impregnates the windings even in the coil slots. With this complete protection, the motor can often be used in applications that call for totally enclosed motors
An Explosion-proof Motor is a totally enclosed motor designed and built to withstand an explosion of dust, gas or vapor within it, and to prevent ignition of dust, gas of vapor surrounding the machine by sparks, flashes or explosions that may occur within the machine casing
It is strongly recommended that all personnel involved with motors be familiar with, and adhere to, NEMA Standard MG2, "Safety Standard for Construction and Guide for Selection, Installation and Use of Electric Motors and Generators."

(2) Unless otherwise specified, motors and electrical equipment should be designed to operate on standard utilization voltages presented in Table 5-9.

TABLE 5-9

Utilization Voltages (EM 1110-1-4001)

Service	Utilization Voltage	System Nominal Voltage
Motors below 1/2 HP	115 v, 1-Phase, 60 Hz 208 v, 1-phase, 60 Hz	120 v 240 v
Motors below 1/2 HP to 200 HP	460 v, 3-Phase, 60 Hz 230 v, 3-Phase, 60 Hz 200 v, 3-Phase, 60 Hz	480 v 240 v 208 v
Lighting	115/200 v, 3-phase, 60 Hz, 4-wire 460 v, 3-phase, 60 Hz, 3-wire 460/265 v, 3-phase, 60 Hz, 4-wire	120/208 v 480 v 480/277 v
Noncritical instruments; power and control; telephone equipment	115 v, 1-phase, 60 Hz	120 v
Telecommunication equipment	48 v DC	-
Shutdown systems, alarms, instrumentation	24 v DC with battery backup	-
Critical loads that do not permit interrupt	120 v, 1-phase, 60 Hz	-
Switchgear control	125 v DC	-
Heat tracing	265/460 v, 3-phase, 60 Hz 115 v, 1-phase, 60 Hz	277/480 v 120 v

c. System Voltage. Typically, single-phase power is used for motors less than ½ horsepower (Fuchs 1992; EM 1110-1-4001). Three phase 208/120V or 240/120V power should be used for motors over ½ horsepower when system loading is less than approximately 75 KVA. For loading in excess of 75 KVA, three phase 480/277V power should be used. The reason for this is mainly economics. Operating motors at higher amperages results in increased capital cost for branch circuit and motor protection equipment, and significantly higher operating electrical costs. To determine system KVA load, multiply the operating (nameplate) amperage by the utilization voltage (start with the lower available utilization voltage). Sum the KVA loads for all equipment, including lighting and heaters. If total system load exceeds 75 KVA at the lower utilization voltage (e.g., 208/120), recalculate the KVA load for a 480/277-volt system.

d. Hazardous (Classified) Locations (NEC Article 500).

(1) Locations where flammable or potentially flammable vapor concentrations or combustible dust may accumulate may be classified as hazardous locations under NEC Article 500. EM 1110-1-4001, Chapter 5 presents general guidance on determining the hazard classification of an area. Additional guidance on classification of hazardous areas may be found in NFPA 497, Class I Hazardous Locations for Electrical Installations in Chemical Plants, and in API RP500A, Classification of Locations for Electrical Installations in Petroleum Facilities classified as Class I Division 1 and Division 2.

(2) Class I, Division 1 and 2, and Class II, Division 1 and 2, atmospheres may be encountered at MPE sites. Class I areas are areas where flammable gases or vapors may be present in potentially explosive quantities. Class II areas are areas where combustible dust is present in potentially explosive quantities. In general, Division 1 locations are areas where a potentially explosive concentration or quantity exists under normal operating or maintenance conditions, while Division 2 locations are those locations where potentially explosive conditions would typically only exist in the event of some failure (i.e., rupture or equipment breakdown). Refer to the NEC and other applicable codes for specific direction on classification of hazardous areas. Designers must use reasonable care and discretion when classifying areas as hazardous, as considerable additional expense will be required for electrical equipment installed in classified areas.

(3) Wherever possible, designers should strive to limit the amount of equipment, sensors and controls that must be located in hazardous areas. Where practicable, equipment such as control panels and motor starters should be located in unclassified areas. As an alternate to using (XP) enclosures for control panels in hazardous locations, NEC article 500-2(a)(3) allows the use of purged and pressurized enclosures in hazardous areas. This method is typically significantly less costly than installing XP enclosures. For additional guidance on the use of purged and pressurized enclosures, designers are referred to NFPA 496, Standard for Purged and Pressurized Enclosures for Electrical Equipment. In addition, intrinsically safe sensors and controls may be substituted for XP sensors located in hazardous areas, in accordance with NFPA Article 500-2(a)(4), and in accordance with ANSI/UL 913-1988, Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, Class II and III, Division 1, Hazardous Locations. Designers must note that intrinsically safe sensors require the use of intrinsically safe relays, and that intrinsically safe wiring must be physically separated from non-intrinsically safe wiring.

e. Electric Service. If the MPE site is on a Military Reservation, the electric utility is normally owned and operated by the Government. The design agent will design any connections or extensions. If Government-owned electric supply is not available, the local utility company will provide services, usually up to the transformer secondary, and at times the service entrance conductors to the site. It is the designer’s responsibility to clarify what service the local utility will provide and what services will be the construction contractor’s responsibility. Local utility connection charges can be expensive (around $30,000/mile of three-phase line) and may take several weeks or more to schedule with the utility. Designers should verify power availability, cost, and time for electrical services at the earliest possible opportunity.

5-9. Waste Stream Treatment Options. Off-gas treatment and wastewater treatment will be discussed briefly in this section. A complete discussion of the design of emission control or wastewater treatment devices is beyond the scope of this manual. Other existing USACE guidance documents are available to assist with the evaluation and design of waste treatment devices. Designers should consult the Federal Remediation Technologies Roundtable (FRTR) Remediation Technologies Screening Matrix and Reference Guide (Van Deuren et al. 1997) for use in conducting preliminary screening of available treatment alternatives. This guidance is available in print form through NTIS or via the Internet at http://www.frtr.gov. Preliminary treatment system capital and operating costs from other government remediation cost data source documents are incorporated into the Screening Matrix Guide to allow the designer to make a preliminary estimate of waste treatment costs. In addition, the USACE has developed several guidance documents to assist designers with establishing requirements for waste treatment equipment, including:

- CEGS-11225 (Oct. 1995, Feb 1997) Downflow Liquid Activated Carbon Adsorption Units.

- CEGS-11226 (DRAFT In Progress) Vapor Phase Activated Carbon Adsorption Units.

- CEGS-11301 (November 1991, July 1997) Air Stripping Systems.

- CEGS-11377 (July 1997) Advanced Oxidation Processes.

- EP 1110-1-21 (1997) Air Pathway Analysis and Design of HTRW Remedial Action Projects.

a. Off-gas. Off-gas contaminant mass loading in MPE applications is typically high due to several factors: 1) MPE technologies are often used at sites where NAPL is present; 2) the high vacuums may volatilize many low-vapor pressure contaminants; 3) turbulence in a TPE drop tube tends to cause it to act as an in-pipe air stripper, transferring volatile contaminant mass to the vapor phase; and, 4) dewatering or desaturating of the capillary fringe during MPE may expose adsorbed contaminants to airflow for subsequent collection by the MPE system. The FRTR provides a summary description of a number of commonly used off-gas treatment technologies. The off-gas treatment technologies discussed in the FRTR include: thermal oxidation, catalytic oxidation, condensation, carbon adsorption, resin adsorption, biofiltration, internal combustion engines, and flares. Additional information can also be found in Principles and Practice of Bioventing, Volume II, Appendix D – Off-Gas Treatment Options (Leeson and Hinchee 1995). Applicable concentration range, capacity range, removal efficiency, secondary waste streams, advantages and limitations of each technology are presented in tabular form in EM 1110-1-4001.

b. Groundwater.

(1) If contaminant concentrations in the extracted groundwater are low enough it may be possible to discharge the extracted groundwater directly to the local POTW or to a NPDES discharge point; however, this is rarely the case, and treatment of the extracted groundwater is generally required. Once the phase separation has been completed, groundwater treatment in MPE applications is similar to other remedial technologies that require treatment of recovered groundwater. Selection of the groundwater treatment alternative will depend on the groundwater flow rate, contaminant type and concentration, discharge permit limits, presence of other constituents in the water (e.g., iron, manganese, calcium), secondary waste stream generation, and capital and operating costs.

(2) Typical groundwater treatment methods for organic compounds include:

- Air stripping.

- Liquid-phase carbon adsorption.

- Advanced oxidation processes .

- Ex-situ bioreactors.

- Resin adsorption.

(3) These groundwater treatment technologies have all been applied as full-scale treatment technologies at government and private sites. Designers should consult the FRTR Remediation Technologies Screening Matrix and Reference Guide (Van Deuren et al. 1997) for information necessary to perform a preliminary screening-level evaluation of the applicability of these various technologies. Once inapplicable technologies have been screened out, the designer should contact water treatment technology vendors to discuss the design basis and establish preliminary component sizing, estimated removal efficiencies, and estimate capital and O&M costs.

c. NAPL. Recovered NAPL is typically stored in a tank and manifested off site as a hazardous waste. If the recovered NAPL is sufficiently pure, free of sediment, and has a sufficiently high heating value, it may be possible to use the recovered NAPL as supplemental fuel for a thermal vapor-phase treatment device (i.e., catalytic oxidation, thermal oxidation, internal combustion engine or flare). This approach will eliminate one waste stream from the project and will reduce treatment costs for another waste stream. Use of this approach is very site specific but should be considered in appropriate cases. Another option may be to send the recovered NAPL to an off-site recycler.

d. Emulsions. Oil-water emulsions may occur during simultaneous extraction or transfer of groundwater and NAPL. The presence of emulsified oil in liquid effluent will typically result in a violation of discharge permit limits for total oil and grease, and/or for total toxic organics. Refer to paragraph 5-6d(3) for a discussion on methods of breaking or treating oil-water emulsions.

5-10. Other System Appurtenances and Design Considerations.

a. Buildings or Enclosures.

(1) Typically, MPE systems are housed in an existing building, in a shed, or in a trailer. Enclosures housing MPE equipment should be equipped with adequate electrical power, heating, lighting and ventilation. The selected enclosure may serve several purposes, such as: 1) protect the MPE equipment from sunlight, precipitation and/or freezing, 2) reduce the chances of damage due to vandalism, and 3) reduce external noise pollution.

(2) Although the enclosure must be sturdy enough to withstand wind and snow loads, designers should be frugal when designing the MPE enclosure. Equipment should be laid out to utilize interior space efficiently without being so cluttered as to make maintenance activities difficult. For sites where a portion of the MPE system enclosure will be classified as a hazardous area, it is often desirable to install a barrier wall to separate the classified and unclassified areas. Designers should strive to include engineering controls (e.g., negative pressure air handling, ventilation, and locating fugitive emission sources outside of enclosed spaces) to prevent the need to have continuous monitoring for explosive conditions. Service panels, control panels, disconnect switches, and other components can be located in the unclassified area to reduce the amount of electrical equipment within the classified area. As an alternative, service panels, control panels and disconnects can be mounted on the exterior of the building. Electrical components mounted outside should be covered with a roof and secured to prevent damage or vandalism.

b. Surface Covers. Surface covers or impermeable caps are used to reduce infiltration and to prevent or reduce short-circuiting of airflow. Surface caps may be constructed of asphalt or concrete, or may be a synthetic material such as high-density polyethylene (HDPE) or low-density polyethylene (LDPE). Existing pavement may require the application of an asphalt sealer to reduce air leakage. It should be noted that existing pavement is not considered an adequate seal if it was installed with a base course. Refer to EM1110-1-4001, Chapter 5, for additional information on use and effectiveness of surface covers.

c. Barrier Walls.

(1) Barrier walls may be used to contain NAPL migration. Barrier walls may be constructed of soil-bentonite (S-B) slurry, steel (or plastic) sheet piles, pressure-injected grout curtains or a synthetic material (e.g., HDPE). USACE guidance indicates that S-B slurry cut-off walls have replaced the use of traditional cutoff barriers such as steel sheet piles or grout curtains at hazardous waste sites. Slurry wall barriers are constructed by excavating a relatively narrow vertical trench, typically 0.6 to 1.5 m (2 to 5 ft) wide, through a pervious soil stratum to an underlying impervious layer. The trench is filled with a bentonite-water slurry during excavation to stabilize the trench walls, - allowing excavation to continue through the slurry, to the desired depth. Once the desired depth has been reached, the slurry trench is backfilled with a soil/bentonite/water mixture designed to provide a low-permeability barrier wall (10^{-7} to 10^{-8} cm/sec). Designers should consult guide specification CEGS 02444, Soil-Bentonite Slurry Trench for HTRW Projects, and other USACE reference documents if considering use of an S-B cut-off wall. Installation of sheet pile barrier walls may be performed using conventional impact or vibratory pile driving techniques. Installation of a synthetic barrier may be accomplished by conventional cut and cover excavation techniques, or the designer may opt to consider a one-pass trenching method to install a vertical HDPE barrier. The type of barrier wall should be selected based on the specific installation configuration, required installation depth, contaminant type, and installation cost.

(2) Designers must consider the potential for groundwater to mound up behind a barrier wall and, either over-top the barrier wall or flow around the limits of the barrier wall. Therefore, barrier walls should, at a minimum, incorporate water level monitoring piezometers on either side of the barrier. Because groundwater and NAPL will build up behind (upgradient of) the barrier, it is generally beneficial to install groundwater recovery wells/trenches, MPE and/or SVE on the hydraulically upgradient side of the barrier. If a barrier wall is contemplated to contain DNAPL migration, the designer must carefully consider whether potential detrimental effects could result during construction of the barrier that could mobilize the DNAPL or allow DNAPL to migrate to previously uncontaminated sub-strata. Refer to other USACE guidance for additional information on design requirements and considerations for construction of vertical barrier walls.

d. Freeze Protection. Heat tape is typically used to provide freeze protection for exposed piping. Heat tape is rated in power output per unit distance (e.g., watts per foot). Calculate the estimated heat loss based on the type of piping, and the expected temperature difference between the process water and the outside air. It is generally best to use a self-regulating heat tape as opposed to a constant wattage heat tape to prevent the heat tape from overheating. If heat tape is to be used in a classified area (e.g., inside a well vault where NAPL is present), consult the manufacturer regarding their procedures for approving the use of their product in a classified location. Many manufacturers will require a design review and use of XP termination kit accessories before approving the use of their product in a classified location.

Heat tape should always be covered with insulation to retain the heat, otherwise the heat input will be dissipated in the surrounding soil or atmosphere. Insulation should be suitable for wet conditions (e.g., closed cell foam) since water may condense on the outside of the piping and because outside piping may be exposed to precipitation. For long-term MPE projects, exposed insulation should be coated or covered to prevent photo-degradation. More information on insulation can be found in CEGS 15080, Thermal Insulation for Mechanical Systems.

e. Alarms. Other appurtenances such as audible alarms and warning lights may also be included as part of a MPE system. Alarms an warning lights may be located within the treatment system enclosure to alert on-site operators or located outside of the building in order to notify outside sources (e.g., facility personnel not associated with the MPE system) that the system is in alarm condition. MPE systems may also be equipped with remote alarm notification that will call the system operator via an autodialer should the system go into alarm condition.