

Models for Design of Free-Product Recovery Systems for Petroleum Hydrocarbon Liquids

Regulatory Analysis and Scientific Affairs Department

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Free-Product Recovery System Analysis

t_{recovery} [yr] =	3
R_c [ft] =	40
μ_o [cp] =	2
K_w [ft/d] =	15
r_{well} [ft] =	0.5

Water Enhanced	
Q_w [gpm] =	5
b_{well} [ft] =	15
$R_{\text{influence}}$ [ft] =	200
s_{well} [ft] =	4.08

Vacuum Enhanced	
$(-) p_w$ [atm] =	0
L_{well} [ft] =	5
k_{ra} =	0.9
Q_{air} [scfm] =	0.0
h_{well} [ft H ₂ O] =	0.00

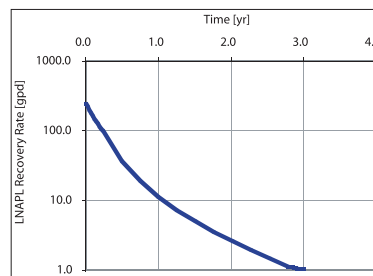
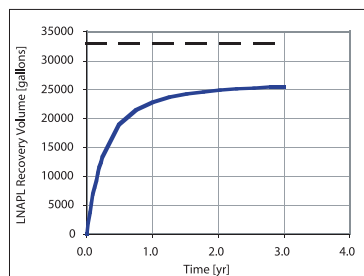
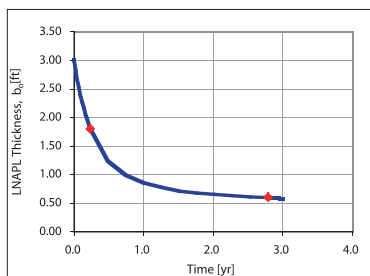
Skimmer Well

If $Q_w = 0$ and $p_w = 0$ then
a skimmer well is assumed

Average drawdown (buildup)
within radius of capture

s_c [ft] = 1.44

Press Ctrl-Shift+S to calculate sheet



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API PUBLICATION 4729

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August 2003



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FORWARD

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PREFACE

This manuscript is presented as a supplement to API Publication Number 4682, *Free-Product Recovery of Petroleum Hydrocarbon Liquids*, which was published in June 1999. Model scenarios are described for free-product hydrocarbon liquid recovery using single- and dual-pump well systems, skimmer wells, vacuum-enhanced well systems, and trenches. Use of spreadsheet software to compute recovery rates, volumes and times is discussed, and example applications are provided. The basic modeling equations and background material are also provided.

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EXECUTIVE SUMMARY

This document addresses the application of proven technologies for recovering free-product petroleum releases to groundwater. The manuscript is a supplement to API Publication Number 4682, and documents spreadsheet models for design and analysis of liquid free-product recovery systems using single- and dual-pump wells, vacuum-enhanced wells, skimmer wells, and trenches. The principles that govern the distribution and movement of free-product petroleum hydrocarbons near the water table in an unconfined groundwater aquifer are reviewed. Models for predicting free-product recovery system performance are presented. Four spreadsheet models [LNAPL(vG-B).xls, LNAPL(vG-M).xls, LNAPL(vG-B-2L).xls, and LNAPL(vG-M-2L).xls] are described, and example applications are presented and discussed.

This manual is useful for evaluating remediation options at sites where free product is present at the water table of an unconfined aquifer or perched on a confining bed. It assumes that the reader has a basic understanding of hydrogeology and is aware of subsurface complexities (e.g., heterogeneity and water-table fluctuation) that complicate estimates of free-product recovery. Background material is presented in API Publication No. 4682, including a description of remediation technologies associated with free-product recovery, physical/chemical parameters that are essential in the design and analysis of free-product recovery systems, and information and data for parameter estimation.

The most significant changes from API Publication No. 4682 that are included in the present model formulation are a focus on the van Genuchten representation for soil retention of fluid, and use of piece-wise linear equations to relate both the LNAPL specific volume and relative permeability functions to the monitoring-well thickness of the LNAPL layer. The explicit representation of the LNAPL-layer relative permeability function results in model predictions that differ most significantly from the previous model when the Mualem relative permeability model is selected. The capability for addressing the transient performance of skimmer wells and trench systems has been added. In addition, a simple case of aquifer heterogeneity with layers of different soil texture properties can be analyzed.

SECTION 1 – INTRODUCTION

1.1 Background and Objectives

The American Petroleum Institute (API) Publication Number 4682, *Free-Product Recovery of Petroleum Hydrocarbon Liquids* (Charbeneau et al., 1999), provides an overview of recovery technologies for petroleum hydrocarbon liquids that are released to the subsurface environment and accumulate near the water table. The primary recovery technologies include skimmer wells that produce hydrocarbon liquids and single- and dual-pump wells that produce both water and hydrocarbon liquids. Hydrocarbon liquid recovery rates may also be enhanced by applying a vacuum pressure to the well to increase the gradient towards the well within the hydrocarbon layer. API 4682 describes two (Excel spreadsheet) models that may be used to characterize the subsurface distribution and mobility of liquid hydrocarbon (lighter-than-water nonaqueous phase liquids, LNAPL), and to calculate the potential recovery rate and time using single- and dual-pump wells, and vacuum-enhanced wells.

The present manuscript is a supplement to API 4682 that describes additional work that was funded through API and supported by its Soil and Groundwater Technical Task Force. The manuscript describes a more general modeling framework for characterization of subsurface LNAPL distribution using the capillary pressure head-saturation model of van Genuchten (1980), and for describing the mobility and potential recovery using single- and dual-pump wells, vacuum-enhanced wells, skimmer wells and trenches. Both the LNAPL layer volume and relative permeability are described by fitting a piecewise linear model to the magnitudes calculated from vertical distributions of hydrocarbon saturation and relative permeability based on the assumption of vertical equilibrium (the valid range for this assumption is discussed in API 4682). The models presented in Appendix A also simulate a simple case of soil heterogeneity with an abrupt vertical change in soil texture, where the upper and lower layers may have differing soil characteristics.

1.2 Scenarios for Free-Product Hydrocarbon Liquid Recovery

Proven technologies for free-product recovery of petroleum hydrocarbon liquids are described in API 4682. Models to provide quantitative estimates of system performance must necessarily be based on simplifying assumptions that will not be applicable to all field conditions. Nevertheless, the models provide insight and guidance that should be helpful in technology selection and system design, and in analysis of system performance. The model scenarios for well systems and trenches are discussed separately.

The subsurface porous media is assumed to be homogeneous, as shown in Figure 1.1. [A simple case of aquifer heterogeneity where a soil layer of one texture overlies a layer with a differing texture, with an abrupt horizontal interface separating the layers, is presented in Appendix A.] Figure 1.1 shows a monitoring well with an LNAPL layer located between the air-NAPL interface z_{ao} and the NAPL-water interface z_{ow} . The total monitoring well LNAPL thickness is b_o . The elevation of the water table, z_{aw} , provides the datum for fluid levels. While the water table is not present because of the LNAPL layer, its elevation is easily determined from the elevations z_{ao} and z_{ow} , and the LNAPL density ρ_o .

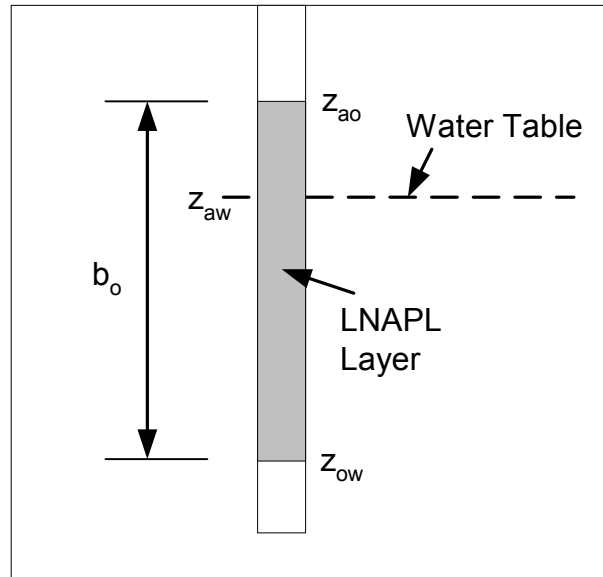


Figure 1.1. Monitoring well LNAPL thickness, b_o

The texture characteristics that must be defined for the porous media include the porosity n ; the van Genuchten parameters N and α ; and the irreducible water saturation, S_{wr} ; and residual LNAPL saturation values for the vadose zone and saturated zone, S_{orv} and S_{ors} . Fluid properties include the LNAPL density, ρ_o (it is assumed that the water density is 1 g/cm^3), and the water and LNAPL surface and interfacial tensions, σ_{aw} , σ_{ao} , and σ_{ow} .

1.2.1. Scenarios for Recovery Well Systems

The basic scenario for free-product recovery using well systems is the same for single- and dual-pump wells, vacuum-enhanced wells, and skimmer wells. The performance of each well is characterized in terms of its radius of capture R_c , with a typical scenario shown in Figure 1.2. This figure depicts a plan view of an LNAPL lens (in gray color) with 11 recovery wells located so that the pattern of wells with their radius of capture will cover the area of the lens. For single- and dual-pump well systems, the radius of capture could extend out to the radius of influence (water production) of the well. For vacuum-enhanced systems, the radius of influence of the vacuum extraction well (which is typically on the order of 30 – 40 feet) limits the radius of capture. For

skimmer wells, the radius of capture is limited to a greater but unknown extent, which is probably on the order of 10 – 20 feet.

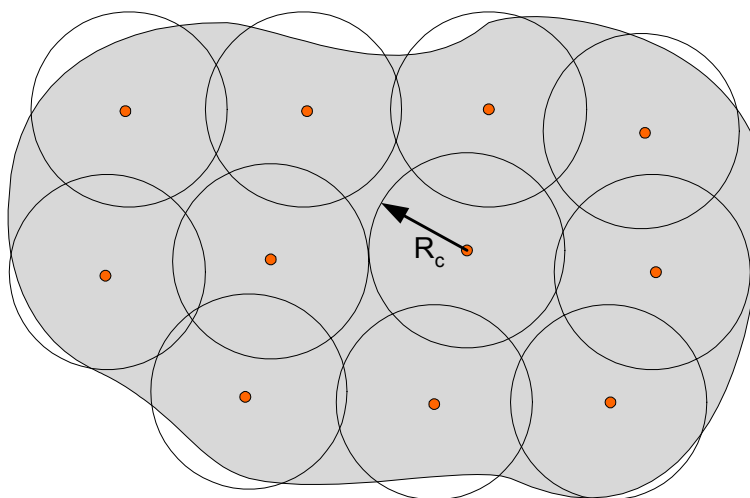


Figure 1.2. Recovery well system with 11 recovery wells showing the radius of capture

The data required for analysis of recovery-well-system performance includes the radius of capture for the well, the LNAPL viscosity (the water viscosity is assumed to be 1 cp), and water production rate for a water-enhanced system or wellhead vacuum pressure for a vapor-enhanced system. For a water-enhanced system, the effective depth of penetration of the well into the aquifer must be specified, while for a vacuum-enhanced system, the screened interval of the vadose zone must be given along with the effective relative permeability of the vadose zone (due to the presence of soil water, the permeability of the vadose zone may be reduced from its air-saturated value). If zero water production and wellhead pressure are specified, then the well is assumed to function as a skimmer well.

1.2.2. Scenario for LNAPL Recovery Using Trenches

The modeling framework may also be used to represent a simple trench recovery system, such as shown in Figure 1.3. The trench has a width W_T transverse to the direction of groundwater flow. The LNAPL lens is of length L_T in the direction of groundwater flow, and width W_T . The natural groundwater hydraulic gradient J_w is transferred to the floating LNAPL layer, and carries it into the trench where LNAPL is

removed by skimmer wells or other technology. The rate of LNAPL discharge into the trench will depend on the effective lens thickness as observed in a monitoring well, soil texture characteristics, the natural groundwater hydraulic gradient, and whether groundwater is also produced from the trench in order to increase the hydraulic gradient. If the trench cuts across an LNAPL lens, then the upstream and downstream sections of the lens must be analyzed separately, with J_w being negative on the downstream side.

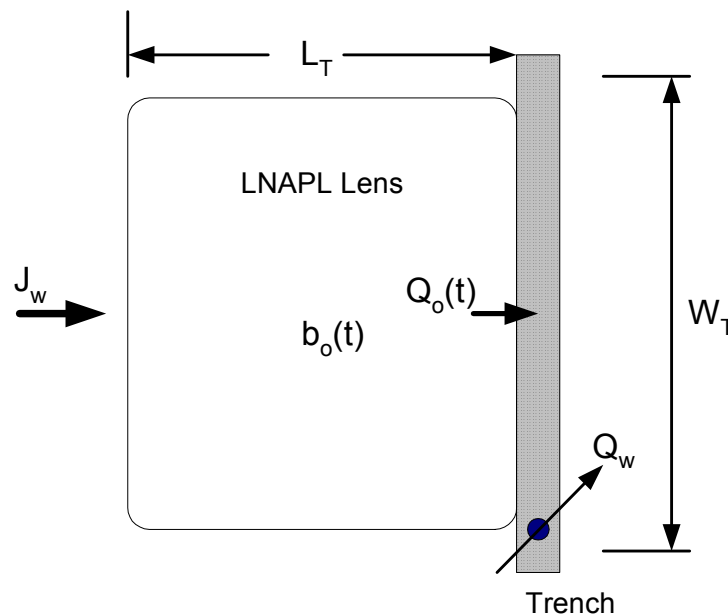


Figure 1.3. Simple Trench System for LNAPL Recovery

1.3. Overview

The models for well and trench recovery systems provide estimates of the recovery volume and rate as a function of time. The mathematical models on which these estimates are based use a simple representation of the LNAPL layer effective saturation and permeability. However, the representation is consistent with the actual formation distributions of LNAPL saturation and relative permeability under conditions of vertical equilibrium, so that “continuity” is maintained within the modeling framework. These representations are described in Section 2, which describes the saturation distribution based on the van Genuchten (1980) capillary pressure model and conditions

of vertical equilibrium. This model was not described in API 4682, which focused on application of the Brooks and Corey (1964) power law model for representing the soil characteristics. The LNAPL layer relative permeability distribution is also described, using both the Burdine (1953) and Mualem (1976) models to relate saturation and relative permeability.

The mathematical models for predicting free-product recovery are developed in Section 3. These models are based on the free-product thickness that one would observe in a monitoring well that was in good communication with the formation fluids (water, LNAPL, air). The rate equations for single- and dual-pump wells, vacuum-enhanced wells, skimmer wells, and trench recovery systems depend on the monitoring well LNAPL thickness and on the discharge of formation fluids (water or air). The principle of continuity is applied to predict how the monitoring well LNAPL thickness (and recovery rate) varies as a function of time. Section 4 presents a series of examples that describe features of the model implementation and model application.

Appendix A describes an extended version of the model that addresses a simple case of aquifer heterogeneity, with two layers having different soil texture characteristics. Calculation of effective layer specific volume and relative permeability are described for this two-layer case, and extension of the time-variable recovery models are presented. Example applications are also provided.

Appendix B provides a listing of the Visual Basic function calls that are used in the spreadsheets. Appendix C provides representative van Genuchten model soil retention parameter values for different soil texture classes. Tables of representative fluid properties can be found in Appendix D. Appendix E contains porosity and residual saturation values from the literature.

SECTION 2 – LNAPL SATURATION AND RELATIVE PERMEABILITY DISTRIBUTIONS

This section describes the vertical distribution of fluid saturation and relative permeability for a homogeneous porous media. The resulting relationships are used to develop simple representations of effective specific volume and relative permeability for an LNAPL lens.

2.1 NAPL Saturation Distribution

This subsection first considers the capillary pressure scaling relationships for different fluid systems, and then the consequences of vertical equilibrium for describing capillary pressure distributions are discussed. Results are used to estimate the saturation distribution for homogenous porous media.

2.1.1 Capillary Pressure Scaling Relationships

According to the van Genuchten (1980) model, the water saturation S_w is related to the suction pressure head h through

$$S_w(h) = S_{wr} + (1 - S_{wr}) \left[\frac{1}{1 + (\alpha h)^N} \right]^M \quad (2.1)$$

In equation 2.1, S_{wr} is the irreducible (residual) water saturation and α , N and M are model parameters (where $M = 1 - 1/N$; $N = 1/(1-M)$). The parameter α is for the air-water fluid system, and its magnitude is inversely related to the thickness of the capillary fringe. The Brooks and Corey (1964) displacement pressure head (Ψ_b) is related to α through the approximate relation $\alpha \sim 1/\Psi_b$. The parameter N is proportional to the pore-size distribution index (λ) of Brooks and Corey, where roughly one has $N = \lambda + 1$. Representative values for a sand soil are $S_{wr} = 0.15$, $\alpha = 2.0 \text{ ft}^{-1}$ and $N = 4.0$. The resulting soil characteristic curve is shown in Figure 2.1.

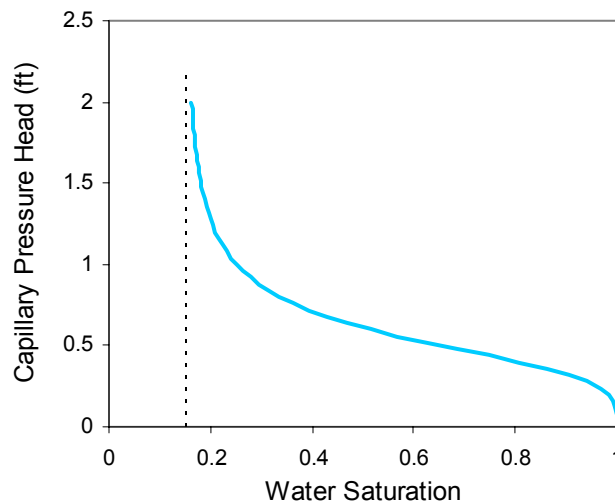


Figure 2.1. Representative soil characteristic curve based on the van Genuchten model with $S_{wr} = 0.15$, $\alpha = 2.0 \text{ ft}^{-1}$, and $N = 4.0$

Equation 2.1 may be used for other fluid combinations if appropriate scaling relationships are introduced. It is assumed that water is the wetting fluid, air the nonwetting fluid, and that LNAPL has intermediate wettability. For the three-phase (water, LNAPL, air) system, Leverett's (1941) assumption is that the water saturation is a function of the LNAPL-water capillary pressure, while the total liquid saturation (water plus LNAPL) is a function of the air-LNAPL capillary pressure.

The introduction of scaling relationships are based on Laplace's equation (for capillary pressures) that relates the pressure difference across an interface between two fluid phases to the radius of curvature of this interface. For fluid phases i and j , this equation may be written

$$\frac{p_{cij}}{\sigma_{ij}} = \frac{2}{r_c} \quad (2.2)$$

In equation 2.2, p_{cij} is the capillary pressure (pressure in the nonwetting phase i minus the pressure in the wetting phase j), σ_{ij} is the surface or interfacial tension between phases i and j , and r_c is the radius of curvature of the interface that separates these phases. The reasoning behind the scaling relationships is as follows. The right side of equation 2.2 should be determined by the distribution of pores within the porous medium and should be directly related to the fluid saturation (with the wetting phase

occupying the smaller pore sequences). A decrease in the radius of curvature would correspond to the interface moving into pores of smaller size with larger capillary pressure. This would correspond to a decrease in wetting phase saturation. [This does not reflect hysteresis, wherein the sequence of filled pores is different upon drainage and imbibition.] The left side of equation 2.2 can be scaled for different fluid combinations.

For fluid combination i - j , the capillary pressure head parameter α may be scaled following Leverett (1941):

$$\alpha_{ij} = \left(\frac{\rho_j - \rho_i}{\rho_w - \rho_a} \right) \left(\frac{\sigma_{aw}}{\sigma_{ij}} \right) \alpha \quad (2.3)$$

In equation 2.3 the term containing the fluid density values appears because capillary pressure head values are being scaled rather than capillary pressures. At standard atmospheric pressure and a temperature of 20° C, the air density is 0.0012 g/cm³ and is usually neglected compared with the water density of 1 g/cm³. Thus, for scaling the capillary pressure head between LNAPL and water, equation 2.3 becomes

$$\alpha_{ow} = \left(\frac{\rho_w - \rho_o}{\rho_w} \right) \left(\frac{\sigma_{aw}}{\sigma_{ow}} \right) \alpha = (1 - \rho_r) \left(\frac{\sigma_{aw}}{\sigma_{ow}} \right) \alpha \quad (2.4)$$

In equation 2.4, ρ_r is the LNAPL/water density ratio, or the LNAPL specific gravity. Similarly, in scaling the capillary pressure heads between air and LNAPL, equation 2.3 takes the form

$$\alpha_{ao} = \rho_r \left(\frac{\sigma_{aw}}{\sigma_{ao}} \right) \alpha \quad (2.5)$$

Equations 2.4 and 2.5 provide the appropriate scaling relationships.

2.1.2 Vertical Equilibrium

Use of equation 2.1 and appropriately scaled capillary pressure relations to describe the vertical distribution of fluid saturation requires the assumption of vertical equilibrium, wherein the pressure in each phase satisfies the hydrostatic pressure equation. To help develop ideas, consider the LNAPL-water system. The hydrostatic

pressure equation for the LNAPL and water phase take the following form for an incompressible fluid.

$$p_o(z) = p_o(z^*) - \rho_o g(z - z^*) \quad (2.6)$$

$$p_w(z) = p_w(z^*) - \rho_w g(z - z^*)$$

In equation 2.6, z^* is a reference elevation that will be selected based on the following discussion. The capillary pressure is the pressure difference between the nonwetting and wetting phases (for this case this is designated as p_{cow}), and thus the capillary pressure distribution between LNAPL and water under conditions of vertical equilibrium is given by

$$p_{cow}(z) = p_{cow}(z^*) + (\rho_w - \rho_o)g(z - z^*) \quad (2.7)$$

It is most useful to select a reference elevation where the capillary pressure vanishes, that is, the pressure in the nonwetting and wetting phases are the same. From equation 2.2, this would require that the radius of curvature of the interface between the phases be large (infinite). This would be the case of a monitoring well in equilibrium with formation fluids, and with reference to Figure 1.1, the elevation $z^* = z_{ow}$ serves as the appropriate datum. Thus the capillary pressure head distribution under conditions of vertical equilibrium may be specified by

$$h_{ow} = \frac{p_{cow}}{(\rho_w - \rho_o)g} = z - z_{ow} \quad (2.8)$$

To show consistency of the scaling relationships for equation 2.1 note that

$$\alpha_{ow} h_{ow} = \left(\frac{\rho_w - \rho_o}{\rho_w} \right) \left(\frac{\sigma_{aw}}{\sigma_{ow}} \right) \alpha \times \frac{p_{cow}}{(\rho_w - \rho_o)g} = \alpha h \quad (2.9)$$

The last step in equation 2.9 follows from equation 2.2, according to which, $p_{cow}/\sigma_{ow} = p_{caw}/\sigma_{aw} = p_c/\sigma$, and $h = p_c/(\rho_w g)$.

In a similar fashion to equation 2.8, for the air-LNAPL system one finds

$$h_{ao} = z - z_{ao} \quad (2.10)$$

In equation 2.10, z_{ao} is the elevation of the air-LNAPL interface in a monitoring well, as shown in Figure 1.1. Finally, using similar arguments for the water phase we have

$$h \equiv h_{aw} = z - z_{aw} \quad (2.11)$$

Together, equations 2.8, 2.10 and 2.11 allow one to calculate the pressure distribution within any phase under conditions of vertical equilibrium. For all developments below, the water table is the elevation datum, and $z_{aw} = 0$. Other elevations are referenced to this datum.

2.1.3 LNAPL and Water Saturation Distribution

Equation 2.1 may be written as

$$\Theta_w(h) = \left(\frac{S_w(h) - S_{wr}}{1 - S_{wr}} \right) = \left[\frac{1}{1 + (\alpha h)^N} \right]^M \quad (2.12)$$

In equation 2.12, Θ_w is the air-water reduced saturation, and it scales the water saturation to range between values of 0 and 1. In order to apply this equation to other fluid-phase pairs, the appropriate reduced saturation functions must be identified, which also must have values that scale to range from 0 to 1. Using the Leverett assumptions for the LNAPL-water pair, along with equations 2.8 and 2.4 for vertical equilibrium and capillary scaling, the water saturation distribution may be represented by the following equation:

$$S_w(z) = S_{wr} + (1 - S_{wr} - S_{ors}) \left[\frac{1}{1 + (\alpha_{ow} (z - z_{ow}))^N} \right]^M \quad (2.13)$$

In equation 2.13, S_{ors} is the residual LNAPL saturation in the saturated zone and z_{ow} is the elevation of the LNAPL-water interface in a monitoring well. In a similar fashion, for the total liquid (water plus LNAPL)-air saturation distribution, equation 2.12 becomes

$$S_t(z) = S_{wr} + S_{orv} + (1 - S_{wr} - S_{orv}) \left[\frac{1}{1 + (\alpha_{ao} (z - z_{ao}))^N} \right]^M \quad (2.14)$$

In equation 2.14, $S_t(z) = S_w(z) + S_o(z)$, S_{orv} is the residual LNAPL saturation in the vadose zone, and z_{ao} is the elevation of the air-LNAPL interface in a monitoring well. For elevation $z < z_{ao}$, all of the pore space is filled with liquid (water plus LNAPL), so $S_t = 1$. Likewise, for elevation $z < z_{ow}$, all of the pore space is filled with water plus residual LNAPL (if any is present), so $S_w = 1 - S_{ors}$.

Given equations 2.13 and 2.14, the LNAPL distribution may be found from

$$S_o(z) = S_t(z) - S_w(z) \quad (2.15)$$

Equation 2.15 predicts the total saturation of LNAPL, and does not reflect the fact that a fraction of this LNAPL phase will remain trapped within the saturated and vadose zones (given by the values of S_{ors} and S_{orv} , respectively).

Figure 2.2 shows the LNAPL saturation distribution corresponding to a monitoring-well LNAPL thickness $b_o = 2.0$ feet, for a soil with same texture properties used in Figure 2.1. The horizontal dashed line marks the elevation of the water table. The box on the right side shows the monitoring-well LNAPL thickness. The LNAPL curve shows the free-product LNAPL saturation distribution, as predicted using equations 2.13 to 2.15. The dashed curve on the left side of the figure marks the residual LNAPL distribution. For this case, residual LNAPL extends above and below the free-product LNAPL layer. The extension of the residual LNAPL distribution within the free-product layer shows the saturation distribution that would become immobile as LNAPL is recovered. However, all LNAPL within the free-product layer is considered mobile. Capillary forces trap LNAPL only as the LNAPL saturation is reduced.