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Standard Guide for
Estimation of LNAPL Transmissivity[1]

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1. Scope

1.1 This guide provides field data collection and calculation methodologies for the estimation of light non-aqueous phase liquid (LNAPL) transmissivity in unconsolidated porous sediments. The methodologies presented herein may, or may not be, applicable to other hydrogeologic regimes (for example, karst, fracture flow). LNAPL transmissivity represents the volume of LNAPL (L^3) through a unit width (L) of aquifer per unit time (t) per unit drawdown (L) with units of (L^2/T). LNAPL transmissivity is a directly proportional metric for LNAPL recoverability whereas other metrics such as apparent LNAPL thickness gauged in wells do not exhibit a consistent relationship to recoverability. The recoverability for a given gauged LNAPL thickness in a well will vary between different soil types, LNAPL types or hydrogeologic conditions. LNAPL transmissivity accounts for those parameters and conditions. LNAPL transmissivity values can be used in the following five ways: *(1)* Estimate LNAPL recovery rate for multiple technologies; *(2)* Identify trends in recoverability via mapping; *(3)* Applied as a leading (startup) indicator for recovery; *(4)* Applied as a lagging (shutdown) indicator for LNAPL recovery; and *(5)* Applied as a robust calibration metric for multiphase models (Hawthorne and Kirkman, 2011 (**1**)[2] and ITRC ((**2**)). The methodologies for LNAPL transmissivity estimation provided in this document include short-term aquifer testing methods (LNAPL baildown/slug testing and manual LNAPL skimming testing), and long-term methods (that is, LNAPL recovery system performance analysis, and LNAPL tracer testing). The magnitude of transmissivity of any fluid in the subsurface is controlled by the same variables (that is, fluid pore space saturation, soil permeability, fluid density, fluid viscosity, the interval that LNAPL flows over in the formation and the gravitational acceleration constant). A direct mathematical relationship exists between the transmissivity of a fluid and the discharge of that fluid for a given induced drawdown. The methodologies are generally aimed at measuring the relationship of discharge versus drawdown for the occurrence of LNAPL in a well, which can be used to estimate the transmissivity of LNAPL in the formation. The focus, therefore, is to provide standard methodology on how to obtain accurate measurements of these two parameters (that is, discharge and drawdown) for multi-phase occurrences to estimate LNAPL transmissivity.

1.2 *Organization of this Guide:*

1.2.1 Section 2 presents documents referenced.

1.2.2 Section 3 presents terminology used.

1.2.3 Section 4 presents significance and use.

1.2.4 Section 5 presents general information on four methods for data collection related to LNAPL transmissivity calculation. This section compares and contrasts the methods in a way that will allow a user of this guide to assess which method most closely aligns with the site conditions and available data collection opportunities.

1.2.5 Sections 6 and 7 presents the test methods for each of the four data collection options. After reviewing Section 5 and selecting a test method, a user of this guide shall then proceed to the applicable portion of Sections 6 and 7 which describes the detailed test methodology for the selected method.

1.2.6 Section 8 presents data evaluation methods. After reviewing Section 5 and the pertinent test method section(s) of Sections 6 and 7, the user of this guide shall then proceed to the applicable portion(s) of Section 8 to understand the methodologies for evaluation of the data which will be collected. It is highly recommended that the test methods and data evaluation procedures be understood prior to initiating data collection.

1.3 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This document is applicable to wells exhibiting LNAPL consistently (that is, LNAPL transmissivity values above zero). This methodology does not substantiate zero LNAPL transmissivity; rather the lack of detection of LNAPL within the well*

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

combined with proper well development and purging procedures are required to confirm zero LNAPL transmissivity.

1.6 *This document cannot replace education or experience and should be used in conjunction with professional competence in the hydrogeology field and expertise in the behavior of LNAPL in the subsurface.*

1.7 *This document cannot be assumed to be a substitute for or replace any laws or regulations whether federal, state, tribal or local.*

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D5088 Practice for Decontamination of Field Equipment Used at Waste Sites

D5521 Guide for Development of Groundwater Monitoring Wells in Granular Aquifers

E2531 Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface

3. Terminology

3.1 *Definitions:*

3.1.1 *air/LNAPL interface (Z_{an})*—The surface shared by air and LNAPL in a control well. (L)

3.1.2 *calculated water-table elevation (Z_{CGW})*—the theoretical location of the air/water surface based on a density correction if LNAPL were not present in a well. (L)

3.1.3 *confined LNAPL*—LNAPL trapped in an aquifer beneath a layer that exhibits a pore entry pressure greater than the capillary LNAPL head, thereby impeding the upward migration of LNAPL limits the upward movement of the LNAPL. The term confined LNAPL is used because the mobile LNAPL is under pressure greater than gauge pressure against the underside of the LNAPL confining layer.

3.1.4 *control well*—well by which the aquifer is stressed or tested.

3.1.5 *discharge*—the flow of a fluid into or out of a well. (L^3/t)

3.1.6 *drawdown*—a pressure differential in terms of fluid head. (L)

3.1.7 *effective well radius*—the radius that represents the area of the well casing and the interconnected porosity of the filter pack. (L)

3.1.8 *equilibrium fluid levels*—gauged fluid levels that represent the oil head and the water head or the calculated water-table elevation of the formation. Under equilibrium fluid levels no net oil or water flow occurs between the formation and the well.

3.1.9 *fluid level*—the level of a fluid interface (either air/oil, LNAPL/water, or potentiometric surface).

3.1.10 *formation thickness (b_{nf})*—the interval that LNAPL flows over in the formation. For unconfined conditions this is approximately equal to the gauged LNAPL thickness. Confined and perched conditions the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

3.1.11 *gauged LNAPL thickness (b_n)*—The difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)

3.1.12 *hydraulic conductivity (derived via field aquifer tests)*—the volume of water at the existing kinematic viscosity that will move in a unit time, under a unit hydraulic gradient, through a unit area, measured at right angles to the direction of flow. (L/t)

3.1.13 *LNAPL*—Light Non Aqueous Phase Liquid.

3.1.14 *LNAPL baildown test*—a procedure which includes the act of removing a measured LNAPL volume from a well and filter pack to induce a head differential and the follow-up gauging of fluid levels in the well.

3.1.15 *LNAPL borehole volume*—the volume of LNAPL existing within the casing and the drainable volume existing within the filter pack of a well. Based on effective radius and gauged thickness of LNAPL. (L^3)

3.1.16 *LNAPL slug test*—a procedure which includes the act of removing or displacing a known volume of LNAPL from a well to induce a head differential and the follow-up gauging of fluid levels in the well.

3.1.17 *LNAPL specific yield (S_{yn})*—the volume of LNAPL an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in LNAPL head for gravity drainage conditions. (unitless)

3.1.18 *LNAPL specific yield filter pack (S_{yf})* —the volume of LNAPL released or takes into storage per unit surface area of the filter pack per unit change in LNAPL head for gravity drainage conditions. (unitless)

3.1.19 *LNAPL storage coefficient (S_n)* —the volume of LNAPL an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in LNAPL head. For a confined aquifer, it is based on the volume of fluid released due to decompression. For an unconfined aquifer, the storage coefficient is approximately equal to the LNAPL specific yield. (unitless)

3.1.20 *LNAPL transmissivity (T_n)*—the volume of LNAPL at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer. (L^2/t)

3.1.21 *observation well*—a well screened across all or part of an aquifer.

3.1.22 *oil/water interface (Z_{nw})*—The surface shared by LNAPL and water in a control well. (L)

3.1.23 *perched LNAPL*—mobile LNAPL that accumulates in the vadose zone of a site for some time period above a layer that exhibits a pore entry pressure greater than the capillary LNAPL head, thereby impeding the downward migration of LNAPL.

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[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.1.24 *potentiometric surface*—see *calculated water-table elevation.*

3.1.25 *radius of influence*—the distance from a well that the pumping induced head differential from non-pumping conditions is zero, head differentials due to background gradients may still exist at this radius. (L)

3.1.26 *slug*—a volume of water or solid object used to induce a sudden change of head in a well.

3.1.27 *test well*—a well by which the aquifer is stressed, for example, by pumping, injection, or change of head.

3.2 For definitions of other terms used in this test method refer to Terminology, Guide D653.

4. Significance and Use

4.1 *Application:*

4.1.1 LNAPL transmissivity is an accurate metric for understanding LNAPL recovery, is directly proportional to LNAPL recoverability and tracking remediation progress towards residual LNAPL saturation.

4.1.2 LNAPL transmissivity can be used to estimate the rate of recovery for a given drawdown from various technologies.

4.1.3 LNAPL transmissivity is not an intrinsic aquifer property but rather a summary metric based on the aquifer properties, LNAPL physical properties, and the magnitude of LNAPL saturation over a given interval of aquifer.

4.1.4 LNAPL transmissivity will vary over time with changing conditions such as, seasonal fluctuations in water table, changing hydrogeologic conditions and with variability in LNAPL impacts (that is, interval that LNAPL flows over in the formation and LNAPL pore space saturation) within the formation.

4.1.5 Any observed temporal or spatial variability in values derived from consistent data collection and analysis methods of LNAPL transmissivity is not erroneous, rather is indicative of the actual variability in subsurface conditions related to the parameters encompassed by LNAPL transmissivity (that is, fluid pore space saturation, soil permeability, fluid density, fluid viscosity, and the interval that LNAPL flows over in the formation).

4.1.6 LNAPL transmissivity is a more accurate metric for evaluating recoverability and mobile LNAPL than gauged LNAPL thickness. Gauged LNAPL thickness does not account for soil permeability, magnitude of LNAPL saturation above residual saturation, or physical fluid properties of LNAPL (that is, density, interfacial tension, and viscosity).

4.1.7 The accurate calculation of LNAPL transmissivity requires certain aspects of the LNAPL Conceptual Site Model (LCSM) to be completely understood and defined in order to calculate LNAPL drawdown correctly. The methodologies for development of the LCSM are provided in Guide E2531. The general conceptual site model aspects applicable to this guide include:

4.1.7.1 Equilibrium fluid levels (for example, air/LNAPL and LNAPL/water).

4.1.7.2 Soil profile over which LNAPL is mobile.

4.1.7.3 LNAPL hydrogeologic scenario (for example, unconfined, confined, perched, macro pores, and so forth).

4.1.7.4 LNAPL density.

4.1.7.5 Hydraulic conductivity for each soil type within the well screen interval.

4.1.7.6 Well screen interval in the vadose and saturated zones.

4.1.8 Incorporation of LNAPL transmissivity can further LCSMs by providing a single comparable metric that quantifies LNAPL recoverability at individual locations across a site.

4.1.9 Each of the methods provided in this document is applicable to LNAPL in confined, unconfined, and perched conditions. Any differences in evaluation are discussed in Section 5.

4.2 *Purpose*—The methods used to calculate LNAPL transmissivity have been published over the past 20 years; however little effort has been focused on providing quality assurance for individual tests or refinement of field procedures. In addition to summarizing the existing methods to calculate LNAPL transmissivity, this document will provide guidance on refined field procedures for data collection and minimum requirements for data sets before they are used to calculate LNAPL transmissivity.

4.2.1 *Considerations*—The following section provides a brief review of considerations associated with LNAPL transmissivity testing.

4.2.1.1 *Aquifer Conditions (confined, unconfined, perched)*—In general, each testing type is applicable to confined, unconfined, and perched conditions; however, consideration should be given to how LNAPL drawdown is calculated from well gauging data relative to formation conditions. Calculation of LNAPL transmissivity for confined and perched conditions is possible; however, the soil profile needs to be considered in combination with the fluid levels to accurately calculate drawdown. Drawdown values for perched and confined conditions can easily be overestimated without proper consideration. This results in LNAPL transmissivity being underestimated. The calculations of drawdown under perched and confined conditions are discussed within this document. Tidal influences or a vertical gradient on the water table also affect measurements and could distort the transmissivity results. Tidal influences are discussed in more detail in Appendix X1.

4.2.1.2 *Well Construction*—Any well being tested should be screened over the entire mobile interval of LNAPL. For locations where multiple discrete mobile intervals exist, it may be preferable to screen individual wells across each mobile interval. This will simplify the calculation of drawdown and derivation of LNAPL transmissivity. The interval of mobile LNAPL does not always correspond to the elevation of the air/LNAPL interface (for example, the mobile interval can be beneath the base of a confining layer under confined conditions). Appropriately screened wells can be substantiated based on vertical delineation of the entire LNAPL impacted interval (see Guide E2531).

4.2.1.3 *LNAPL Type*—No limitations have been identified for LNAPL type. However, the specific gravity of the LNAPL must contrast with that of the water to be measurable with an interface probe.

4.2.1.4 *Well Development*—In order to derive the most accurate LNAPL transmissivity value, appropriate well development should be conducted to ensure connectivity between LNAPL in the formation and the well (Hampton 2003) (**3**). Industry experience has observed that LNAPL can require up to several months following well installation to saturate the filter pack and establish connectivity within the well. Well development can help to reduce this time frame and should be completed in accordance with Guide D5521.

4.2.2 *Analysis Method*—An understanding of the analysis method and theory is necessary prior to the field testing to ensure that all appropriate dimensions and measurements are properly recorded.

4.3 *Precision and Bias*—At this time this document aims to provide methodologies for data collection and analysis to yield an accuracy of LNAPL transmissivity values within a factor of two (compared with the unknown actual value). This modest accuracy is reasonable based on the overall industry experience in implementing these procedures and the lack of comparison studies. The objectives initiated through development of this document are to provide improved guidance for more consistent data collection and analysis methodology, which in turn will provide a larger and more accurate data set on which to base future methodology revisions and improvements.

5. Method Selection

5.1 The following section describes each of four test methods for the user to evaluate which methodology best fits their data objectives, site setting, and hydrogeologic conditions. An overview of this section is provided in Table A2.1 and Table A2.2. A review of the required parameters to be measured is provided in Tables A2.3-A2.9.

5.2 *Baildown/Slug Testing:*

5.2.1 *Overview*—The LNAPL baildown/slug test consists of either removing the entire LNAPL from the well casing and filter pack or the displacement of a partial volume to induce a head differential, respectively. Following the induction of the head differential, fluid levels are gauged during recovery.

5.2.2 *Data Analysis*—The LNAPL baildown/slug test field procedure is used in conjunction with LNAPL slug test analytical procedures to provide estimates of LNAPL transmissivity at any well exhibiting sufficient LNAPL thickness (that is, at least 0.5 ft/15.2 cm).

5.2.3 *Waste Disposal*—The baildown/slug test provides an advantage over other tests in that it does not typically require the disposal of large quantities of LNAPL or water that may be produced, nor does it require specialized equipment.

5.2.4 *Aquifer Extent Represented*—LNAPL baildown/slug tests reflect conditions near the well, and therefore represent a limited radius of influence. LNAPL transmissivity values from baildown/slug tests may not compare well with transmissivity values estimated using recovery system-based data (5.3) because of the differences in scale of evaluation between the two methods. However, increasing or decreasing trends in transmissivity will be seen in both recovery system-based data and baildown testing-based data.

5.2.5 *Capital Cost*—The capital cost for this method is low because it can be implemented on existing wells exhibiting LNAPL, does not require the construction of a recovery system nor does it require specialized equipment above and beyond other methods.

5.2.6 *Test Duration*—The test length timeframe is inversely related to the transmissivity of LNAPL and directly related to the effective well radius. LNAPL baildown/slug tests may require minutes to months to completely recover as LNAPL transmissivity may vary by several orders of magnitude across sites. However, in cases of slow recovery (that is, greater than a month) and where high confidence exists that the initial fluid levels represent equilibrium conditions, it is not necessary to allow the well to fully recover. A data set representing partial recovery combined with substantiated equilibrium fluid levels can be used to estimate an LNAPL transmissivity or at a minimum place an upper bound on recoverability.

5.2.7 *Special Considerations:*

5.2.7.1 Existence of a vertical gradient or tidal influences on the water table may limit the accuracy of the slug and/or baildown test, because the initial thickness in the well may be exaggerated (downward hydraulic gradient) or thin (upward hydraulic gradient), compared with static conditions. The relationships between LNAPL thickness, vertical gradient, and LNAPL recovery (recharge) rate may be complex and distort test data and the interpretation and are beyond the scope of this guide.

5.2.7.2 Periodic LNAPL removal events from wells have historically resulted in wells in a continual state of non-equilibrium and result in inaccurate equilibrium fluid levels. Equilibrium fluid level data is required for accurate drawdown calculations. LNAPL drawdown has historically been one of the primary variables inducing significant error to LNAPL baildown/slug tests.

5.2.7.3 The baildown test methodology provided minimizes filter pack recharge effects and is applicable where formation storativity effects are not significant in test results. Slug tests will exhibit larger borehole storage effects at a given well because the slug represents a relatively small percentage of the LNAPL volume in the well and filter pack. However, slug tests are more ideal for an instantaneous removal event, which is needed where steady state conditions are not well approximated due to formation storage effects. The advantage of baildown test methods with their larger removal volumes and stresses is the minimization of borehole storage induced errors. The advantage of slug test methods with their smaller, faster removal is the minimization of non-instantaneous effects. The quantified magnitude of these individual differences has not been widely studied.

5.2.7.4 The error associated with the recharge rate calculations is directly related to the error in gauged LNAPL thickness measurement. Smaller equilibrium thicknesses either result in fewer data points being collected or data points representing smaller changes in well recovery. Based on the accuracy of estimating the LNAPL/water and air/water interface with available interface probes, it is possible but generally not recommended to complete baildown tests at wells with a gauged LNAPL thickness of less than 0.5 ft (for 2-in. or 4-in. wells). Baildown/slug testing should not be attempted at wells with a measured thickness of LNAPL less than 0.2 ft.

5.3 *Manual LNAPL Skimming Tests:*

5.3.1 *Overview*—The manual LNAPL skimming test is conducted by removing LNAPL at a rate that maintains drawdown in the well until a consistent LNAPL recovery rate is achieved.

5.3.2 *Data Analysis*—This manual LNAPL skimming test field procedure is used in conjunction with a skimming test analytical method, to derive estimates of LNAPL transmissivity.

5.3.3 *Waste Disposal*—The manual LNAPL skimming test typically generates more waste than baildown/slug or tracer tests and less than recovery system methods.

5.3.4 *Aquifer Extent Represented*—The manual LNAPL skimming test provides an advantage over other tests in that; the longer period of time the test is performed, the larger the area of the formation it represents and the accuracy of recovery volume estimates increase, which are used in the calculation of LNAPL transmissivity.

5.3.5 *Capital Cost*—The capital cost of this method is relatively low as it can be completed at existing wells with LNAPL and typically requires similar equipment to baildown tests. If LNAPL transmissivity is sufficiently high then the use of a pump could incur additional costs. This method requires less capital cost than recovery system-based or tracer tests.

5.3.6 *Test Duration*—The length of the manual skimming tests is inversely related to the LNAPL transmissivity and directly related to the well diameter and LNAPL storativity in the formation. The manual skimming test duration is similar or longer in time frame compared with baildown/slug tests and a shorter timeframe than tracer tests.

5.3.7 LNAPL skimming tests may be completed at any well exhibiting a gauged LNAPL thickness. This test is especially useful for wells exhibiting a gauged thickness less than 0.5 ft because it allows the measurement of LNAPL volume aboveground. In addition, the error associated with estimating the recharged LNAPL volume at this initial gauged thickness can be more accurately estimated above-ground than in-situ.

5.3.8 Recovery system based-data transmissivity values may not compare identically with "instantaneous" and "point" transmissivity method results (for example, manual skimming test results) because of the differences in scale of evaluation between the two methods. However, increasing or decreasing trends in transmissivity will be seen in both recovery system-based data and manual skimming testing-based data.

5.3.9 Manual LNAPL skimming tests may be conducted in all types of aquifer materials.

5.3.10 Manual LNAPL skimming tests do not provide data to graphically estimate equilibrium fluid levels. Therefore, a good understanding of fluid level behavior (for example, hydrograph) is required to ensure initial fluid levels represent equilibrium conditions for accurate calculation of LNAPL drawdown.

5.4 *Recovery Data-Based Methods:*

5.4.1 This guide provides general procedures for deriving LNAPL transmissivities using data obtained from continuous operation of LNAPL skimmer pumps and/or other types of product recovery systems where aquifer conditions approach steady-state conditions. These recovery systems are designed to extract LNAPL, groundwater and/or formation air/vapor from a recovery well.

5.4.2 Because LNAPL transmissivity is being continually reduced through product recovery, steady-state conditions can be approached but not reached. Steady-state conditions are approximated when the maximum radius of influence (ROI) is reached for the current drawdown induced via the given technology.

5.4.3 The derivation of LNAPL transmissivity using recovery system data is based on the theory of radial fluid flow. Subsurface barriers (for example, building foundations) or significant heterogeneities can result in an under-estimation of LNAPL transmissivity when calculation methods involve the use of the radius of influence parameter. The equation for radial fluid flow will provide an average LNAPL transmissivity for all directions. However, it will under estimate LNAPL transmissivity in directions away from a subsurface barrier. Changes in soil type or lithologic properties affecting the hydraulic or pneumatic permeability of the formation and occurring within the recovery system radius of influence can affect the accuracy of the LNAPL transmissivity results. This effect is not significant when the fluid production ratio equations are used and the changes in subsurface conditions affect all extracted fluids and phases similarly. Accounting for such variability via site characterization data and accurate site conceptual models is necessary to achieve the most accurate results.

5.4.4 If the recovery system is operating consistently and the LCSM is well developed and understood, this method can provide high accuracy and repeatability of transmissivity calculations. However, use of recovery system-based data for estimation of LNAPL transmissivity requires a well-defined LCSM and frequent monitoring of recovery system operational parameters. LNAPL transmissivity values estimated from recovery data are representative of a region within an area of mobile LNAPL that is proportional to drawdown induced, recovery well spacing, and operational time. In other words, the area represented by an LNAPL transmissivity value is proportional to the drawdown induced, length of time run and distance between recovery well locations. As a result, recovery data transmissivity values may differ significantly from those obtained using "instantaneous" and "point" transmissivity method results (for example, baildown/slug test results) because of the differences in scale of evaluation between the methods. However, increasing or decreasing trends in transmissivity will be seen in both recovery system-based data and baildown testing-based data.

5.4.5 LNAPL transmissivity measurement by long-term operation of a skimming device or other LNAPL recovery system assumes continuous operation over the temporal interval of interest. Complete knowledge and maintenance of the system operation representing optimal conditions (for example, pump depth corresponds to the interval of mobile LNAPL or ensuring sufficient storage tank capacity) is necessary to obtaining representative LNAPL transmissivity values.

5.4.6 The LNAPL transmissivity values derived by recovery system data are based on fluid flow through a porous media and not karst environments or fractured rock. Attempts to apply this document to estimate LNAPL transmissivities in fractured rock, karst environments or other non-porous media may result in inaccurate LNAPL transmissivity values.

5.4.7 Fluctuations of water table elevation during the LNAPL recovery data collection period that significantly change the relationship between the groundwater/LNAPL interface (or the air/LNAPL interface) relative to the location of the recovery pump(s) can result in inaccurate transmissivity determinations. In addition, both horizontal and vertical pneumatic formation permeability must be determined when estimating the air radius of influence for determining transmissivity using LNAPL systems that incorporate vacuum-enhanced recovery.

5.4.8 The relative depths of the recovery well screen intervals, the groundwater/LNAPL interface, the air/LNAPL interface, and the depth of pump(s) intake(s) must be known. In addition, the configuration of the well construction, interfaces, and pump(s) intake(s) must be appropriate for the specific recovery system used to derive LNAPL transmissivity.

5.4.9 This guide provides analytical equations to calculate LNAPL transmissivity (T_n) using recovery system-based data from four types of remediation technologies:

5.4.9.1 LNAPL only liquid removal (skimming).

5.4.9.2 Vacuum-enhanced LNAPL only liquid removal (vacuum-enhanced skimming).

5.4.9.3 Water-enhanced LNAPL removal (total fluids pumping, single or dual pump).

5.4.9.4 Water and vacuum-enhanced LNAPL removal (multi-phase fluid extraction [MPE]).

5.5 *Tracer Test-Based Methods:*

5.5.1 *Overview*—This tracer test field procedure shall be utilized in conjunction with a tracer test analytical procedure to derive LNAPL flux and estimates of LNAPL transmissivity at any properly screened well exhibiting LNAPL thickness greater than 0.2 ft.

5.5.2 Tracer tests can be conducted under conditions of a natural or imposed gradient. Imposed gradient test can be conducted about active recovery wells. Natural gradient tests do not require fluid extraction.

5.5.3 *Test Duration*—Natural gradient tests are conducted over several weeks or months and, therefore, provide temporally-averaged and vertically-averaged transmissivity values. Imposed gradient tests can be conducted in period of hours to days.

5.5.4 *Waste Disposal*—LNAPL or water disposal is not required since the testing method does not generate water or LNAPL.

5.5.5 *Data Analysis*—Data reduction methods assume steady-state conditions, which can occur under natural or ambient conditions, or during steady-state recovery.

5.5.6 The LNAPL flux measurement is representative of a few feet outside the borehole. The LNAPL gradient is representative of the LNAPL surface within the well network density.

5.5.7 Although the flux measurement does not require a uniform flow field, it is combined with the LNAPL gradient to calculate an LNAPL transmissivity value. The LNAPL gradient estimates assume a uniform flow field between wells. Therefore, this method is more applicable to a uniform LNAPL flow field. Uniform LNAPL flow fields occur in homogenous conditions and can be induced by active recovery.

5.5.8 LNAPL tracer tests may be conducted in unconfined, perched and confined aquifer materials where the fluid levels are in equilibrium with the formation.

5.5.9 Inputs for data analysis (analytical procedure) should be known prior to the field testing to ensure that all appropriate dimensions and measurements are properly recorded.

5.5.10 *Specialized Equipment Needed*—A hydrophobic fluorescent tracer and a UV/VIS spectrometer with a down hole fiber optic cable are needed to make measurements of tracer concentration through time.

5.5.11 *Screening Factors for Test Method Selection:*

5.5.11.1 Using hydrophobic tracers to determine LNAPL transmissivity is a relatively new method, and it is expected that this method will become more refined in the future. The following methods have been proven at a laboratory scale (Smith et al, 2011) (**4**) and at seven field sites (Mahler et al, 2011) (**5**).

5.5.11.2 *Measurement of LNAPL Gradient*—The local LNAPL gradient must be measured or estimated as an input to the equation for LNAPL transmissivity using tracer tests.

TEST METHODS

6. Short-Term Aquifer Testing-Based Methods

6.1 *Baildown/Slug Testing Field Methods*—This test method describes the field procedures involved in conducting an instantaneous LNAPL baildown/slug test. The LNAPL baildown/slug test method involves causing a sudden change in LNAPL head in a control well and measuring the fluid level response within that control well. Head change is induced by removing a known and measurable LNAPL volume from the control well.

6.1.1 *Apparatus*—This test method describes the types of equipment that can be used. Since there can be an infinite variety of testing conditions and because similar results can be achieved with different apparatus, engineering specifications for testing equipment are not discussed in this document. This test method specifies the results to be achieved by the equipment to satisfy the requirements of this guide.

6.1.1.1 *LNAPL Displacement Equipment*—Because a variety of equipment can be used to induce a change in LNAPL head, this method will not provide engineering specifications of the exact means in which head is changed, but will rather identify how common types of equipment can affect the final results. Single slug displacement or removal methods such as solid slugs or bailers, respectively, will provide a more instantaneous change in LNAPL head. This is useful at well locations exhibiting higher LNAPL transmissivities. The use of solid slugs is acceptable since their volume can easily be measured. However use of equipment such as peristaltic pumps to remove the entire volume of LNAPL in the well casing and borehole will result in minimizing filter pack recharge effects. It is strongly recommended to use equipment that can remove LNAPL from the well and allow the use of graduated containers to measure the total volume within 10 %. Vacuum trucks at best have a detection limit of 5 gal and an accuracy of 1 gal above 5 gal (19 L). Down-hole non-intrinsically safe electrical pumps need to remain submerged below the air/LNAPL interface to prevent explosions; therefore down-hole electrical pumps used to evacuate LNAPL to zero thickness, for example, are not acceptable practices.

6.1.1.2 In some cases the LNAPL removal equipment available will not be able to remove LNAPL at a high enough rate to completely purge the control well. If this occurs during the test, a slug test or any of the other LNAPL transmissivity test methods discussed in this document can be applied.

6.1.1.3 *Fluid Level Measurement Equipment*—Typically, the air/LNAPL and LNAPL/water interfaces will be gauged using an interface probe. Currently the most precise available interface probes utilize optical and electrical resistivity technologies. Additionally, current technology allows for probes to be relatively small (⅝-in.) in diameter. The optical and electrical resistivity type interface probes increase the ability to measure fluid interfaces to typical accuracies from 0.01 to 0.02 ft (0.3 to 0.6 cm). The small probe diameter causes less displacement to fluids in the well. When the recovery of LNAPL occurs rapidly (that is, less than 1 h), tests can be conducted with an intrinsically safe pressure transducer, where the pressure transducer is set near the bottom of the well (in the water phase). Then the field staff only will be required to measure the depth to the air/LNAPL interface following removal of LNAPL. By only measuring the air/LNAPL interface less disturbance will be introduced to the well during recovery since the probe does not need to penetrate the fluid column to measure the LNAPL/water interface. Two pressure transducers can still be used, where one transducer is placed in the water phase and a second within the LNAPL phase; however, they are not necessary.

6.1.1.4 *Time Piece*—Used to record the elapsed time of the test.

6.1.1.5 *Graduated Container*—A container for water and LNAPL collection that is graduated to measure within 10 % of total estimated recovery volume (unit conversion: 1 gallon = 3.825 litres = 3,825 millilitres (mL) = 0.134 cubic feet). For example, a container that can measure 0.1 gal (~400 mL) intervals for an expected 1 gal (~4000 mL) of recovered product, or a container that can measure 1 gal (~4000 mL) intervals for an expected 10 gal (40 000 mL) of recovered LNAPL.

6.1.1.6 *Decontamination Equipment*—Typically, LNAPL in a well can foul measuring devices and should be cleaned with an appropriate cleaning agent. If multiple wells are tested, equipment should be cleaned of well fluids between testing separate wells.

6.1.1.7 *Test Forms*—Test forms should be used to record the parameters listed in 6.1.2 and 6.1.3 (that is, Conditioning & Procedure). Semi-log graph paper should be used to plot data during the test in order to understand when equilibrium is reached and the test is completed. Fig. 1 provides an example of LNAPL thickness reaching equilibrium during a test.

6.1.2 *Conditioning:*

6.1.2.1 *Pre-Test Well Information*—The following well construction information needs to be obtained prior to initiating the baildown tests:

(1) Borehole diameter of well to be tested (feet).

(2) Casing and screen diameter (inches).

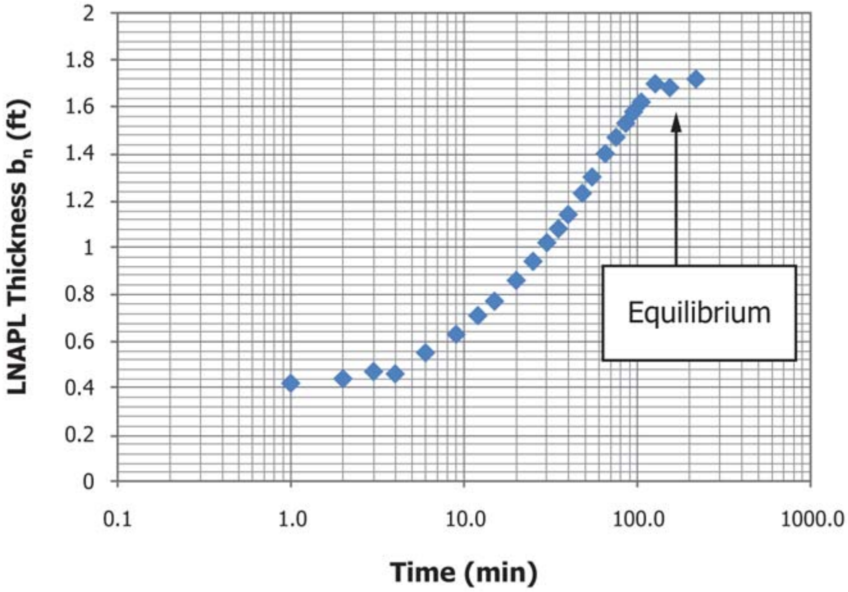
(3) Top of screen relative to top of casing (feet).

(4) Bottom of screen interval relative to top of casing (feet).

(5) Total well depth (feet).

(6) Verify interval that the well is screened over the formation thickness.

6.1.2.2 Baildown/slug tests are used to evaluate the transmissivity of LNAPL in the aquifer. It is recommended that the



Graph illustrating how the frequency of gauging data should be based on consistent changes in LNAPL thickness rather than time, and demonstrating the attainment of recharge equilibrium conditions.

FIG. 1 Gauging Data Graph

LNAPL existing within the well and borehole need to be occasionally evacuated prior to the baildown test in order for the LNAPL to stay in communication with the formation. The maximum lag time between removal events is two years.

6.1.2.3 Prior to the test, the well being tested should be fully recharged; this will ensure the starting LNAPL thickness, LNAPL head, and potentiometric surface head are all representative of equilibrium formation conditions.

6.1.3 *Pre-Test Procedure:*

6.1.3.1 *Measuring Pre-Test Fluid Levels*—Measure the fluid levels in the well before the test for a period longer than the time it will take the well to recover in order to ensure equilibrium fluid levels are known and to calculate the effective well volume. This should be established during the initial evacuation of LNAPL from the well prior to the test (see 6.1.2.2).

6.1.3.2 Errors associated with erroneously assumed equilibrium fluid levels will reduce test accuracy and may invalidate the test.

6.1.3.3 Plan on gauging the well until complete equilibration occurs (Fig. 1) for wells where recovery behavior is not well understood or the pretest gauging data is realized not to represent equilibrium conditions.

6.1.3.4 The scope of work should plan for gauging to potentially be conducted over days or even weeks.

6.1.3.5 For unconfined conditions, the filter pack typically holds the majority of the stored LNAPL volume within the effective well radius. Partial displacement or removal of the LNAPL will result in the test being dominated by filter pack recharge.

6.1.3.6 Filter pack effects can be reduced through larger displacement volumes for slug tests or the complete removal of LNAPL in the filter pack and casing during baildown tests. The following equations can be used to approximate the volume of LNAPL within the well casing and borehole.

$$V_b = S_{yf} b_b \pi (r_b^2 - r_c^2) \tag{1}$$

$$V_c = b_n \pi r_c^2 \tag{2}$$

$$V_t = V_c + V_b \tag{3}$$

where:

V_t = total effective borehole LNAPL volume (L^3),
V_b = volume of LNAPL in the borehole (L^3),
V_c = volume of LNAPL in the casing (L^3),
b_b = LNAPL thickness existing within borehole (L),
b_n = gauged LNAPL thickness (L),
r_c = well casing radius (L),
r_b = well borehole radius (L), and
S_{yf} = specific yield or storage coefficient of well filter pack.

6.1.3.7 To account for borehole porosity and LNAPL saturation, a storage coefficient needs to be estimated. Empirical data suggest that 0.175 to 0.190 is a good value for this parameter at any site. If viscosity of the LNAPL is known, an alternate method of estimating storage coefficient that has been tested between viscosities of 0.7 and 2 centipoises can be derived by using Eq 4 (Lundy, 2005) (**6**). Using Eq 2 combined with viscosities of 0.5 cp and 5 cp results in a range in storativity of 0.23 to 0.13 where the geometric mean is 0.175. The empirical data and Eq 4 suggest an average value of 0.175 and the range should not vary by more than a factor of 50 %.

$$S_{yf} = -0.0418 ln(\mu_n) + 0.2007 \tag{4}$$

where:

S_{yf} = filter pack LNAPL specific yield, and
μ_n = dynamic viscosity of LNAPL (M/Lt).

6.1.3.8 Well construction data will need to be reviewed to evaluate if the filter pack exists over the entire gauged interval of LNAPL. If the well screen and filter pack do not exist across the entire gauged thickness, then the filter pack thickness, used in Eq 1 will have to be reduced from the gauged thickness value.

6.1.4 *Test Procedure:*

6.1.4.1 Where the LNAPL transmissivity or recharge behavior is not well known, plan to start the baildown portion of the test early in the work day and on a day when you will be able to return frequently to the well. This will ensure that sufficient measurement frequency can be obtained within the first 8 h of the test.

6.1.4.2 Remove the known LNAPL volume up to a maximum as calculated using Eq 3. Smaller removal volumes will exhibit larger filter pack recharge effects and be more instantaneous. Larger removal volumes will minimize filter pack recharge effects although may not be instantaneous relative to the test duration.

6.1.4.3 Baildown/slug test LNAPL head change rate must be induced in a time that is 1/100th or less of the total test duration, in order to approximate instantaneous head change. If full removal of LNAPL from filter pack and well casing requires longer time and an analysis method that relies on instantaneous withdrawal is being used (for example, Cooper-Jacob), then a slug method or alternative method should be used.

6.1.4.4 Instantaneous removal or slug introduction is relative to total length of test. For example 15 min of purging can be considered instantaneous if the length of the test is 1 day or more. Non-instantaneous removals can potentially be corrected in conjunction with steady state based slug test solutions (that is, Bouwer-Rice), which is discussed in Section 8. However, efforts should be made to complete the slug/fluid removal in as short of a timeframe as is practical so that removal approximates an 'instantaneous' head change.

6.1.4.5 Record the start and finish time of LNAPL removal. Record the total volume of LNAPL and water removed or slug length and volume. If large volumes (over 5 gal/ 19 L) of LNAPL are removed or removal occurs for a relatively long period of time (over 30 min), record several interim measurements of volume removed and time.

6.1.4.6 Baildown tests conducted in wells containing low viscosity LNAPL (that is, <1 centipoise) generally require 30 min or less for purging, while higher viscosity LNAPL (that is, >2 centipoises) can require a few hours. This is acceptable if the baildown test takes days to complete, the time for removal in this case would approximate instantaneous head change relative to the test duration.

6.1.4.7 Following LNAPL removal, begin recording the time and measuring the depth to the air/LNAPL and LNAPL/

water interfaces. Depth to the air/LNAPL interface should be decreasing (or remaining the same). The gauged LNAPL thickness should be increasing. Re-measure and report any readings that do not match these trends. Record notes regarding the methodology taken to confirm or revise anomalous data.

6.1.4.8 The depth to the air/LNAPL interface could decrease if the overall groundwater elevation at the site is dropping. To verify whether the water-table elevation is dropping, a nearby control well can be measured prior to and during testing.

6.1.4.9 The best practice for gauging fluid levels during the baildown test is to collect a measurement at a maximum frequency of every 0.05 to 0.1 ft (1.5 cm) change in LNAPL thickness from static. A minimum change in thickness that is reasonable for use in data analysis is 0.05 to 0.1 ft (1.5 cm) of change in thickness.

6.1.4.10 The best practice also consists of gauging fluid levels at a minimum frequency corresponding to a change in thickness that represents 5 % of the equilibrium gauged LNAPL thickness or 0.05 ft (that is, 1.5 cm), whichever is less. This methodology is conducted for the first 100 min of recovery. The remainder of the test can be completed by gauging measurements on a frequency corresponding to a change of 5 to 10 % of the equilibrium thickness. This methodology will result in data being collected on a logarithmic timescale which is appropriate for data analysis. Because the recovery rate will drop as the well recovers, measurements can be collected on a logarithmic time scale (that is, at some point, the well may only have to be gauged weekly or monthly).

6.1.4.11 The minimum practical time for measuring fluid levels with a single interface probe is at 1-minute intervals since two interfaces need to be gauged.

6.1.4.12 After the first 100 min of a test, the data should be reviewed and a schedule should be prepared by the field staff based on the collected data set.

6.1.4.13 Plotting the recovered LNAPL thickness versus the log of time will help to forecast future events and help to provide data to support the conclusion of the test (see Fig. 1).

6.1.4.14 The time point representing the next change in thickness of 5 to 10 % of the static thickness or 0.05 ft (1.5 cm), whichever is less, can then be forecast based on the graph. For example, if over the initial 100 min the well has recovered less than 5 % of its initial thickness, the next measurement would be at least an additional 100 min from the current time.

6.1.4.15 In order to ensure that equilibrium fluid levels are understood and can be used to calculate LNAPL drawdown, gauging data representing consistent equilibrium fluid levels must exist for a period that is equal to the length of a completed test. This data can represent fluid levels prior to start of test or following test.

6.1.4.16 If the initial gauging data is insufficient to ensure equilibrium fluid levels (for example, one data point immediately before the test) then plan on obtaining test measurements until the LNAPL thickness has stabilized to its static thickness. This will provide the most complete insight into the LNAPL distribution in the formation and confirm the initial equilibrium fluid levels. A typical indication of LNAPL thickness stabilizing is when the LNAPL thickness reaches a plateau for approximately one quarter to one half of a log cycle. This should be documented with 3 measurements over that period (see Fig. 1).

6.1.4.17 The actual time and date of each measurement should be recorded, particularly when it may deviate from the initial schedule. If the change in LNAPL thickness between each event is less than the percentages listed above, then the frequency of measurements may be decreased. However, if the change in LNAPL thickness is greater than the percentages listed above, then measurement frequency should be increased.

NOTE 1—During the test, accurate measurements of the depths to LNAPL and water are critical. Every effort should be made to ensure that these readings are consistent and reliable. It is important to evaluate the data as it is collected and confirm any apparent erratic gauging data. Confirmation readings should be supported with comments on the field form. LNAPL thickness should ideally be increasing (or remaining the same) from one measurement to the next, not decreasing.

6.1.4.18 In some cases, fluid levels may change more rapidly than can be measured manually. Under these circumstances a LNAPL baildown test can be conducted using a pressure transducer. Conduct a baildown test with a pressure transducer with the following modifications from the procedure described above:

(1) Synchronize the transducer clock with the time piece used to collect gauging measurements. Next, set the measurement schedule to collect a minimum of 50 readings over the estimated test duration. Ensure that the pressure transducer has the appropriate battery life and is calibrated.

(2) Lower the pressure transducer to the bottom of the well and gauge the well until the fluid levels have stabilized again.

(3) Following stabilization, record and compare the gauged measurements to the reading on the pressure transducer to ensure it is working properly.

(4) Start and run the test as described above in 6.1.4 except that the LNAPL/water interface does not need to be gauged during the test. The air/LNAPL and LNAPL/water interfaces should be gauged prior to initiating the test and following completion of the test for use in calibration of the pressure transducer depth.

(5) Gauge the air/LNAPL interface as frequently as possible throughout the test.

(6) Review manufacturer specifications to understand the accuracy and precision of transducer data collected and ensure the data to be potentially used is not limited by equipment specifications.

(7) Post-Test Procedure—Conduct preliminary analysis of data before leaving the field and evaluate the test regarding the criteria given in this test method. The test data should be analogous to the trend shown in Fig. 1. The drawdown and time magnitudes are expected to vary but the overall trend on a semi-log plot should be similar.

6.1.5 *Report:*

6.1.5.1 Include the information listed below in the report of the field procedure:

(1) Well identification.

(2) Well construction (well depth, filter pack and screen interval, inner casing, screen, and borehole diameter).

(3) Date and time of initial fluid gauging data.

(4) Initial fluid levels.

(5) Field staff.

(6) Known LNAPL characteristics (for example, LNAPL density and product type).

(7) Well Identification (ID), casing diameter and other known well information.

(8) Method of LNAPL withdrawal removal notes.

(9) Calculated well volume.

(10) Establish and record the measurement point from which all measurements of fluid levels were made.

(11) All gauging data collected prior to and during the test.

(12) Start and stop date and time of LNAPL purge event or slug withdrawal.

(13) Volume of LNAPL and water removed during purge or slug withdrawal event.

(14) If the fluid levels are measured with a pressure transducer, report the model type of the pressure transducer used, recorded pressure versus time data, and the data used to convert pressure data to fluid depth (that is, calibration fluid level data and the fluid density).

6.1.6 *Precision and Bias:*

6.1.6.1 *Precision*—It is not practical to specify the precision of this specific test method because the response of aquifer systems during testing is dependent upon ambient system stresses.

6.1.6.2 *Bias*—No statement can be made about bias because no true reference values exist.

6.2 *Manual Skimming Field Methods*—This test method describes the field procedures involved in conducting a LNAPL manual skimming test. This test consists of the removal of LNAPL from the well casing and borehole on a repeated basis, without allowing more than approximately 25 % of recharge to occur in between product removal events. The rate of removal is therefore dependent on well recharge behavior. The key criterion is that greater than 75 % of the maximum skimming drawdown must be consistently induced. Purging is completed until the recovery rate stabilizes. The LNAPL discharge or recovery rate for each LNAPL removal step is calculated. The recovery volume and gauging data, along with the volume of LNAPL removed, can be used to estimate the LNAPL transmissivity and recoverability. LNAPL transmissivity is calculated from the stabilized LNAPL discharge data. This test ranges from a few hours for wells exhibiting higher LNAPL transmissivities to in excess of weeks for wells exhibiting lower LNAPL transmissivities. The manual skimming test can be performed on most wells that contain LNAPL.

6.2.1 *Apparatus*—This section describes the types of equipment that can be used. Since there are an infinite variety of testing conditions and because similar results can be achieved with different apparatus, engineering specifications for apparatus are not discussed in this guide. This test method specifies the results to be achieved by the equipment to satisfy the requirements of this guide.

6.2.1.1 *LNAPL Removal Equipment*—Because a variety of equipment can be used to induce a change in LNAPL head, this method will not provide engineering specifications of the exact means in which head is changed, but rather identify how common types of equipment can affect the final results.

6.2.1.2 *Fluid Level Measurement Equipment*—Typically, the air/LNAPL and LNAPL/water interfaces will be gauged using an interface probe. Currently the most precise available interface probes utilize optical and electrical resistivity technologies. Additionally, current technology allows for probes to be relatively small (5⁄8-in.) in diameter. The optical and electrical resistivity type interface probes increase the ability to measure fluid interfaces to typical accuracies from 0.01 to 0.02 ft (0.3 to 0.6 cm) and the small probe diameter causes little displacement to fluids in the well.

6.2.1.3 *Time Piece*—Used to record the elapsed time of the test.

6.2.1.4 *Graduated Container*—A container for water and LNAPL collection that is graduated to measure within 10 % of total estimated recovery volume between fluids removal events. For example, a container that can measure 0.1 gal intervals for an expected 1 gal of recovered product, or a container that can measure 1 gal intervals for an expected 10 gal of recovered LNAPL.

(1) Decontamination Equipment—Typically, LNAPL in a well can foul measuring devices and should be cleaned with an appropriate cleaning agent. If multiple wells are tested, equipment should be cleaned of well fluids between testing separate wells.

(2) Test Forms—Test forms should be used to record the parameters listed in 6.3.2 and 6.3.4 (that is, Conditioning and Procedure).

6.2.2 *Conditioning:*

6.2.2.1 *Pre-Test Well Information*—The following well construction information needs to be obtained prior to initiating the manual skimming tests:

(1) Borehole diameter of well to be tested.

(2) Casing and screen diameter.

(3) Top of screen relative to top of casing.

(4) Bottom of screen interval relative to top of casing.

(5) Total well depth.

(6) Verify interval that the well is screened over the formation thickness.

6.2.2.2 Manual skimming tests are used to evaluate the transmissivity of LNAPL in the formation. It is recommended that the LNAPL existing within the well and borehole be occasionally evacuated prior to the manual skimming test in order for the LNAPL to stay in communication with the formation. Prior to the test, the well being tested must be fully recharged. This will ensure the starting fluid levels surface head are all representative of equilibrium formation conditions.

6.2.2.3 *Measuring Pre-Test Fluid Levels*—Measure the fluid levels in the well before beginning the test to determine the pre-test fluid levels.

6.2.2.4 The pre-test fluid levels need to represent equilibrium conditions in order for the accurate calculation of LNAPL drawdown.

6.2.2.5 No other pre test procedures are required.

6.2.3 *Test Procedure:*

6.2.3.1 Because of the LNAPL extraction and measurement frequency needed over the first 8 h, plan to start the manual skimming portion of the test early in the work day and on a day when you will be able to return frequently to the well.

6.2.3.2 The test consists of the following four steps:

(1) Initial gauging of fluid levels.

(2) Purging the well and borehole of the LNAPL.

(3) Periodically returning to the well to:

(a) Gauge fluid levels.

(b) Purge any recovered LNAPL.

(c) Gauge fluid levels following purging.

(4) Data analysis.

6.2.3.3 To start the test, remove LNAPL until further LNAPL removal is not possible while minimizing the groundwater recovered. Record the start and finish time of LNAPL removal. Record the total volume of LNAPL and water removed. If large volumes (over 5 gal/19 L) of LNAPL are removed or removal occurs over a long period of time (over 30 min), record several interim measurements of volume removed and time. Try not to disturb the static potentiometric surface level during LNAPL removal. Methods of LNAPL removal may include bailers, peristaltic pumps, vacuum truck removal and other skimmer pumps as long as the volumes can accurately be measured.

6.2.3.4 Remove LNAPL until the product is no longer being removed.

6.2.3.5 Begin recording the date/time and measured depths to the air/LNAPL interface and LNAPL/water interface immediately after removing the LNAPL. Once the well has recovered ¼ of the initial thickness, re-purge the LNAPL in the well. Record the start and stop time of purging and the gauging data before and after each purging event. The time elapsed between the completion of the initial purge and the start time of the following purging event will provide an estimated return time for the next event.

6.2.3.6 A best practice of the test is to gauge and purge the well before the well recovers ¼ of the original thickness. The following frequencies are provided as an initial recommendation and should be adjusted based on field observations:

(1) First hour: every 10 min (6 measurements).

(2) 2 h to 4 h: every 30 min (4 measurements).

(3) 4 h till end of first day (1 measurement).

(4) Second day: 2 to 3 times.

(5) Subsequent days: At least twice per day until the LNAPL discharge rate has stabilized.

6.2.3.7 The actual time and date of each measurement should be recorded, especially when it may deviate from the initial schedule. The calculated recharge will typically start out high and decrease until it reaches a constant value. The test should continue until the calculated recharge into the well stabilizes. At some locations this may take a week. Following the first 4 h and the first day of testing, the data should be reviewed to improve the timeline with which gauging and purging events will be conducted. If previous knowledge of the recovery behavior for a given well is available, the provided timescale can be modified based on those data.

6.2.3.8 If the well is recovering less than ¼ of its initial thickness between each measurement, the frequency of measurements may likely be decreased. However, if the LNAPL thickness recovers to more than ¼ of the initial thickness, frequency of gauging and purging should be increased.

6.2.3.9 The maximum practical measurement and purge frequency is 5 min for a single field staff due to the constraints of gauging, fluid removal activities, recovered fluid volume removal measurement and documentation. It is not necessary to increase the frequency beyond this. If the well recovers too fast for these conditions to be met then an alternate testing methodology should be employed, such as a pilot test with an automated skimming pump in conjunction with the recovery system-based field and analysis method.

6.2.3.10 The test is complete when three or four consecutive discharge rates are within 25 % of each other and no consistently decreasing trend is observed.

6.2.3.11 During the test, accurate measurements of the recovered volume and depths to air/LNAPL and LNAPL/water interfaces are critical. Every effort should be made to ensure that these readings are consistent and reliable. Re-measure and document any readings that seem anomalous and then make notes regarding the methodology taken to confirm or revise anomalous data.

6.2.3.12 Ensure that the bucket/container used for measuring recovered volume spans the volumes being recovered each period. Typically the removal volumes for each purging event will be less than ½ gal. A 5-gal bucket is not precise enough for measuring the recovered volume following the initial removal. See section 6.3.1 (Apparatus).

6.2.3.13 *Post-Test Procedure*—Make a preliminary analysis of the data before leaving the field and evaluate the test regarding the criteria given in this test method to determine if the test should be rerun.

6.2.4 *Report*—Include the information listed below in the report of the field procedure:

6.2.4.1 Well identification.

6.2.4.2 Well construction (well depth, filter pack and screen interval, inner casing, screen, and borehole diameter).

6.2.4.3 Date and time of initial fluid gauging data.

6.2.4.4 Initial fluid levels.

6.2.4.5 Field staff.

6.2.4.6 Known LNAPL characteristics (for example, LNAPL density and product type).

6.2.4.7 Casing diameter and other known well information.

6.2.4.8 Method of LNAPL withdrawal removal notes.

6.2.4.9 Calculated well volume.

6.2.4.10 Establish and record the measurement point from which all measurements of fluid levels were made.

6.2.4.11 All gauging data collected prior to the test.

6.2.4.12 Date and time of test start.

6.2.4.13 Depth to fluid levels before and after each purge event.

6.2.4.14 Start and stop date and time of each gauging and purge event.

6.2.4.15 Volume of LNAPL and water removed during each purge event.

6.2.5 *Precision and Bias:*

6.2.5.1 *Precision*—It is not practical to specify the precision of this test method because the response of aquifer systems during LNAPL manual skimming tests is dependent upon ambient system stresses.

6.2.5.2 *Bias*—No statement can be made about bias because no true reference values exist.

6.3 *Long-term Recovery System Method*—This test method describes the field procedures involved with collecting product recovery system data for the purposes of estimating LNAPL transmissivity under steady state conditions. LNAPL transmissivity calculations for recovery systems are based on the achieved LNAPL recovery rate versus drawdown induced. Therefore, this section is focused on methods used to estimate LNAPL recovery rate for all systems and specific methods used to estimate drawdown induced by the specific technologies.

6.3.1 *Apparatus*—The equipment consists of storage containers which allow for measurement of fluid volumes recovered over time, flow meters for individual and/or total fluids and instantaneous flow measurements. In addition, equipment used to measure pneumatic and/or hydraulic head at individual well locations and/or for the system as a whole. Because there are an infinite number of recovery system designs, this guide does not specify the equipment to be used, but rather the equipment used must meet the data objectives set forth in the guide.

6.3.2 *Conditioning*—All recovery wells where LNAPL transmissivity is estimated should be properly developed in order to ensure non-linear head losses are minimized. Maintenance schedules should consist of development following well installation, as well as, periodic rehabilitation to prevent deterioration of the well performance to scaling and biofouling. One time well development is not sufficient for most active recovery systems that run longer than five years.

6.3.3 Verify interval that the well is screened over the formation thickness.

6.3.4 *Procedure*—Because the procedure for measurement is dependent on system design and equipment, it is not feasible to specify the measurement procedure for each parameter in this method. Field forms for individual technologies are provided in Annex A1 and identify the minimum field parameters, as well as, where additional measurements would provide multiple lines of evidence for LNAPL transmissivity calculations.

6.3.5 *Report*—Field forms included in Annex A1 identify the reporting requirements for individual technologies. The report consists of measured input values and justification for each parameter measured on the field forms and variables provided in Tables A2.5-A2.8.

6.3.6 *Precision and Bias:*

6.3.6.1 *Precision*—It is not practical to specify the precision of this test method because the response of aquifer systems during LNAPL recovery is dependent upon ambient system stresses.

6.3.6.2 *Bias*—No statement can be made about bias because no true reference values exist.

7. Tracer Test Field Methods

7.1 This test method describes field procedures for conducting LNAPL tracer tests.

7.2 *Apparatus*—This section describes the types of equipment that can be used. Because of the infinite variety of testing conditions, engineering specifications for apparatus are not provided. This test method specifies the results to be achieved by the equipment to satisfy the requirements of this guide.

7.2.1 *Spectrometer/Fiber Optic Cable and Computer*—To date, a temperature regulated, visible light spectrometer has been used to measure the tracer presence and relative concentration in the LNAPL. The spectrometer consists of a light source to induce fluorescence in the tracer. The output from the spectrometer is converted to a digital signal and transmitted to a laptop computer, Program Logic Controller (PLC), or similar device to store and display the measured values.

7.2.2 The fiber optic cable used to date consists of multiple fibers. A portion of the fibers within the cable are used to transmit the excitation light source to the tracer in the LNAPL in the well, and others return the resulting fluorescence response back to the spectrometer.

7.2.3 The spectrum of excitation and measured fluorescence response is key as fiber optic cables tend will attenuate signals too rapidly to be of use if they are not appropriate for the excitation and fluorescence spectrums of intent. Typically, attenuation occurs more rapidly for shorter wavelengths (for example, less than 290 nm).

7.2.4 To date, a laptop computer equipped with software to communicate with the spectrometer has been used to control the spectrometer and display a graph of the spectrum (intensity versus wavelength) and record output.

7.2.5 *Tracer:*

7.2.5.1 The tracer used to date is BSL 715.[4] This tracer is a concentrated liquid hydrocarbon which has unique fluorescence peaks at 545 and 580 nm when excited at 470 nm. It fluoresces yellow under ultraviolet light and is used in the automotive industry to detect oil leaks. This tracer is specifically listed (Sale et. al., 2008) (**7**) because it has undergone testing to ensure that it will not decrease in concentration over time in the well based on non-flow related mechanisms such as dissolution, volatilization, or sorption. Any new tracer used to estimate LNAPL transmissivity will need to be tested to ensure that it acts as a conservative tracer.

7.2.5.2 The tracer has the following characteristics:

(1) It is detectable in LNAPL at low concentrations (less than 1 ppm in Soltrol 220, Woodlands, Texas).

(2) It is insoluble in water.

(3) It has no significant effect (at application concentrations) on the physical properties of LNAPL.

(4) It fluoresces at a wavelength where most LNAPLs have low background fluorescence.

(5) It has low toxicity relative to constituents present in most LNAPLs.

7.2.6 *In-Well Calibration Standards*—In-well calibration standards are used to correct for potential non-tracer related florescence from the LNAPL induced by the 470 nm light source. Small diameter pipes are inserted within the test well to occlude a volume of LNAPL without tracer and a volume of

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[4] The sole source of supply of the apparatus known to the committee at this time is Bright Solutions Inc., Troy, Michigan. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

LNAPL with the initial tracer concentration. A small-diameter pipe is inserted into the test well, through the LNAPL before tracer is added, for Eq 5 this well is called C_0. Tracer is then added and mixed with the LNAPL. A second pipe is then inserted into the test well through the LNAPL. This well is called C_{100} in Eq 5. The two pipes, one without tracer and one with the initial tracer concentration allow for in-well spectrometer calibrations to be made with each tracer concentration measurement. Measurements of remaining tracer in the test wells at the end of each measurement period are corrected using the calibrations assuming a linear relationship between fluorescence and intensity can be calculated as:

$$\frac{C_{T_{t+\Delta t}}}{C_{T_t}} = \frac{\dfrac{I_{test\_well_{t+\Delta t}} - I_{Cal\_well.C_{0_{t+\Delta t}}}}{I_{Cal\_well.C_{100_{t+\Delta t}}} - I_{Cal\_well.C_{0_{t+\Delta t}}}}}{\dfrac{I_{test\_well_t} - I_{Cal\_well.C_{0_t}}}{I_{Cal\_well.C_{100_t}} - I_{Cal\_well.C_{0_t}}}} \tag{5}$$

where:

$C_{T_{t+\Delta t}}$ = concentration of tracer mass remaining at time of measurement (M/L^3),
C_{T_t} = concentration of initial tracer mass (M/L^3),
$I_{test\_well_{t+\Delta t}}$ = fluorescence intensity in test well at time of measurement (unitless),
$I_{Cal\_well.C_{0t+\Delta t}}$ = fluorescence intensity in C_0 calibration well at time of measurement (unitless),
$I_{Cal\_well.C_{100t+\Delta t}}$ = fluorescence intensity in C_{100} well at time of measurement (unitless),
$I_{test\_well_t}$ = initial fluorescence intensity in test well (unitless),
$I_{Cal\_well.C_{0t}}$ = initial fluorescence intensity in C_0 well (unitless), and
$I_{Cal\_well.C_{100t}}$ = initial fluorescence intensity in C_{100} well (unitless).

7.2.7 *Interface Probe*—An interface probe should be used to record LNAPL thickness in the test well each time tracer concentration is measured. Additionally, the interface probe is used to measure the LNAPL and hydraulic gradients occurring throughout the test duration.

7.2.8 *Pressure Transducer*—The use of a pressure transducer should be considered for sites where the fluid levels are expected to vary the LNAPL gradient over the length of the test and where site gauging events are expected to be infrequent.

7.2.9 *Decontamination Equipment*—LNAPL must be cleaned from the fiber optic cable between calibration standard measurements and test well measurements to ensure that there is no transfer of tracer dye between standards or test well. A cleaning agent such as detergent or isopropyl alcohol should be used to clean the fiber optic cable between readings. Further information on decontamination can be found in Practice D5088. Additionally, LNAPL can foul other fluid-level measurement devices. These devices should be cleaned with an appropriate cleaning agent. If multiple wells are tested, equipment should be cleaned of fluids between testing of separate wells.

7.3 *Conditioning:*

7.3.1 Collect representative LNAPL samples from monitoring wells to be used for testing prior to initiating the LNAPL tracer tests. Measure and record fluorescence of the LNAPL sample using the spectrometer. Add tracer to the LNAPL sample, thoroughly mix the sample, and measure and record fluorescence of the sample. Repeat the preceding step adding increasing amounts of tracer to evaluate the dose-response relationship between tracer concentration and fluorescence intensity. Initial tracer concentrations should be determined for each LNAPL type based on the following guidelines.

7.3.2 Review well construction logs to ensure the current LNAPL thickness is within the well screened interval.

7.3.3 Collect representative LNAPL samples from monitoring wells to be used for testing prior to initiating the LNAPL tracer tests. Measure background fluorescence and conduct titration tests to evaluate the dose-response relationship between tracer concentration and fluorescence intensity for each LNAPL type. Initial tracer concentrations should be determined for each LNAPL type based on the following guidelines.

7.3.3.1 All fluorescence measurements throughout this methodology should be made in triplicate to ensure the readings are within 1 %.

7.3.3.2 A tracer fluorescence peak that is at least twice that of the background LNAPL is desirable to ensure that the tracer fluorescence signal is not overwhelmed by background LNAPL fluorescence and remains detectable for a sufficient period of time.

7.3.3.3 Generally, a plot of tracer concentration versus fluorescence intensity will have a linear segment followed by a non-linear asymptotic segment, beyond which the relationship between tracer concentration and LNAPL flow through the well becomes difficult to quantify. It is therefore important to ensure that the initial quantity of tracer added results in a concentration that falls within the linear range for the LNAPL type in the well.

7.3.4 Large tracer concentrations may alter the physical properties of the LNAPL that govern flow, and therefore the smallest amount of tracer that can be used to conduct the test is recommended.

7.3.5 Verify interval that the well is screened over the formation thickness.

7.4 *Procedure:*

7.4.1 *Test Initiation*—Consists of the following procedures:

7.4.1.1 Measure the depth to the air/LNAPL and LNAPL/water interfaces, and LNAPL thickness in the test well. Review well construction logs to ensure that the LNAPL within the test well is in communication with the screened interval of the test well.

7.4.1.2 Conduct a baseline scan of the LNAPL within the test well using the spectrometer and down-well fiber optic cable to measure background fluorescence. Decontaminate and inspect the fiber optic cables and reflectance probe (at the tip of the fiber optic cable) prior to use to ensure there are no sources of light interference that may yield erroneous data. Decontamination and inspection will be conducted prior to each reading using the down-well fiber optic cable and spectrometer.

7.4.1.3 Insert a small diameter pipe into each well selected for testing to isolate a volume of LNAPL from the contents of the well. The pipe will be inserted to the bottom of each well to ensure that the LNAPL remains isolated during the test period. The isolated LNAPL sample, hereafter referred to as

C_0, represents the LNAPL within the formation materials and is used throughout the duration of the LNAPL tracer test to calibrate the spectrometer against the background fluorescence of the LNAPL. The smallest diameter pipe that can accommodate a down hole fiber optic cable within its inner diameter should be used.

7.4.1.4 After isolating a volume of LNAPL within the well in the C_0 pipe, calculate the total volume of LNAPL in the well, and calculate the volume of tracer that will need to be mixed with the LNAPL in accordance with the guidelines outlined in 7.3. Carefully remove a small vial of LNAPL from the well and amend with the previously determined volume of LNAPL soluble tracer. After mixing the LNAPL and tracer thoroughly in the weighted vial, carefully lower the mixture into the well, and gently raise and lower the vial beneath the air/LNAPL interface until all of the LNAPL/tracer mixture is mixed into the LNAPL within the test well. Make sure that none of the liquid in the vial splashes onto the well casing, which could slowly drip back into the well over the duration of the test and potentially introduce error to the LNAPL transmissivity estimates.

7.4.1.5 Scan the column of LNAPL/tracer in the well using the spectrometer and down-hole fiber optic cable to ensure that the tracer is well mixed throughout the well. If the fluorescence readings vary with depth through the LNAPL column, mix the LNAPL and tracer together. A small air line should be lowered into the test well to a depth beneath the water-LNAPL interface. The air line is then used to mix the LNAPL to a "well-mixed" condition. Once adequately mixed, confirm that the fluorescence readings in the LNAPL/tracer mixture agree with the targeted fluorescence.

7.4.1.6 After mixing the desired proportions within the well, insert a second small diameter pipe to isolate a volume of the initial LNAPL/tracer mixture. The drop pipe will be inserted to the bottom of the test well to ensure that a sample representative of the initial LNAPL/tracer mixture remains isolated during the test period. This sample is referred to as C_{100} and used throughout the tracer test to calibrate the spectrometer with the initial tracer concentration introduced into the LNAPL within the test well. Each time the concentration of tracer is measured within the test well (C_{WELL}) the spectrometer is calibrated using the in-well standards (C_{100} and C_0).

7.4.1.7 Scan and record intensity readings for C_0, C_{100}, and C_{WELL}, and then repeat these measurements, making sure that consecutive readings for each of the controls (C_0 and C_{100}) and the fluorescence readings in the test well (C_{WELL}) are within 2 % of the previous readings. If the readings are not within 2 %, remix the test well and recollect the data until all of the readings are within 2 %.

7.4.2 *Routine Data Collection:*

7.4.2.1 Thoroughly mix the LNAPL/tracer mixture in the well with a down-well airline, the calibration standard pipes, or other appropriate method; mixing should be sufficient to create a 'well mixed' condition. Mixing too aggressively can push tracer out of the well resulting in erroneously high readings. Verify that the LNAPL/tracer mixture is adequately mixed by conducting a vertical scan through the LNAPL column in the well using the down-well fiber optic cable and spectrometer. Decontaminate and inspect the fiber optic cables and reflectance probe (at the tip of the fiber optic cable) prior to each use to ensure there are no sources of light interference that may yield erroneous data.

7.4.2.2 Measure and record depth to the air/LNAPL and LNAPL/water interfaces using an oil-water interface probe in the test well. Do not gauge the well with the interface probe prior to mixing, as removing small volumes of poorly mixed LNAPL or LNAPL/tracer mixture (even volumes as small as the quantity that sticks to the interface probe) could potentially introduce error to the mass-balance calculations used to estimate LNAPL flux through the well.

7.4.2.3 Measure and record LNAPL fluorescence within the in-well standard pipes (C_0 and C_{100}) and the test well (C_{WELL}). Decontaminate the fiber optic cable between readings to prevent transfer of dyed or undyed LNAPL between calibration standards and the test well. Repeat measurement of LNAPL fluorescence within the in-well standard pipes (C_0 and C_{100}) and the test well (C_{WELL}). Two percent or less variability between the first and second measurements of $C_0$0, C_{100}, and C_{WELL}, respectively, are desirable. Additional mixing of the LNAPL and additional measurement repetition may be necessary to achieve the target variability.

7.4.2.4 The test should be terminated, or re-started by adding more tracer to the test well (C_{WELL}) when the tracer concentration in the test well approaches the natural background fluorescence in C_0 due to accuracy of the spectrometer. Generally, when the tracer concentration in the test well (C_{WELL}) is less than 20 % greater than C_0, the test should be restarted or terminated.

7.5 *Report:*

7.5.1 Include the information listed below in the report of the field procedure:

7.5.1.1 Date, time, and well identification.

7.5.1.2 Volume of tracer added.

7.5.1.3 Background florescence of LNAPL in C_0.

7.5.1.4 LNAPL fluorescence in C_{100}.

7.5.1.5 All gauged LNAPL thickness measurements in test well.

7.5.1.6 All gauged depth to air/LNAPL interface measurements.

7.5.1.7 All gauged depth to LNAPL/water interface measurements.

7.5.1.8 Diameter of well.

7.5.1.9 Diameter of small diameter pipes (isolation tubes) and type of material.

7.6 *Precision and Bias:*

7.6.1 Repetition of readings increases test precision. At a minimum, duplicate readings are taken and the duplicate readings should match within two percent of previous readings. There is no known bias in the testing method. Site-to-site test precision has not yet been quantified based on variability in site conditions and instruments utilized for testing.

7.6.2 It can be envisioned that if there is no LNAPL transmissivity, tracer will never leave the well due to advective processes, but there is still connection between LNAPL in the well and the LNAPL in the formation, so tracer can still diffuse from the well. The lower detection limit of the method is governed by the rate if diffusion of tracer from the well into the formation. Taylor (2004) (**8**) developed a rigorous solution to calculate the lower detection limit based on the effective diffusion coefficient of the tracer.

7.6.3 The method precision will be discussed in a qualitative sense. There are issues associated with the precision of the method based on variability of collecting individual tracer concentration data points. The data that is collected in the field is fit to a non-linear analytic model, much like the other methods. Each time a fluorescence concentration is measured, a duplicate reading is collected. The goal for the duplicate readings is to achieve two percent (on a normalized basis) variability. If the LNAPL transmissivity is very low, and the readings are taken over a small time period, it can be envisioned that the two percent variability within each data point might be larger than the actual decrease in tracer concentration. This results in the inability to calculate an absolute transmissivity value; however, an upper limit transmissivity could be still be calculated generating data where LNAPL transmissivities can be reported as less than a time weighted absolute transmissivity value.

8. Data Analysis

8.1 *Calculations for General Parameters*—This section provides guidance on how to calculate standard parameters potentially applicable to any methodology.

8.1.1 *Calculating Fluid Levels from Pressure Transducers*—Setups can include the use of one, two or three pressure transducers. This section will cover how to estimate the air/LNAPL interface, LNAPL/water interface and the calculated water-table elevations.

8.1.1.1 Pressure transducers measure either the absolute pressure or gage pressure (pressure relative to atmospheric pressure). For this discussion it is assumed that absolute pressures are measured. If the air/LNAPL interface is the objective of a given transducer then the measured pressure will need to be corrected for LNAPL density for estimating LNAPL head.

8.1.1.2 To use a pressure transducer, the density of the LNAPL should be known prior to interpreting the test results.

8.1.1.3 Eq 6 assumes the transducer provides absolute pressure data. These equations, combined with calibration gauging data and LNAPL density data, will allow calculation of each fluid interface elevation whether one pressure transducer is being used in conjunction with gauging of the air/LNAPL interface or two pressure transducers are being used, one in each fluid phase.

$$Z_{CGW} = Z_{P1} + \frac{P_{P1} - P_{atm}}{\rho_w g} \tag{6}$$

where:

Z_{P1} = elevation of water phase pressure transducer (that is, pressure transducer P1) (L),
Z_{CGW} = elevation of the calculated water-table level (L),
P_{P1} = measured absolute pressure from pressure transducer P1 (M/t^{2}L),
P_{atm} = measured atmospheric pressure inside the well casing (M/t^{2}L),
ρ_w = groundwater density (M/L^3), and
g = gravitational acceleration (L/T^2).

8.1.1.4 Eq 6 combined with atmospheric pressure data and pressure transducer data is used to calculate the corrected water-table elevation.

$$Z_{AN} = Z_{P2} \mp \frac{P_{P2} - P_{atm}}{\rho_n g} \tag{7}$$

where:

Z_{P2} = elevation of LNAPL phase pressure transducer (that is, pressure transducer P2 located within the LNAPL column in the well) (L),
Z_{AN} = elevation of the air/LNAPL interface (L),
P_{P2} = measured absolute pressure from pressure transducer P2 (M/t^{2}L),
ρ_n = LNAPL density (M/L^3), and
g = gravitational acceleration (L/T^2).

8.1.1.5 Eq 7 combined with the atmospheric pressure data and pressure transducer data is used to calculate the elevation of the air/LNAPL interface.

$$Z_{OW} = \frac{Z_{CGW} - \rho_r Z_{AN}}{1 - \rho_r} \tag{8}$$

where:

Z_{OW} = elevation of the LNAPL/Water interface (L), and
ρ_r = the relative LNAPL to water density, that is, $\rho_r = \rho_n/\rho_w$ (unitless)

8.1.2 Eq 8 results in the LNAPL/water interface elevation. Eq 8 requires the density of LNAPL and the elevations of the calculated water-table level and the air/LNAPL interface to be known. The required fluid elevations can be measured in any combination of gauging data or pressure transducer data that provides these required input elevations. LNAPL density should be estimated based on laboratory analysis of site specific LNAPL.

8.1.3 *Calculation of LNAPL Drawdown*—The calculation of LNAPL drawdown must compare the pressure (head) existing in a given extraction well to the equilibrium pressure (head) of LNAPL within the mobile interval in the formation. For every case the top of the mobile interval of LNAPL in the formation is the reference point for drawdown. If multiple soil horizons exist then the interval estimated to exhibit the highest transmissivity would be selected at the primary interval and therefore would represent the reference point for drawdown calculations. A silt overlying a fine sand may have some mobile LNAPL but would be insignificant compared to the underlying sand. In this case, the top of the underlying sand would be selected for the reference point to calculate drawdown.

8.1.3.1 *Unconfined*—Drawdown under unconfined conditions is given by the following equation for air/LNAPL interface drawdown:

$$S_{nt} = Z_{AN*} - Z_{AN(t)} \tag{9}$$

where:

Z_{AN*} = the air/LNAPL interface elevation for equilibrium conditions (L),
$Z_{AN(t)}$ = the air/LNAPL interface elevation at time t (L), and

S_{nt} = LNAPL drawdown at time t (L).

8.1.3.2 *Confined LNAPL Drawdown*—Drawdown for confined conditions is not solely based on the air/LNAPL interface elevation because as LNAPL is extracted from a well both LNAPL and water can rise above the mobile interval of LNAPL (that is, the confining layer), and drawdown calculation must consider the entire fluid column and fluid density between the mobile interval and air/LNAPL interface.

(1) Where the calculated water-table elevation is equal to equilibrium conditions, the LNAPL/water interface is above the confining contact and LNAPL is recovering from a baildown test or being removed via a skimming technology, Eq 10 can be used to estimate the LNAPL drawdown. In this scenario of a constant calculated water-table, drawdown is constant so long as the LNAPL/water interface remains above the confining contact elevation because as a given mass of LNAPL flows into the well, an equal mass of water flows out of the well. For this constant LNAPL drawdown condition the fluid pressure distribution across the mobile interval of LNAPL remains constant.

$$S_{nt} = b_{nf}\frac{1-\rho_r}{\rho_r} \tag{10}$$

where:

b_{nf} = mobile interval of LNAPL in the formation, which is not equal to the gauged LNAPL thickness (L).

(2) Once the elevation of the LNAPL/water interface has decreased below the confining contact, the LNAPL drawdown is calculated using the difference in air/LNAPL interface (that is, Eq 9).

(3) Note that the formation thickness of confined LNAPL can be estimated by taking the difference in the static LNAPL/water interface and the confining contact elevation in the formation, typically estimated based on soil boring data such as soil type and LNAPL impacts.

(4) When confined LNAPL exists, the LNAPL/water interface is above the confining contact, the calculated water-table is less than equilibrium, and LNAPL is recovering from a baildown/slug test or continuous liquid extraction, Eq 11 can be used to estimate LNAPL drawdown.

$$S_{nt} = \frac{\left(Z_{AN*}-Z_{cc}\right)\rho_n - \left(Z_{NW(t)}-Z_{cc}\right)\rho_w - \left(Z_{AN(t)}-Z_{NW(t)}\right)\rho_n}{\rho_n} \tag{11}$$

where:

S_{nt} = the drawdown at time t for LNAPL existing in a confined state below the confining contact elevation,
Z_{cc} = elevation of confining contact (L),
$Z_{NW(t)}$ = elevation of LNAPL/water interface at time t (L), and
Z_{AN*} = elevation of air/LNAPL interface for equilibrium conditions (L).

(5) If well extraction has resulted in the air/LNAPL interface occurring below the confining layer then drawdown is calculated with Eq 9 (that is, same as unconfined conditions). This equation will hold until the air/LNAPL interface reaches the confining contact. During this scenario for confined LNAPL, drawdown is not constant and will decrease with time. It is possible that Eq 9-11 are all required to cover the span of a recovery event (baildown, slug or liquid extraction).

(6) Each equation covers a specific set of conditions that may or may not be present during any given test where confined LNAPL exists.

8.1.3.3 *Perched*—The drawdown for perched LNAPL conditions is the same as for unconfined except that the maximum possible drawdown for liquid only extraction is equal to the mobile interval of LNAPL in the formation. Vacuum enhanced extraction can increase this drawdown and the equations are discussed under 8.2. The mobile interval of LNAPL in the formation is equal to the difference in the equilibrium air/LNAPL interface and the perched layer contact. The contact for perched LNAPL can be estimated based on soil boring data such as soil type and LNAPL impact data.

8.1.4 *Data Analysis–Baildown Testing:*

8.1.4.1 *General Boundary Conditions:*

(1) The primary condition which needs to be met is that the relationship between LNAPL drawdown and LNAPL discharge to the well from the formation, (that is, well recharge) is a direct relationship and the data would trend such that the discharge and drawdown would reach zero simultaneously. Fig. 2 provides the ideal behavior.

(2) Baildown test that meet this criterion need not be run to completion since the data trends confirm that the fluid level used to represent equilibrium conditions is a reasonable value.

(3) Baildown test data that exhibit deviations from this ideal trend indicate that the data is not suitable for analysis or that the value used for equilibrium conditions is inaccurate. Equilibrium fluid levels should be checked and can be corrected to represent the final fluid levels if these data are more representative of equilibrium conditions based on gauging data trends obtained during the baildown test. If a correction is not reasonable then the data not exhibiting the correct trend should not be analyzed with the baildown test methods provided. Where uncertainty occurs with equilibrium fluid levels, the baildown test should be run to completion to understand the equilibrium fluid levels. The test can then be repeated or an alternate method in this guide used to estimate LNAPL transmissivity.

(4) Data that initially trends towards zero drawdown where the discharge would still be positive typically represents perched or confined LNAPL behavior (Fig. 3).

(5) Data that initially trends towards zero discharge where the drawdown would still be positive typically represents filter pack recharge and should not be analyzed (Fig. 4).

(6) Eq 12 is used to calculate the recovered thickness attributable to filter pack recharge, where all recovery up to this thickness should be considered filter pack recharge. Eq 12 is only applicable where the initial gauged thickness of LNAPL in a well exists completely within the screened interval.

$$b_r = b_n - \frac{V_r}{\pi\left(S_{yf}\left(r_b^2 - r_c^2\right) + r_c^2\right)} \tag{12}$$

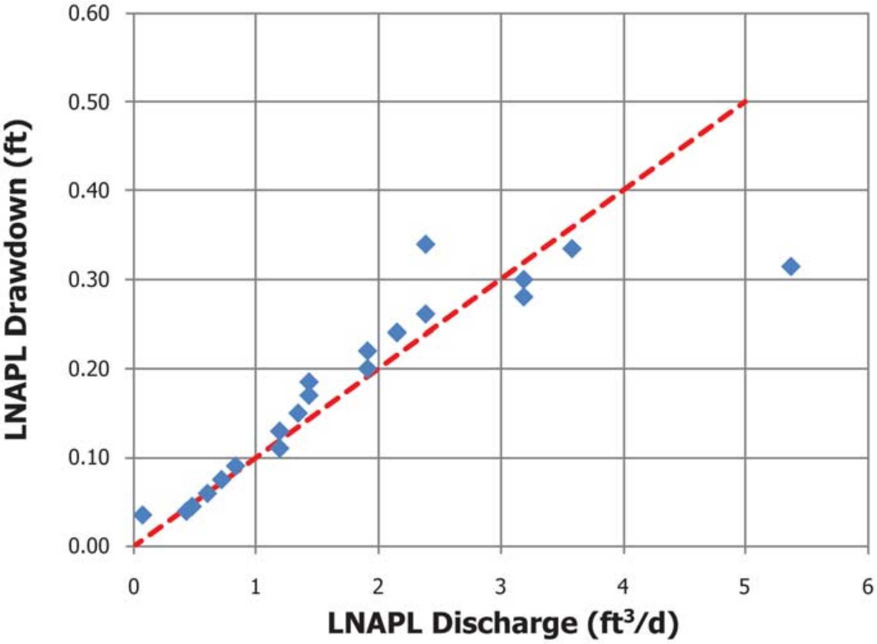


FIG. 2 Baildown Test Data Representing the Ideal Relationship between Drawdown and Discharge

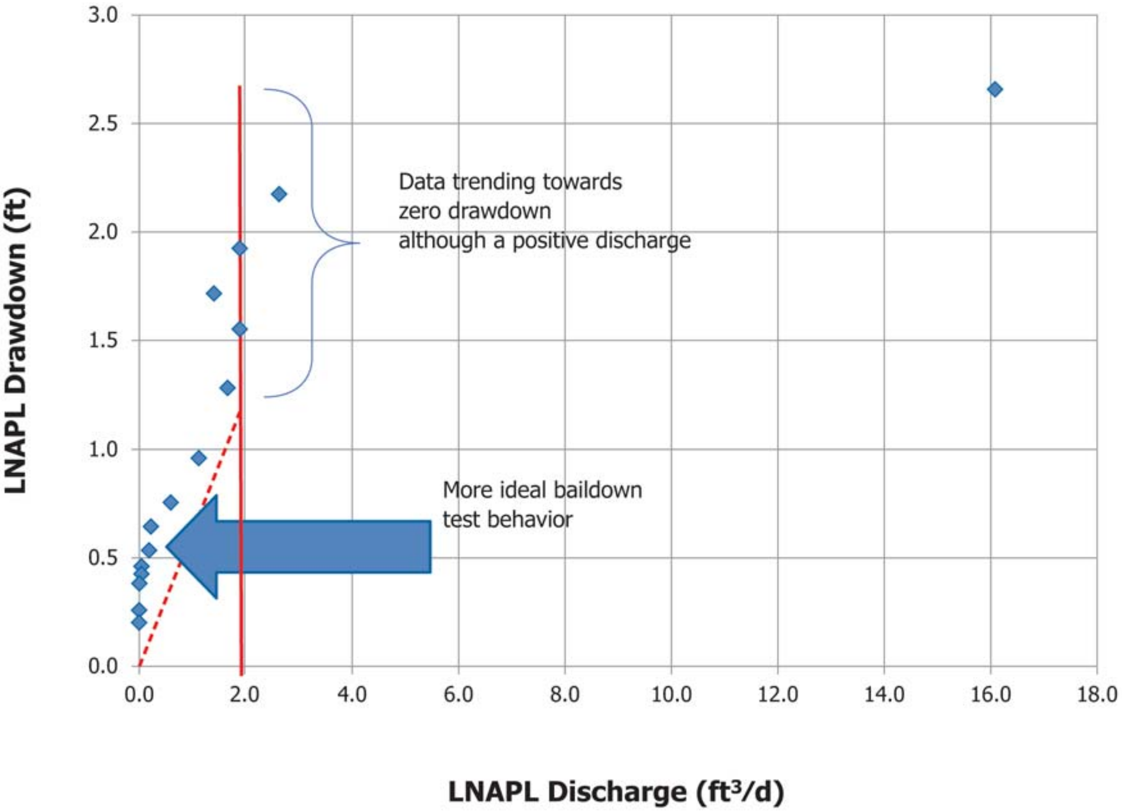


FIG. 3 Baildown Test Data Representing Confined or Perched Discharge Behavior

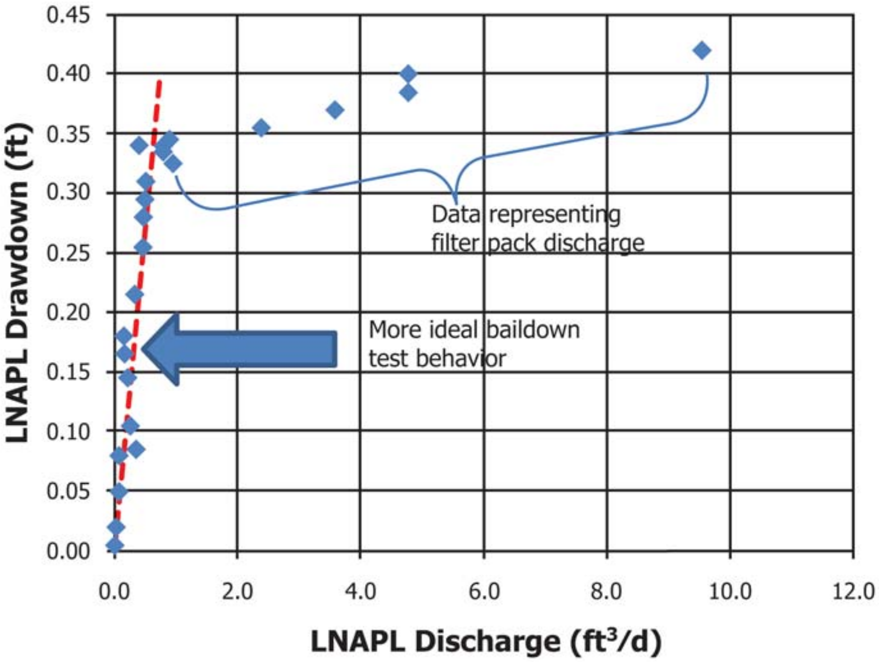


FIG. 4 Baildown Test Data Initially Representing Filter Pack Discharge Behavior and then Becomes Ideal

where:

V_r = volume of LNAPL initially recovered or displaced (L^3),

b_r = recovered LNAPL thickness due to filter pack recharge (L), and

b_n = initial gauged LNAPL thickness prior to removal (L).

(7) Data that consistently trends such that it intersects the zero discharge with remaining drawdown or zero drawdown with remaining discharge likely represents that the fluid levels being used for equilibrium conditions are inaccurate (Figs. 3 and 4).

(8) Best practices will utilize equilibrium fluid levels that are confirmed by reviewing the fluid levels at the start to the end of the test where the well was gauged until it fully recovered. However, where variables such as extended test times combined with fluctuating water-table conditions exist, an alternative method can be employed to confirm equilibrium fluid levels. Equilibrium fluid levels can also be ensured by gauging the well 10 times over a period equal to the test duration analyzed prior to the start of the test. These data will allow for an understanding of variability in water-table conditions near the time the test was conducted.

(9) Wells need to be in good communication with the formation. This consists of well being properly developed and not containing weathered LNAPL induced by stagnant well conditions. Fluid gauging data exhibiting repeatable fluid levels following LNAPL removal events for a given well is the best practice to establish equilibrium fluid levels are accurate.

(10) If the water-table varies by a magnitude greater than 20 % of the max drawdown induced over the period of analysis, then an alternative method should be used to evaluate LNAPL transmissivity.

(11) All equilibrium fluid levels need to be compared to the soil profile to identify the possibility of perched or confined LNAPL. This will enable the identification of perched or confined LNAPL conditions. These conditions affect how drawdown is calculated.

(12) The use of a storativity term in the numerical analysis of baildown/slug test data accounts for non-steady state recharge (that is, transient) conditions such as in the Jacob-Lohman Method. However, many tests are not significantly affected by transient behavior and one can use methods more representative of steady state origins such as the Bouwer-Rice method.

(13) The Bouwer-Rice solution is useful for baildown test analysis because the translation method (Butler 1998) **(9)** can be applied where the slug introduction was not instantaneous. This may happen more frequently with tests where LNAPL is more completely removed from the casing and filter pack for the purposes of minimizing filter pack recharge effects.

(14) The Jacob-Lohman based analysis is useful for cases where transient effects are observed in the recharge response and the slug or fluid withdrawal meets instantaneous conditions.

(15) Instantaneous should be relative to the test duration, the removal period should be less than 100th of the entire test duration.

(16) If the slug/fluid removal approximates instantaneous and no significant transient effects are observed, then both analysis methods can be used and should correlate well.

8.1.4.2 *Bouwer and Rice:*

(1) LNAPL transmissivity calculation methods for baildown testing analysis theory via the Bouwer-Rice method are provided in detail in Lundy and Zimmerman (1996) **(6)** and Huntley (2000) **(10)**, and in Bouwer and Rice (1976) **(11)** and Bouwer (1989) **(12)**.

(2) The primary assumptions include a quasi-steady-state model for recharge to the well (the model assumes steady radial flow to the well with rate dependent on the well drawdown; no storage effects are included) and that the ratio of change in LNAPL head to LNAPL thickness (ds_n/db_n) is constant. This ratio will be referred to as the *j*-ratio.

(3) The magnitude of the *j*-ratio has been discussed in two published papers. Where the water transmissivity through the well screen is significantly lower than the LNAPL transmissivity, this ratio equals unity (1) (Lundy and Zimmerman, 1996) **(6)**. An example of this behavior is shown in Figs. 5 and 6. Where the water transmissivity is significantly higher than the LNAPL transmissivity through the well screen and the potentiometric surface in consistent throughout the analyzed portion of data, this ratio equals unity minus relative density ($1 - \rho_r$) (Huntley, 2000) **(10)**. For an example of this type of behavior see Figs. 7 and 8.

(4) The magnitude of *j*-ratio need not be assumed 'a priori' because every baildown or slug test provides necessary data to evaluate if a constant slope between LNAPL thickness and head exists, along with the magnitude of this ratio. By plotting the thickness on the *x*-axis versus the drawdown as calculated based on the difference in air/LNAPL interface from equilibrium on the *y*-axis the data can be reviewed for a period exhibiting a consistent slope. The value of that slope represents the ratio that should be used in the solution. This can be tested by plotting the change in the air/LNAPL interface (that is, drawdown) versus gauged LNAPL thickness.

(5) If at any point in the test a constant slope between gauged LNAPL thickness and drawdown exists and the recharge is not representative of filter pack recharge, the boundary condition is met and the Bouwer-Rice methodology can be applied to that time sequence. Butler describes a translation method for non-instantaneous slug tests initiation which can be applied to this method (Butler, 1998) **(9)**.

(6) The greater the variability in *j*-ratio, the larger the error associated with the Bouwer-Rice methodology. Large variability suggests that the Jacob-Lohman methodology should be applied.

(7) According to Bouwer-Rice method, the logarithm of the drawdown varies as a linear function of time. A straight line may be fit to the drawdown-time data and the slope of this line is used to determine the LNAPL transmissivity. When the line if fit using linear regression, the variance of the slope of the line can be used to estimate the LNAPL transmissivity standard deviation.

$$T_n = r_w^2 \frac{\ln\left(\frac{s_o}{s_n}\right)\ln\left(\frac{R_{oi}}{r_w}\right)}{2jt} \qquad (13)$$

where:

T = LNAPL Transmissivity (L^2/t),
s_o = maximum drawdown induced; estimated from *y*-intercept of the drawdown versus log-time plot fitted to the selected data range (L),
s_n = LNAPL drawdown at time t (L),
j = ratio of change in drawdown to change in thickness over the recovery period being analyzed,
t = elapsed time (t),
R_{oi} = radius of influence, and
r_w = effective well radius.

(8) The ratio of the radius of influence to the effective well radius may be calculated using the polynomial approximation presented by Butler (1998) **(9)**. This is based on the results presented by Bouwer and Rice (1976) **(11)**.

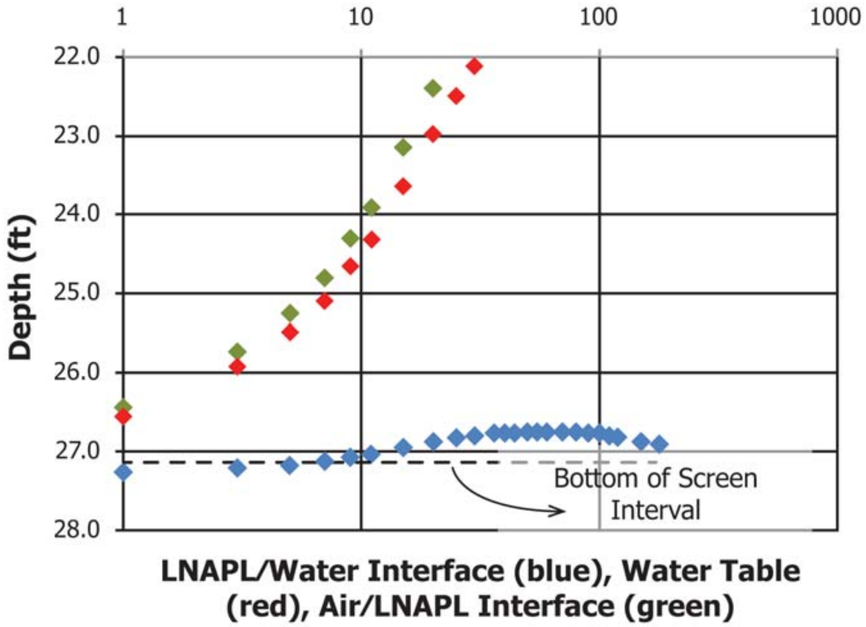


FIG. 5 Hydrograph of Baildown Test Recovery Illustrating a Constant LNAPL/Water Interface during Recovery

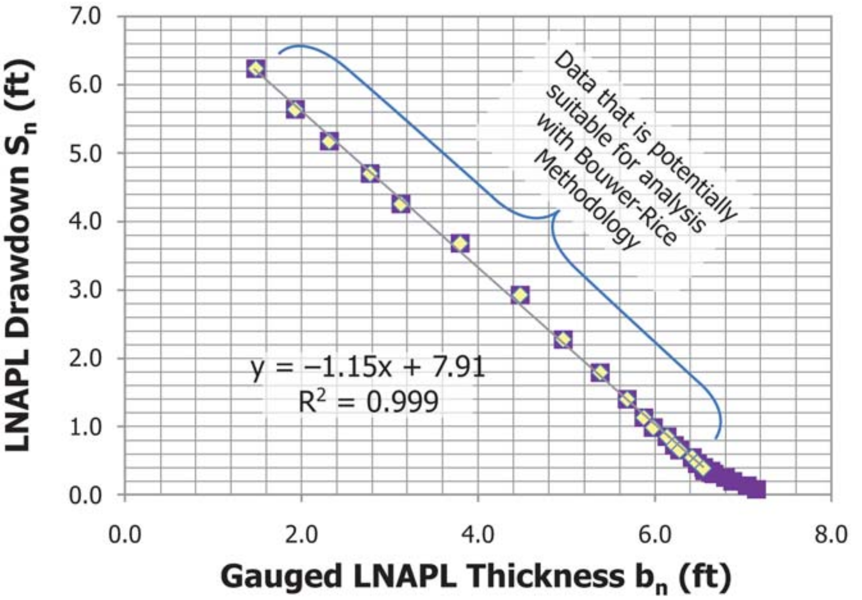


FIG. 6 Gauged LNAPL Thickness versus LNAPL Drawdown for Baildown Test Approximating a Change in Thickness to Decrease in Drawdown Ratio Value of One

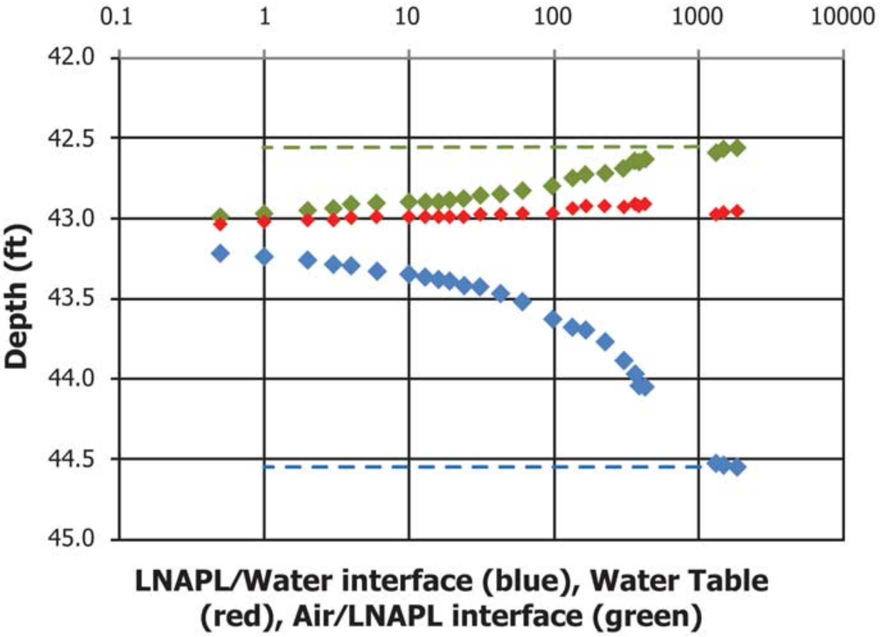


FIG. 7 Hydrograph of Baildown Test Recovery Approximating a Constant Calculated Water-table Elevation During Recovery

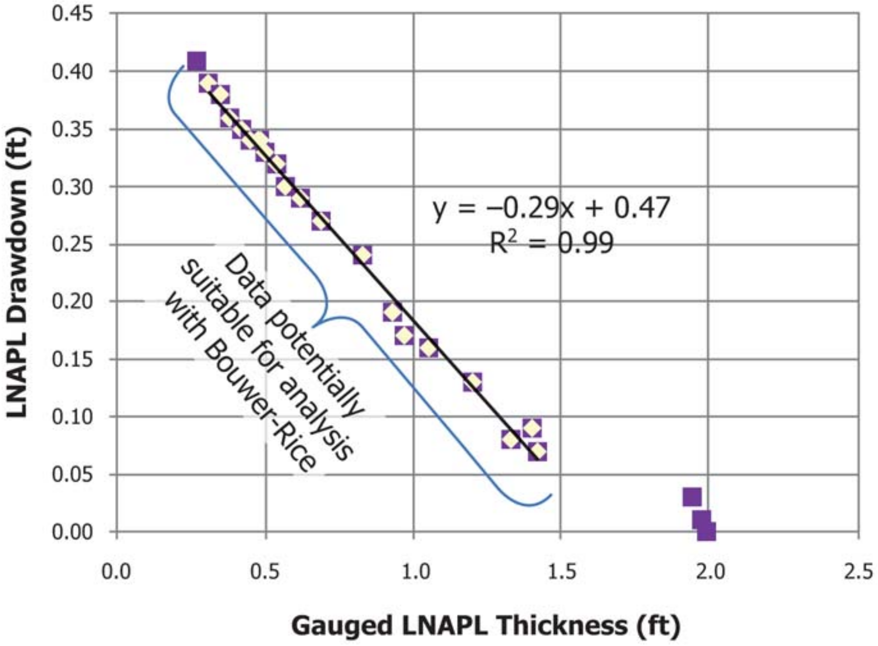
(9) Jacob-Lohman—The theory of baildown/slug testing analysis via Jacob-Lohman methods is provided in detail in Huntley (2000) (**10**) and Jacob and Lohman (**13**). Although three different methods are presented by Huntley (2000) (**10**) from Jacob and Lohman's (**13**) modification of the Cooper-Jacob method for constant drawdown-variable discharge conditions of LNAPL baildown testing, only the sum of the squared residual (SSR) method has been found to consistently provide an applicable method. The other Cooper-Jacob (that is, methods 1/Q and s/Q) provided by Huntley do not consistently provide comparable or accurate results and are not recommended as part of this guide.

8.1.4.3 Because the recharge rate is calculated independently of drawdown, no relationship between the change in recovered gauged thickness and drawdown is required to hold.

8.1.4.4 This analysis method accounts for transient recharge conditions and storage effects.

8.1.4.5 The primary condition which needs to be met is that the relationship between drawdown and discharge to the well from the formation (that is, recharge) is a direct relationship and the trend will simultaneously intersect zero for each variable (see Fig. 2).

(1) Sum of the Squared Residual Method—The Sum of the Squared Residual (SSR) method is useful to minimize any



Approximating a change in thickness to decrease in drawdown ratio value of the quantity relative density minus one; where the relative density is estimated to be 0.8.

FIG. 8 Gauged LNAPL Thickness versus LNAPL Drawdown for Baildown Test

scatter induced by deviations from the primary assumption of constant, known drawdown. The primary assumption is still constant, known drawdown, but the methodology allows for minimization of error introduced by the resulting scatter when the drawdown is variable (Huntley, 2000) (**10**).

(2) Although Huntley provides the recommendation to solve for both LNAPL transmissivity and storativity, experience has found that it is prudent to iteratively select a storativity value based on the LNAPL transmissivity. Guidance values are provided in Table 1. Therefore start with a value of 0.1 then solve for LNAPL transmissivity. Based on that LNAPL transmissivity reselect the storativity to match the new transmissivity. Repeat until results are within a factor less than 2.

(3) Use of Table 1 will result in reasonable estimates of LNAPL transmissivity in conjunction with the SSR Method. The error associated with varying storativity by plus or minus half an order of magnitude results in a variability of plus or minus approximately 30 %.

TABLE 1 Storativity Estimates for a Given LNAPL Transmissivity

Resulting LNAPL Transmissivity (ft^2/day)	General Estimate for LNAPL Storativity/Specific Yield (Volume/Bulk Volume)
50	0.175
20	0.1225
10	0.07
5	0.0525
1	0.035
0.1	0.008

(4) The SSR Method is completed by calculating the left side of the Eq 14 below and running a numerical solution to fit the right side of the equation by varying LNAPL transmissivity.

$$S\Delta t = \frac{Q_n \Delta t}{4\pi T_n}\ln\left(\frac{2.25T}{r_w^2 S}\right) \tag{14}$$

where:

Q = LNAPL discharge rate from the formation to the well, (that is, well recharge rate), and
S = LNAPL specific yield.

8.1.4.6 Alternatively the SSR method can be used in the following form which each side of the equation represents a more tangible value of measured recovered volume to calculated recovered volume of volume recovered in each time step.

$$Q\Delta t = \frac{4\pi sT}{\ln\left(\frac{2.25T}{r_w^2 s}\right)}\Delta t \tag{15}$$

8.2 *Data Analysis—Manual Skimming Test:*

8.2.1 To calculate LNAPL Transmissivity from manual skimming test data, use the following equation (Charbeneau, 2007) (**14**):

$$T_n = \frac{Q_n \ln\left(\frac{R_{oi}}{r_w}\right)}{2\pi s_n} \tag{16}$$

where:

T_n = LNAPL transmissivity (L^2/t),
Q_n = measured LNAPL recovery rate (L^3/t),
R_{oi} = radius of influence (L), and

r_w = well radius (L).

NOTE 2—The value of the term $\ln(R_{oi}/r_w)$ can be assumed to equal 4.6 with the introduction of little additional error.

8.2.2 The drawdown value for a given period should be taken as the geometric mean of the starting and ending drawdown values.

8.2.3 The drawdown value can be directly measured using the fluid level gauging data and the guidance provided in 8.1.3.

8.2.4 The maximum skimming drawdown for unconfined conditions is given by Eq 15. The maximum drawdown for confined and perched conditions is given by Eq 16 and Eq 17 respectively.

8.2.5 To calculate LNAPL Transmissivity, take the stabilized LNAPL recovery rate (Q_n) and estimate the drawdown that corresponds to this discharge and calculate T_n using the manual skimming test equation, above. If you have perched or confined LNAPL then the drawdown must be adjusted as noted in 5.4.

8.2.6 The accuracy of this equation is most sensitive to the accuracy of the measured LNAPL recovery rate and drawdown. Consistent operation of the skimming system such that the induced drawdown is know and consistent will improve accuracy of calculations.

8.3 *Data Analysis—Long Term Recovery System Data:*

8.3.1 *LNAPL Skimming*—Eq 16 can be used to estimate LNAPL transmissivity, however the assumptions for LNAPL drawdown vary from those in the manual skimming test.

8.3.1.1 The drawdown value can be directly measured using the fluid level gauging data and the guidance provided in 8.1.3 or through assumptions based on equilibrium fluid levels if the system is designed to maintain close to zero gauged LNAPL thickness in the well. Routine direct measurement will provide the best accuracy.

8.3.1.2 The maximum skimming drawdown for unconfined conditions is given by Eq 17. The maximum drawdown for confined and perched conditions is given by Eq 18 and Eq 19 respectively.

$$s_{n\_unconfined} = b_n(1 - \rho_r) \tag{17}$$

$$s_{n\_confined} = b_{nf}\frac{1 - \rho_r}{\rho_r} \tag{18}$$

$$s_{n\_perched} = b_{nf} \tag{19}$$

8.3.1.3 Unless an automatic fluid level system is being utilized, long-term continuous recovery requires estimates of drawdown that are based on point measurements representing long periods of time. The accuracy of this method is based on the ability of the recovery systems to maintain a constant LNAPL drawdown and how water-table fluctuations affect the mobile interval in the formation.

8.3.1.4 The skimming methodology when using periodic drawdown measurements provides estimates for LNAPL transmissivity that are likely within an order of magnitude of the actual LNAPL transmissivity value, however weekly or monthly measurements of drawdown can often span significant fluctuations in water-table.

8.3.1.5 The value of the term, $\ln(R_{oi}/r_w)$ can be assumed to equal 4.6 with the introduction of little additional error.

8.3.2 *Vacuum-Enhanced LNAPL Only Liquid Recovery (Vacuum-Enhanced Skimming)*—LNAPL transmissivity may be determined from a vacuum-enhanced recovery system using air and LNAPL discharge data, assumed formation air permeability and air-water viscosity ratio, and formation hydraulic conductivity across the screened interval above the LNAPL. For vacuum-enhanced skimming, transmissivity can be calculated using the following equation (Charbeneau, 2007) **(14)** :

$$T_n = \frac{Q_n k_{ra} K_w b_a \rho_r}{\mu_{ar} Q_a} \tag{20}$$

where:

Q_a = air discharge rate in terms of standard air pressure and temperature (L^3/t),
k_{ra} = relative permeability of open screen length in the vadose zone to air (unit less),
K_w = saturated hydraulic conductivity value for corresponding to the soil type existing in the vadose zone immediately above the mobile LNAPL interval (L/t),
b_a = screen length open to the portion of the vadose zone representative of the saturated hydraulic conductivity value used (L), and
μ_{ar} = relative viscosity of air to water (unitless).

NOTE 3—The value for relative viscosity, μ_{ar}, is assumed to be 0.018 and relative permeability to air, k_{ra}, is assumed to be 0.9. Use of site-specific data for these parameters is also acceptable.

8.3.2.1 Additionally, if the air discharge rate is unknown Eq 16 can be used where the LNAPL drawdown due to vacuum enhanced skimming and ratio of radius of influence to well radius are known. The LNAPL drawdown term in this equation will be equal to the sum of the vacuum applied to the formation and the LNAPL skimming drawdown.

8.3.2.2 Where the LNAPL skimming drawdown is one tenth or less of the applied vacuum to the formation it does not have to be considered and only the applied vacuum needs to be measured.

8.3.2.3 The applied vacuum to the formation must account for head losses in the system and filter pack. Well head vacuums ahead of any supplemental air release valves are applicable but step pilot test data provide the best calibration to additional losses through the casing and filter pack. The air flow based calculation is typically more accurate relative to using applied vacuum because no estimation of head loss is required.

8.3.3 *Water-Enhanced LNAPL Recovery (Total Fluids Pumping, Single or Dual Pump)*—LNAPL transmissivity may be determined using water and LNAPL discharge data from a water-enhanced recovery system, provided the recovery system is operated at a sufficiently low pumping rate to ensure small drawdown at the recovery well to prevent significant smearing (Charbeneau, 2007) **(14)**. Eq 21 uses the water discharge rate, the LNAPL discharge rate and the hydraulic transmissivity to estimate LNAPL transmissivity. However this assumes that the drawdown induced with water extraction is much larger than the drawdown that is achievable via skimming. If the water induced drawdown is 10 times or greater than the skimming drawdown then Eq 21 (Charbeneau, 2007) **(14)** can be used. Cases where the skimming drawdown is greater than one-tenth of the water extraction induced drawdown then Eq 22 is more appropriate.

$$T_n = \frac{Q_o T_w \rho_r}{Q_w} \quad (21)$$

where:

Q_w = water discharge rate in terms of standard air pressure and temperature (L^3/t), and
T_w = aquifer transmissivity (L^2/t).

8.3.3.1 Eq 21 is useful especially for systems with variability in water extraction rates and even frequent periods of down time. Only the LNAPL and water volumes for a given period need to be measured. If the system down time was unknown, LNAPL transmissivity can still be accurately calculated because the time period cancels out of the equation for the LNAPL and water discharge terms. The discharge terms could also be converted in to volumes of oil and water recovered. The transmissivity calculated will be representative of the average LNAPL transmissivity for the period those volumes were recovered over.

$$T_n = \frac{Q_n T_w}{Q_w} \frac{1}{\left(\frac{1}{\rho_r} + \frac{S_{skim}}{S_w} \right)} \quad (22)$$

where:

S_{skim} = the maximum skimming drawdown (see 8.3.1.2).

8.3.3.2 Eq 22 approaches Eq 21 as the skimming drawdown becomes small relative to the water extraction induced drawdown.

8.3.4 *Water and Vacuum-Enhanced LNAPL Recovery*—Multiphase extraction being conducted as total fluids (that is, single stinger extraction) or dual phase extraction (that is, stinger combined with one or more liquid pumps) can also provide data to estimate LNAPL transmissivity.

8.3.4.1 Estimates of LNAPL transmissivity for multi-phase extraction are based on the summation of the total LNAPL production based on the drawdown induce from each phase. Eq 23 provides the LNAPL transmissivity estimate using the ratio of water and air flows to LNAPL flow from a well (Kirkman 2009) **(15)**.

$$T_n = \frac{Q_n \rho_r}{\frac{\mu_{ar} Q_a}{k_{ra} K_w b_a} + \frac{Q_w}{T_w}} \quad (23)$$

8.3.4.2 The equation to estimate of LNAPL transmissivity for multi-phase extraction using the applied vacuum to the formation and the LNAL and water production rates is provided as Eq 24 (Hawthorne 2010) **(16)**.

$$T_n = \frac{Q_n \rho_r}{\frac{2\pi s_n}{\ln\left(\frac{R_{oi}}{r_w}\right)} + \frac{Q_w}{T_w}} \quad (24)$$

8.3.4.3 The difference in equipment application between total fluids and dual-phase extraction will not affect the resulting LNAPL recovery performance beyond the head losses induced via the equipment. As discussed in 8.1 head losses associated with applied vacuum must be accounted for such that the applied vacuum value used to estimate LNAPL drawdown in Eq 24 represents applied vacuum to the formation. Step tests and an understanding of well screen length versus water-table and vacuum conditions are required.

8.4 *Data Analysis—Tracer Testing*—The tracer test has the following assumptions:

8.4.1 Flow under natural gradients is at steady state.

8.4.2 Fluid levels are constant throughout the duration of the test.

8.4.3 The LNAPL in the well is in hydraulic connection with the LNAPL in the formation.

8.4.4 The tracer is initially well mixed at time zero for the test.

8.4.5 The tracer is well mixed again prior to each measurement.

8.4.6 Relationship between tracer mass and fluorescence is assumed to be linear or known a priori.

8.4.7 Diffusive transport of tracer from the well is small and can be neglected.

8.4.8 Cross-sectional flow on the up and down gradient side of the well are equal.

8.4.9 If any of the above assumptions are violated, the practitioner should be determine the effects on the data reduction and calculated transmissivity by violating the assumptions.

8.4.10 The following is an implicit analytical solution for estimating the LNAPL Transmissivity as a function of changes in tracer concentrations in LNAPL in a well between intermittent mixing events. Also presented is an analysis of the limits on time between mixing-measurement events.

$$\frac{C_{T_{t_o+\Delta t}}}{C_{T_{t_o}}} = \frac{2a\cos\left(\frac{T_n i_{LNAPL} \alpha \Delta t}{2 r_w b_{wL}}\right) - \sin\left[2a\cos\left(\frac{T_n i_{LNAPL} \alpha \Delta t}{2 r_w b_{wL}}\right)\right]}{\pi} \quad (25)$$

$$\text{for} \quad \frac{T_n i_{LNAPL} \alpha \Delta t}{2 r_w b_{wL}} < 1$$

where:

$C_{T_{t+\Delta t}}$ = the tracer concentrations after mixing (M/L^3),
C_{T_t} = the initial tracer concentrations (M/L^3),
Δt = the time between mixing events (T),
T_n = the LNAPL transmissivity (L^2 /T),
i_{LNAPL} = the LNAPL gradient (unitless),
r_w = the radius of monitoring well (L),
b_{wL} = the thickness of LNAPL in the monitoring well (L), and
α = the flux convergence factor, often assumed to be equal to a value between 0.5 and 2 or a mean of 1.7 (unitless).

8.4.10.1 A full derivation is presented in Smith **(17)**.

8.4.11 *Limit on Maximum Elapsed Time Between Mixing Events*—LNAPL transmissivity through the well and adjacent geologic formation includes vertical variations in LNAPL saturations and correspondingly relative permeability to LNAPL (Farr **(18)**). Given the assumptions of a uniform porous media, the following advances a maximum time between mixing without violating any of the assumptions from 7.6.1 is defined as:

$$\Delta t_{max} = \frac{2r_w}{q_{wL_{ave}}} \frac{k_{r_{ave}}}{k_{r_{max}}} \quad (26)$$

where:

Δt_{max} = the maximum time allowed between intermittent mixing events (T),

$q_{wL_{ave}}$ = the vertical LNAPL flux in the well (L/T),

$k_{r_{ave}}$ = the vertical averaged relative permeability (unitless), and

$k_{r_{max}}$ = the maximum relative permeability (unitless).

8.4.11.1 Further analysis of limits on Δt_{max} and full derivation is provided in Smith (**17**).

ANNEXES

(Mandatory Information)

A1. FIELD FORMS

Well____________________ Site____________________

Manual Skimming Test Field Form

Project #:		**Site Name:**	
Well:		**Samplers:**	
Evacuation Method:		**Weather:**	

Well Information		**LNAPL Information**	
Casing Diameter:		**Fluid Type:**	
Total Depth:		**Volume Removed:**	
Depth to Top of Screen:		**Evacuation Method:**	
Screen Length:		**LNAPL Well Volume:**	

Length and volumetric units need to be specified

Length Units: **Volume Units:**

Borehole Diameter (INCHES):
Filter Pack Specific Yield (LNAPL)
0.175

Effective Well Radius (FT)

	LNAPL Well Volume
ft^3	
gal	
ml	

Pump	**Date**	**Time Hour Time Minute**	**Elapsed Time (min)**	**LNAPL Volume Removed**	**Water Volume Removed**	**Depth to LNAPL**	**Depth to Water**	**Comments**
Static		:						
Pump On		:						Test Start
Pump Off		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						

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Well____________________ Site____________________

Pump	Date	Time Hour Time Minute	Elapsed Time (min)	LNAPL Volume Removed	Water Volume Removed	Depth to LNAPL	Depth to Water	Comments
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						
		:						

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Well ______________________ Site ______________________

Baildown/Slug Test Field Form

Project #:		**Site Name:**	
Well:		**Samplers:**	
Evacuation Method:		**Weather:**	

Well Information		**LNAPL Information**	
Casing Diameter (INCHES):		**Fluid Type:**	
Total Depth (FT):		**Volume Removed:**	
Depth to Top of Screen (FT):		**Evacuation Method:**	
Screen Length (FT):		**LNAPL Well Volume:**	

Length and volumetric units need to be specified

Length Units: **Volume Units:**

Borehole Diameter (INCHES):
Filter Pack Specific Yield (LNAPL)
0.175

	Effective Well Radius (FT)
	LNAPL Well Volume
ft^3	
gal	
ml	

Period	Date	Time HH:MM	Elapsed Time (min)	DTP (feet)	DTW (feet)	Comments
Initial						
Removal Start						Test Start
Removal Stop						LNAPL/Slug Volume Removed (gal): Water Volume Removed (gal):

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Well____________________ Site____________________

Period	Date	Time HH:MM	Elapsed Time (min)	DTP (feet)	DTW (feet)	Comments

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Well____________________ Site____________________

Skimming Recovery Field Form

Project #:		**Site Name:**	
Well:		**Field Staff:**	
		Weather:	

Well Information		**Recovery System Information**	
Casing Diameter:		**Pump Type:**	
Total Well Depth:		**Recovered Volume Measurement Method:** **(Tank Volume, Totalizer, Instantaneous)**	
Depth to Top of Screen:			
Screen Length:			

Length and volumetric units need to be specified

Length Units: **Volume Units:**

Operational (Y/N)	Date	Time HH:MM	LNAPL Volume Recovered	Water Volume Recovered	Depth to LNAPL	Depth to Water	Pump Depth	Comments

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Well ______________________

Site ______________________

Water Enhanced Recovery Field Form

Project #:		**Site Name:**	
Well:		**Field Staff:**	
		Weather:	

Well Information		**Recovery System Information**	
Casing Diameter:		**Pump Type:**	
Total Well Depth:		**Recovered Volume Measurement Method:** **(Tank Volume, Totalizer, Instantaneous)**	
Depth to Top of Screen:			
Screen Length:			

Length and volumetric units need to be specified

Length Units: **Volume Units:** **Vacuum Units:** **Air Flow Units:**

Note: Either measure the Recovered LNAPL and water volumes separately (i.e., dual pump) or measure the total fluids recovered and oil/water ratio (i.e., total fluids pump)

Operational (Y/N)	Date	Time HH:MM	LNAPL Volume Recovered	Water Volume Recovered	Total Fluids Recovered	Oil/Water Ratio	Depth to LNAPL	Depth to Water	Pump Depth	Comments

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Well ______________________ Site ______________________

Vacuum Enhanced Recovery Field Form

Project #:			**Site Name:**	
Well:			**Field Staff:**	
			Weather:	

Well Information			**Recovery System Information**	
Casing Diameter:			**Pump Type:**	
Total Well Depth:			**Recovered Volume Measurement Method:** **(Tank Volume, Totalizer, Instantaneous)**	
Depth to Top of Screen:				
Screen Length:				

Length, volumetric, vacuum, and air flow units need to be specified

Length Units: **Volume Units:** **Vacuum Units:** **Air Flow Units:**

Note: Recovered volumes, airflow and well vacuum required

Operational (Y/N)	**Date**	**Time HH:MM**	**LNAPL Volume Recovered**	**Water Volume Recovered**	**Airflow**	**Well Vacuum**	**Depth to LNAPL**	**Depth to Water**	**Pump/ Stinger Depth**	**Comments**

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Well____________ Site____________

Multiphase Recovery Field Form

Project #:		**Site Name:**	
Well:		**Field Staff:**	
		Weather:	

Well Information		**Recovery System Information**	
Casing Diameter:		**Pump Type:**	
Total Well Depth:		**Recovered Volume Measurement Method: (Tank Volume, Totalizer, Instantaneous)**	
Depth to Top of Screen:			
Screen Length:			

Length, volumetric, vacuum, and air flow units need to be specified

Length Units: **Volume Units:** **Vacuum Units:** **Air Flow Units:**

Note: Either measure the Recovered LNAPL and water volumes separately (i.e., dual pump) or measure the total fluids recovered and oil/water ratio (i.e., total fluids pump); Air flow and vacuum required.

Operational (Y/N)	Date	Time HH:MM	LNAPL Volume Recovered	Water Volume Recovered	Total Fluids Recovered	Oil/water ratio	Airflow	Well Vacuum	Depth to LNAPL	Depth to Water	Pump/ Stinger Depth	Comments

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A2. TABLES

TABLE A2.1 Method Selection Table—Part One

NOTE 1—All of these methods may be used for confined, unconfined or perched aquifer scenarios; however, the use of recovery system data must be limited to data from technologies applicable for the given hydrogeologic scenario.

Methods	Detection Limit	Test Duration	Area Represented	Frequency of Method Transmissivity Values	Key Data List
Baildown/Slug Test	Typically 0.005 ft^2/day is reasonably achievable with minor water-table changes over length of test. No theoretical limit exists, therefore lower detections are feasible given reasonable test conditions. However, fluctuating water-tables may inhibit analysis of long-term data required for lower detection limits. (See thickness limitations)	Minutes to months–Actual duration is dependent on the recharge rate. However, this method is applicable when time is limited. Partial recovery can be analyzed if starting levels represent equilibrium.	"Point" Value, limited to the radius of influence for the test which is a few feet beyond borehole	Singular event period	-Well Construction -Equilibrium fluid levels -Soil profile across mobile LNAPL interval -LNAPL density -Volume of LNAPL removed/slug -Gauging data prior to test and over recovery period
Manual Skimming	Typically 0.001 ft^2/day is reasonably achievable. No theoretical limit exists, therefore lower detections are feasible given reasonable test conditions. However, fluctuating water-tables may inhibit analysis of long-term data required for lower detection limits.	Hours to weeks–Lower transmissivity wells will require more time, however this method is applicable when time is limited.	″Point″ Value, limited to the radius of influence for the test which is a few feet beyond borehole.	Singular event period	-Well Construction -Equilibrium fluid levels -Soil profile across mobile LNAPL interval -LNAPL density -Recovered volume over time -Gauging data prior to test and over recovery period
Recovery System Data	Detection limits based on combination of the recovery equation input parameter detection limits and/or values. Theoretical limit exists for water enhanced recovery calculations based on accuracy of LNAPL/water ratio measurement and the magnitude of aquifer transmissivities (for example, Aquifer transmissivity of 5,000 ft^2/day and an oil/water ratio detection limit of 0.001 for a gasoline will result in a detection limit of 3.75 ft^2/day).	Because recovery is representative of a relatively large area, steady state conditions need to be reached and maintained. Ongoing estimates are easily obtained based on the frequency of data collection.	"Area" Value, limited by the operational parameters of system and length of continual operation time which result in a given radius of capture. In general, representative of a larger area than other methods.	Continual time series representation	-Well Construction -Equilibrium fluid levels -Soil profile across mobile LNAPL interval -LNAPL density -Recovered LNAPL volume over time -Air/water flow rates -Well vacuum -Gauging data during recovery
Tracer Testing	Field trials have shown 1 ft^2/day is readily achievable with some tests achieving 0.2 ft^2/day. These values are based on a limited number of field trials completed to date. There is no theoretical limitation to the lower bound for transmissivity measurement. However, a simplifying assumption in the analysis is that diffusive dye loss is negligible as compared to loss due to LNAPL movement in the formation. This simplifying assumption may not be valid for measurement of ultra low transmissivity values.	Typical test duration is 3 to 6 months. A long test duration is recommended because the method is based on the natural gradient and a longer duration provides better averaging of individual measurement variability.	"Point" Value, The flux measurement is representative of a few feet outside the borehole. The gradient is representative of the well network density. This method is more applicable to a uniform LNAPL flow field. Uniform LNAPL flow fields occur in homogenous conditions and are often induced by active recovery.	Time-averaged over duration of test	-Well construction -Fluid levels -Hydraulic gradient of air/oil interface -Gauging data prior to test and after test

TABLE A2.2 Method Selection Table—Part Two

Methods	Influenced by Non-Ideal Conditions	LNAPL Type	In-Well Gauged LNAPL Thickness	Capital Cost	Data Analysis Cost	Startup/Shutdown Metric
Baildown Test	Long-term tests likely affected by background changes in water-table. This includes areas affected by fluctuating rivers, changing pumping conditions and tidal environments	No Limitations have been identified	<0.5 ft - not recommended <0.2 ft - not acceptable	**Low to Medium** Higher costs incurred when tests require excessive time (that is, weeks) to complete at remote sites	**Moderate** Boundary conditions must be check for data set being analyzed	Startup and Shutdown
Manual Skimming	Long-term tests likely affected by background changes in water-table. However, the variability can be better averaged across representative site conditions. Additionally, LNAPL drawdown can be kept at a maximum versus baildown and slug testing where the continually reducing drawdown becomes more susceptible to changes in the water-table	No limitations have been identified	No constraints	**Low** Typically results can be obtained within 1 to 3 days.	**Low to Medium**	Startup and Shutdown
Recovery System Data	Although recovery system data is affected by changes in water-table, the continual time series nature of the data collection can allow for periods of constant water-table elevations to be isolated and analyzed.	No limitations have been identified	No constraints	**Medium** System design needs to include contingencies for accurate parameter measurements. Redundancy for performance parameters is also recommended. Method is more cost effective for time-weighted averaging than baildown or manual skimming tests conducted at same frequency.	**Moderate** Quality assurance is required to confirm system operational efficiency, pump/stinger depth settings and collection of performance data.	Shutdown only
Tracer Testing	LNAPL flux measurements can be affected by changes in the water-table. Negative flux values have been observed under dynamic water table conditions. However, long test duration provides time-weighted averages that mitigates measurement-to-measurement variability. Fluid level fluctuations may complicate LNAPL gradient measurement.	High viscosity LNAPLs can be problematic. In-well LNAPL calibration standards for viscous LNAPLs may be depleted through repeated measurements that coat the measurement tools with LNAPL.	>0.2 ft	**Medium to High** Specialized field equipment is required and data is collected routinely over a period of weeks to months. Method is more cost effective for time-weighted averaging than baildown or manual skimming tests conducted at same frequency.	**Low**	Startup and Shutdown (representativeness may improve after recovery homogenizes LNAPL distribution).

TABLE A2.3 LNAPL Baildown/Slug Test

Measurement Parameter	Equation Symbol	Apparatus/Method
Equilibrium Fluid Interface Depth: Air-NAPL interface depths	Z_{AN*}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
LNAPL-water interface depths	Z_{NW*}	Optical/electrical resistivity interface probe Second pressure transducer w/ LNAPL & water density correction
LNAPL Volume: LNAPL removal measurement	V	Peristaltic pump; submersible pump; bailer, solid slug
LNAPL/H_2O Volume: LNAPL/water removal measurement		Graduated container measurable to 0.1 gal
Fluid Density: LNAPL density	ρ_n	ASTM Test D1298, ASTM Test D1217 ASTM Test D1480, ASTM Test D1481 ASTM Test D4052, ASTM Test D5002
Groundwater density, specific gravity	ρ_w	ASTM Test D1429
Time: Elapsed test time	t	Timepiece measurable to 1 second
Fluid Interface Elevation: Air-LNAPL interface elevation	Z_{AN}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
LNAPL-water interface	Z_{NW}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
Soil profile across mobile LNAPL interval		Soil boring log from visual or other soil characterization tool (ASTM E2531)
Well Construction Data: Casing radius	r_c	Well Construction Log
Borehole radius	r_b	Well Construction Log
Screen Interval		Well Construction Log
Gauged LNAPL thickness	b_n	Difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)
Formation thickness	b_{nf}	Interval that LNAPL flows over in the formation. For unconfined conditions, this is approximately equal to the gauged LNAPL thickness. Under confined and perched conditions, the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

TABLE A2.4 Manual LNAPL Skimming Test

Measurement Parameter	Equation Symbol	Apparatus/Method
LNAPL Discharge: Stabilized LNAPL recovery rate	Q_n	Graduated container measurable to 0.1 gal Timepiece measurable to 1 second
Effective Radius / Borehole Radius: Dimensionless ratio of effective radius of formation influence to borehole (well) radius	$\ln(R_o/r_w)$	Often assumed equal to 4.6
Fluid Interface Elevation: Air-LNAPL interface elevation at equilibrium	Z_{AN*}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
Air-LNAPL interface	Z_{NW*}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
Soil profile across mobile LNAPL interval		Soil boring log from visual or other soil characterization tool (ASTM E2531)
Well Construction Data: Casing radius	r_c	Well Construction Log
Borehole radius	r_b	Well Construction Log
Screen Interval		Well Construction Log
LNAPL Skimming Drawdown: Unconfined LNAPL at equilibrium	s_n	$Z_{AN*} - Z_{AN(t)}$
Maximum Skimming Drawdown confined LNAPL	s_n	$Z_{CC} - Z_{NW*}$
Maximum Skimming Drawdown perched LNAPL	s	$Z_{AN*} - Z_{CC}$
LNAPL-Only Discharge: Stabilized LNAPL recovery rate	Q_n	Totalizer records (normalized for all system downtime)
Effective Radius / Borehole Radius: Dimensionless ratio of effective radius of formation influence to borehole (well) radius	$\ln(R_o/r_w)$	Often assumed equal to 4.6
Gauged LNAPL thickness	b_n	Difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)
Formation thickness	b_{nf}	Interval that LNAPL flows over in the formation. For unconfined conditions, this is approximately equal to the gauged LNAPL thickness. Under confined and perched conditions, the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

TABLE A2.5 LNAPL Skimming Data

Measurement Parameter	Equation Symbol	Apparatus/Method
LNAPL Discharge: Stabilized LNAPL recovery rate	Q_n	Graduated container measurable to 0.1 gal Timepiece measurable to 1 second
Effective Radius / Borehole Radius: Dimensionless ratio of effective radius of formation influence to borehole (well) radius	$\ln(R_o/r_w)$	Estimated based on pilot test or calibration of equation to a set of known conditions Often assumed equal to 4.6
Fluid Interface Elevation: Air-LNAPL interface elevation at equilibrium	Z_{AN^*}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
Air-LNAPL interface	Z_{NW^*}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
Soil profile across mobile LNAPL interval		Soil boring log from visual or other soil characterization tool (ASTM E2531)
Well Construction Data: Casing radius	r_c	Well Construction Log
Borehole radius	r_b	Well Construction Log
Screen Interval		Well Construction Log
LNAPL Skimming Drawdown: Unconfined LNAPL at equilibrium	s_n	$Z_{AN^*} – Z_{AN(t)}$
Maximum Skimming Drawdown unconfined LNAPL	s_n	$Z_{AN^*} – Z_{CGW}$
Maximum Skimming Drawdown confined LNAPL	s_n	$Z_{CC} – Z_{NW^*}$
Maximum Skimming Drawdown perched LNAPL	$s_n s_n$	$Z_{AN^*} – Z_{CC}$
LNAPL-Only Discharge: Stabilized LNAPL recovery rate	Q_n	Totalizer records (normalized for all system downtime)
Gauged LNAPL thickness	b_n	Difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)
Formation thickness	b_{nf}	Interval that LNAPL flows over in the formation. For unconfined conditions, this is approximately equal to the gauged LNAPL thickness. Under confined and perched conditions, the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

TABLE A2.6 Vacuum-Enhanced LNAPL Skimming Data

Measurement Parameter	Equation Symbol	Apparatus/Method
LNAPL-Only Discharge: Stabilized LNAPL recovery rate (L^3/t)	Q_n	Flow meter and totalizer records (normalized for all system downtime)
Effective Radius / Borehole Radius: Dimensionless ratio of effective radius of formation influence to borehole (well) radius	$\ln(R_o/r_w)$	Estimated based on pilot test or calibration of equation to a set of known conditions Only required if using drawdown based equations Airflow based equations do not require this parameter
Open Screen Length: Screened interval open to vadose zone air flow (L)	b_a	Well Construction data and Soil Boring Log (ASTM E2531)
Air-Phase Relative Permeability: Formation pneumatic permeability	k_{ra}	Generally assumed = 0.9
Hydraulic Conductivity: Formation water saturated hydraulic conductivity (L/t)	K_w	ASTM D4043
Air-Water Viscosity Ratio: Viscosity ratio	μ_{ar}	Usually = 0.018
Air Discharge Rate: Air discharge rate from vacuum system (L^3/t)	Q_a	Airflow meter (normalized for all system downtime)
Vacuum Head: Head reduction in well induced by vacuum system (L)	s_a	Wellhead vacuum gauge Only required if using drawdown based equations Airflow based equations do not require this parameter
Gauged LNAPL thickness	b_n	Difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)
Formation thickness	b_{nf}	Interval that LNAPL flows over in the formation. For unconfined conditions, this is approximately equal to the gauged LNAPL thickness. Under confined and perched conditions, the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

TABLE A2.7 Water-Enhanced LNAPL Recovery Data

Measurement Parameter	Equation Symbol	Apparatus/Method
LNAPL-Only Discharge: Stabilized LNAPL recovery rate	Q_n	Flow meter and totalizer records
LNAPL-Water Density Ratio: Density ratio	ρ_r	ρ_{oil}/ρ_{water}
Groundwater Discharge: Groundwater system recovery rate	Q_w	Flow meter and totalizer records
Groundwater Transmissivity: Formation hydraulic conductivity multiplied by saturated thickness in well screen	T_w	ASTM D4043
Effective Radius / Borehole Radius: Dimensionless ratio of effective radius of formation influence to borehole (well) radius	$\ln(R_o/r_w)$	Estimated based on pilot test or calibration of equation to a set of known conditions Only required if using drawdown based equations Oil/water ratio based equation does not require this parameter
Groundwater Drawdown: Groundwater drawdown in recovery well	S_{water}	Estimated by gauging data or via Thiem equation (see Bouwer and Rice, 1976) **(11)** Drawdown will need to be converted into LNAPL head Only required if using drawdown based equations
Gauged LNAPL thickness	b_n	Difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)
Formation thickness	b_{nf}	Interval that LNAPL flows over in the formation. For unconfined conditions, this is approximately equal to the gauged LNAPL thickness. Under confined and perched conditions, the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

TABLE A2.8 Water- and Vacuum-Enhanced LNAPL Recovery Data

Measurement Parameter	Equation Symbol	Apparatus/Method
LNAPL-Only Discharge: Stabilized LNAPL recovery rate	Q_n	Flow meter and totalizer records (normalized for all system downtime)
LNAPL-Water Density Ratio: Density ratio	ρ_r	ρ_{oil}/ρ_{water}
Groundwater Discharge: Groundwater system recovery rate	Q_w	Flow meter and totalizer records (normalized for all system downtime)
Groundwater Transmissivity: Formation hydraulic conductivity multiplied by saturated thickness in well screen	T_w	ASTM D4043
Air-Water Viscosity Ratio: Viscosity ratio	μ_{ar}	Usually = 0.018
Hydraulic Conductivity: Formation water saturated hydraulic conductivity	K_w	ASTM D4043
Air-Phase Relative Permeability: Formation pneumatic permeability	k_{ra}	Generally assumed = 0.9
Air Discharge Rate: Air discharge rate from vacuum system (SCFM)	Q_a	Airflow meter
Open Screen Length: Screened interval above LNAPL level	b_a	
Well vacuum head Water head	s_{aw}	Wellhead vacuum gauge Only required if using vacuum head based equations Airflow based equations do not require this parameter
Pneumatic radius of influence Effective radius of influence of formation air pressure drop	$\ln(R_o/r_w)$	Estimated based on pilot test or calibration of equation to a set of known conditions Only required if using vacuum head based equations Airflow based equations do not require this parameter
Gauged LNAPL thickness	b_n	Difference between the gauged air/LNAPL interface and the water/LNAPL interface in a well. (L)
Formation thickness	b_{nf}	Interval that LNAPL flows over in the formation. For unconfined conditions, this is approximately equal to the gauged LNAPL thickness. Under confined and perched conditions, the gauged LNAPL thickness under equilibrium conditions is not equal to the formation thickness. (L)

TABLE A2.9 LNAPL Tracer Test

Measurement Parameter	Equation Symbol	Apparatus/Method
Equilibrium Fluid Interface Depth: Air-LNAPL interface depths	Z_{AN*}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
LNAPL-water interface depths	Z_{NW*}	Optical/electrical resistivity interface probe Second pressure transducer w/ LNAPL & water density correction
Fluid Density: LNAPL density	ρ_n	ASTM Test D1298, ASTM Test D1217 ASTM Test D1480, ASTM Test D1481 ASTM Test D4052, ASTM Test D5002
Groundwater density, specific gravity	ρ_w	ASTM Test D1429
Time: Elapsed test time	t	Timepiece measurable to 1 second
Initial Tracer Concentration	C_i	Measured via Spectrometer prior to test
Tracer Concentration after mixing	$C_{i+\Delta}$	Measured via Spectrometer prior to test
LNAPL Gradient	i_{LNAPL}	Measured via site gauging data
Flux Convergence Factor	α	Alpha is often assumed to be equal to a value of 1.7
Fluid Interface Elevation: Air-LNAPL interface elevation	Z_{AN}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
LNAPL-water interface	Z_{NW}	Optical/electrical resistivity interface probe Pressure transducer w/ LNAPL density correction
Soil profile across mobile LNAPL interval		Soil boring log from visual or other soil characterization tool (ASTM E2531)
Well Construction Data: Casing radius	r_c	Well Construction Log
Borehole radius	r_b	Well Construction Log
Screen Interval		Well Construction Log

APPENDIXES

(Nonmandatory Information)

X1. APPLICATION OF LNAPL TRANSMISSIVITY METHODS IN TIDALLY INFLUENCED ENVIRONMENTS

X1.1 *Introduction* —Special precautions needs to be taken when measuring LNAPL transmissivity using the methods discussed in this guide under tidal conditions.

X1.1.1 In tidally influenced environments, formation and in-well LNAPL thicknesses (and by extension formation saturations) continuously change with the tide.

X1.1.2 Hence both the variability in the instantaneous LNAPL transmissivity and the effective LNAPL transmissivity average over several tidal cycles may both be of importance.

X1.1.3 The tidal stress will confound the result of a LNAPL transmissivity test at least on the time scale of the tidal cycle or less.

X1.1.4 Adjustments have to be made to the data collection procedure or the timing of the test to account for this effect.

X1.1.5 In some instances, a particular method's utility may be limited due to the time scale for test completion relative to the tidal cycle.

X1.1.6 Also, even in cases where a method may be applicable, the normal accuracy of a test may be compromised under tidal conditions.

X1.1.7 However, useful transmissivity information can still be obtained to improve site understanding, to aid CSM development and guide decision making.

X1.1.8 The magnitude of tidal cycles varies over lunar cycles and should be accounted for in any field test design.

X1.2 *Scope*—The following appendix provides more specific comment for the LNAPL transmissivity methods as applied to tidally influenced environments.

X1.3 *Short-Term Aquifer Testing Methods*:

X1.3.1 These LNAPL transmissivity measurement methods (LNAPL baildown, slug, and manual LNAPL skimming test) are most affected by tides because of the instantaneous nature of the applied stress relative to the tidal cycles.

X1.3.2 In low LNAPL transmissivity formations where the time to recovery is long relative to the tidal cycle, the results of these short-term methods will be severely impacted by the tides and it is recommended that one the long-term test methods (that is, recovery data-based or tracer methods) or a modification of the recovery data-based method used to estimate an average LNAPL transmissivity for the tidal cycle.

X1.3.3 If the recovery period is short relative to the tidal cycle, the short-term test can be used as outlined below; however, the accuracy of the test will be lower than under non-tidal conditions.

X1.3.4 *LNAPL Baildown Test/Manual Skimming Test:*

X1.3.4.1 If the recovery period of these test are short relative to a tidal cycle (4 h), then these short-term test can be done as outlined in this document, however, the test will be less accurate.

X1.3.4.2 Also, it is recommended that these tests be done covering periods of high tides and low tide to provide a bound on the LNAPL transmissivity value at the tested location.

X1.3.4.3 Data from the pilot test can be analyzed by appropriate method proposed in this document to provide bounds on LNAPL transmissivity.

X1.3.4.4 If the recovery period is long relative to a tidal cycle and the discharge versus drawdown relationship identified in Section 6 cannot be met, then baildown and slug test methods cannot be employed and a long-term method should be employed.

X1.3.4.5 Additionally, if a manual skimming test is used and requires a longer time frame relative to a tidal cycle, the a long-term method should be employed.

X1.4 *Long-Term Aquifer Testing Methods*:

X1.4.1 *Considerations:*

X1.4.1.1 Because of the long-term nature of the applied stress for LNAPL for recovery data-based and tracer methods relative to the time scale of a tidal cycle, these methods can be used as outlined in the standard to estimate LNAPL transmissivity under tidal conditions.

X1.4.1.2 LNAPL recovery systems operate from months to years and the leaching process for tracer tests takes weeks to months.

X1.4.1.3 To determine the LNAPL transmissivity from a tracer test, an estimate of the LNAPL gradient is needed and the shifting gradient induced by the tides will have to be taken into account.

X1.4.1.4 To provide an estimate of the net gradient, a pressure transducer tidal study could be done over several tidal cycles.

X1.4.1.5 A tidal filtering algorithm should be applied to remove tidal effects, and the effective gradient estimated from the unfiltered data for methods relying on absolute drawdown values and/or gradients (that is, skimming and tracer testing).

X1.4.1.6 Data from the pilot test can be analyzed by appropriate method proposed in this document to provide LNAPL transmissivity estimates.

X1.4.1.7 The LNAPL transmissivity determined from these long term tests will averaged over the tidal cycles and effective over the capture/leaching zones of the LNAPL recovery system/tracer test for the time scales measured.

X1.5 *Short-Term Pilot Tests*—If an LNAPL recovery system is not in place or it's impractical to conduct a LNAPL tracer test, a modification of the recovery data-based method can be used; that is, a water enhanced pilot test can be done to provide estimates of LNAPL transmissivity.

X1.5.1 However, it is recommended that either a minimum of two of these tests be done (one covering each extreme of the tidal cycle) or the test be run continuously across a minimum of two tidal cycles.

X1.5.2 Ideally, the pilot test should be run over several tidal cycles.

X1.5.3 The LNAPL transmissivity in the formation may change over the test due to changes within the water level in the formation and mobile LNAPL saturation, however this test would be able to provide both a bound on the range in variability and an average value if designed to collect data at a frequency higher than the tidal cycles (that is, data collection every 1 to 2 h).

X1.5.4 If the data frequency is greater than tidal cycles then only an average value will be obtained.

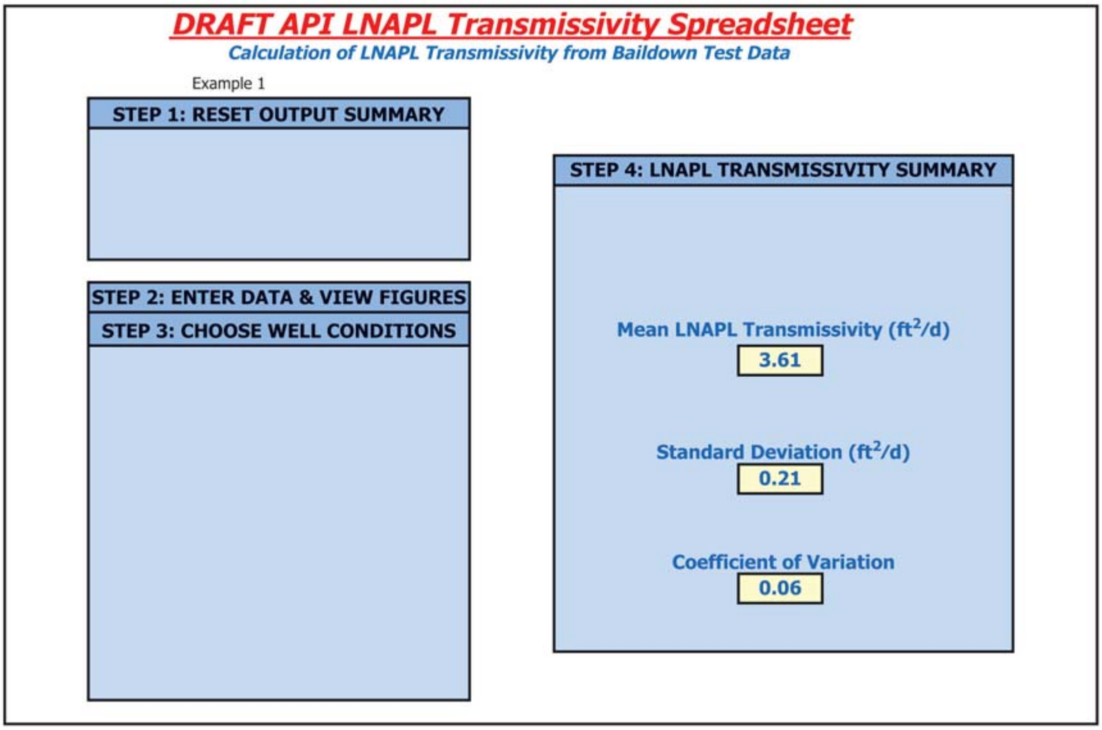
X1.5.5 Data from the short-term pilot test can be analyzed by the appropriate method proposed in this guide to provide bounds on the LNAPL transmissivity over the capture zone of the test at the time scale of the test.

X1.5.6 The resulting LNAPL transmissivity will be averaged over tidal cycles and effective over the capture zone and time scale of the test.

X1.5.7 Water-enhanced pilot tests are a reasonable method because the analysis relies on the oil/water ratio produced, LNAPL relative density and aquifer transmissivity; the variation in equilibrium fluid levels induced by tidal cycles will not affect the analysis.

X2. BAILDOWN TEST EXAMPLES

X2.1 Figs. X2.1-X2.23



DRAFT API LNAPL Transmissivity Spreadsheet

Calculation of LNAPL Transmissivity from Baildown Test Data

Example 1

STEP 1: RESET OUTPUT SUMMARY

STEP 2: ENTER DATA & VIEW FIGURES

STEP 3: CHOOSE WELL CONDITIONS

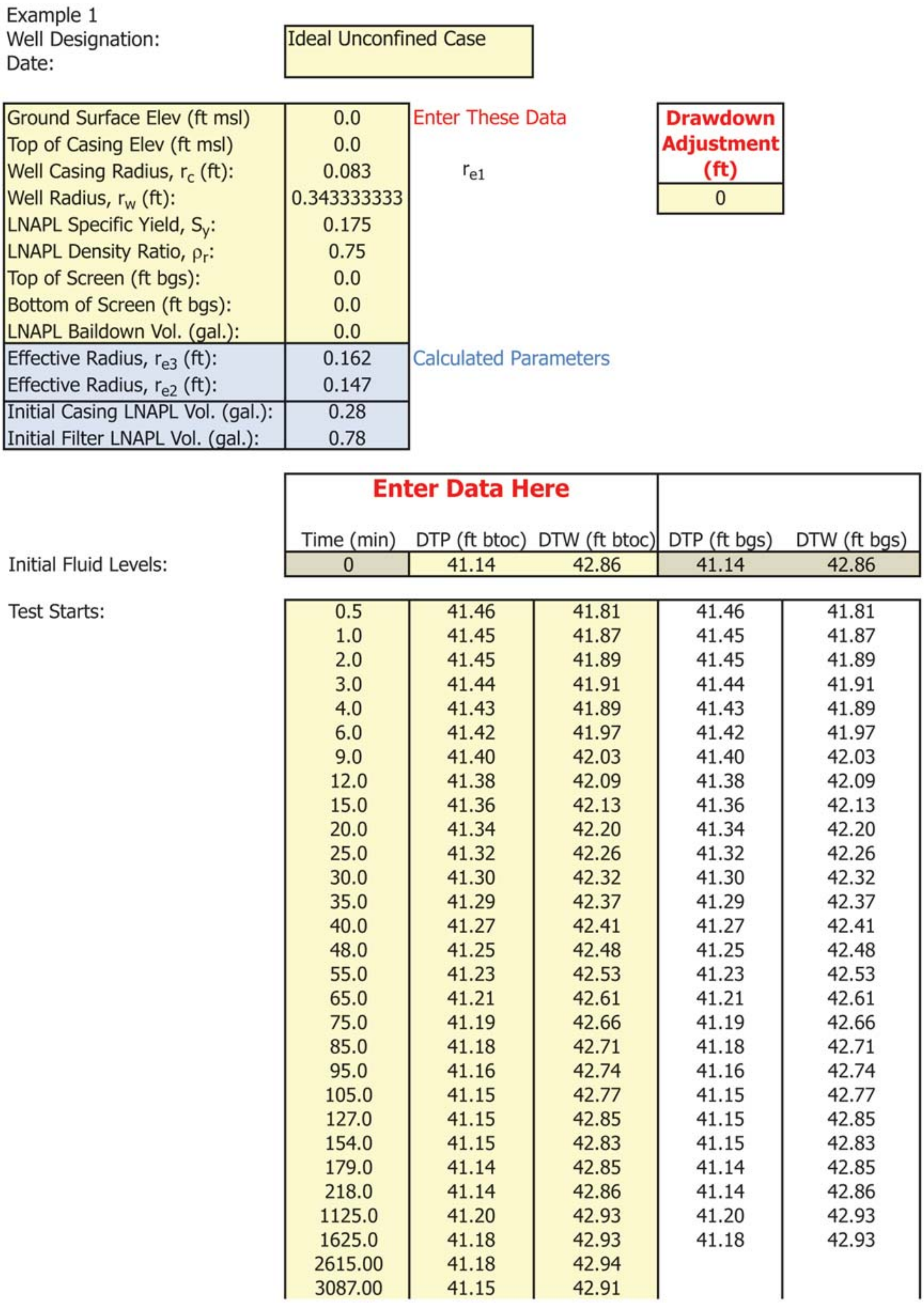
STEP 4: LNAPL TRANSMISSIVITY SUMMARY

Mean LNAPL Transmissivity (ft^2/d): 3.61

Standard Deviation (ft^2/d): 0.21

Coefficient of Variation: 0.06

FIG. X2.1 Results Page—Constant Potentiometric Surface



Example 1
Well Designation: Ideal Unconfined Case
Date:

Ground Surface Elev (ft msl)	0.0	Enter These Data
Top of Casing Elev (ft msl)	0.0	
Well Casing Radius, r_c (ft):	0.083	r_{e1}
Well Radius, r_w (ft):	0.343333333	
LNAPL Specific Yield, S_y:	0.175	
LNAPL Density Ratio, ρ_r:	0.75	
Top of Screen (ft bgs):	0.0	
Bottom of Screen (ft bgs):	0.0	
LNAPL Baildown Vol. (gal.):	0.0	
Effective Radius, r_{e3} (ft):	0.162	Calculated Parameters
Effective Radius, r_{e2} (ft):	0.147	
Initial Casing LNAPL Vol. (gal.):	0.28	
Initial Filter LNAPL Vol. (gal.):	0.78	

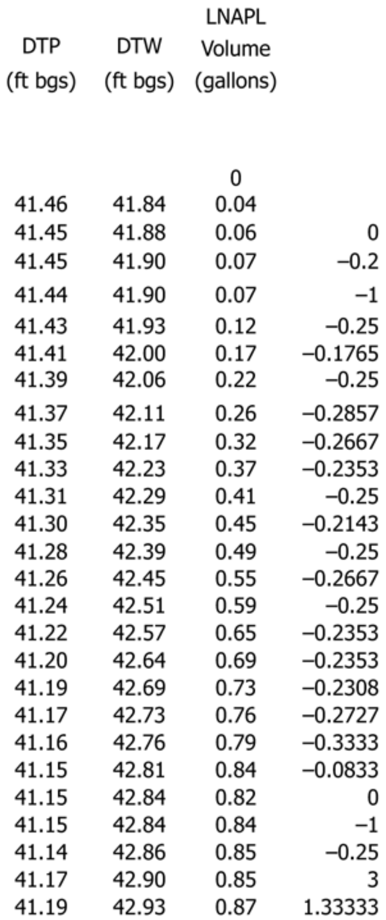
Drawdown Adjustment (ft)
0

	Enter Data Here				
	Time (min)	DTP (ft btoc)	DTW (ft btoc)	DTP (ft bgs)	DTW (ft bgs)
Initial Fluid Levels:	0	41.14	42.86	41.14	42.86
Test Starts:	0.5	41.46	41.81	41.46	41.81
	1.0	41.45	41.87	41.45	41.87
	2.0	41.45	41.89	41.45	41.89
	3.0	41.44	41.91	41.44	41.91
	4.0	41.43	41.89	41.43	41.89
	6.0	41.42	41.97	41.42	41.97
	9.0	41.40	42.03	41.40	42.03
	12.0	41.38	42.09	41.38	42.09
	15.0	41.36	42.13	41.36	42.13
	20.0	41.34	42.20	41.34	42.20
	25.0	41.32	42.26	41.32	42.26
	30.0	41.30	42.32	41.30	42.32
	35.0	41.29	42.37	41.29	42.37
	40.0	41.27	42.41	41.27	42.41
	48.0	41.25	42.48	41.25	42.48
	55.0	41.23	42.53	41.23	42.53
	65.0	41.21	42.61	41.21	42.61
	75.0	41.19	42.66	41.19	42.66
	85.0	41.18	42.71	41.18	42.71
	95.0	41.16	42.74	41.16	42.74
	105.0	41.15	42.77	41.15	42.77
	127.0	41.15	42.85	41.15	42.85
	154.0	41.15	42.83	41.15	42.83
	179.0	41.14	42.85	41.14	42.85
	218.0	41.14	42.86	41.14	42.86
	1125.0	41.20	42.93	41.20	42.93
	1625.0	41.18	42.93	41.18	42.93
	2615.00	41.18	42.94		
	3087.00	41.15	42.91		

FIG. X2.2 Data Page 1—Constant Potentiometric Surface

Water Table Depth (ft)	LNAPL Drawdown s_n (ft)	Index	Average Time (min)	LNAPL Discharge Q_n (ft^3/d)	s_n (ft)	b_n (ft)	r_e (ft)
41.57	0.43					1.72	
41.55	0.32	1.0					
41.56	0.31	2.0	0.7	16.694	0.32	0.42	0.162
41.56	0.31	3.0	1.5	2.385	0.31	0.44	0.162
41.56	0.30	4.0	2.5	3.577	0.31	0.47	0.162
41.55	0.29	5.0	3.5	−1.192	0.29	0.46	0.162
41.56	0.28	6.0	5.0	5.366	0.29	0.55	0.162
41.56	0.26	7.0	7.5	3.180	0.27	0.63	0.162
41.56	0.24	8.0	10.5	3.180	0.25	0.71	0.162
41.55	0.22	9.0	13.5	2.385	0.23	0.77	0.162
41.56	0.20	10.0	17.5	2.146	0.21	0.86	0.162
41.56	0.18	11.0	22.5	1.908	0.19	0.94	0.162
41.56	0.16	12.0	27.5	1.908	0.17	1.02	0.162
41.56	0.15	13.0	32.5	1.431	0.15	1.08	0.162
41.56	0.13	14.0	37.5	1.431	0.14	1.14	0.162
41.56	0.11	15.0	44.0	1.341	0.12	1.23	0.162
41.56	0.09	16.0	51.5	1.192	0.10	1.30	0.162
41.56	0.07	17.0	60.0	1.192	0.08	1.40	0.162
41.56	0.05	18.0	70.0	0.835	0.06	1.47	0.162
41.56	0.04	19.0	80.0	0.715	0.04	1.53	0.162
41.56	0.02	20.0	90.0	0.596	0.03	1.58	0.162
41.56	0.01	21.0	100.0	0.477	0.01	1.62	0.162
41.58	0.01	22.0	116.0	0.434	0.01	1.70	0.162
41.57	0.01	23.0	140.5	−0.088	0.01	1.68	0.162
41.57	0.00	24.0	166.5	0.143	0.00	1.71	0.162
41.57	0.00	25.0	198.5	0.031	0.00	1.72	0.162
41.63	0.06	26.0	671.5	0.001	0.03	1.73	0.162
41.62	0.04	27.0	1375.0	0.005	0.05	1.75	0.162

FIG. X2.3 Data Page 2—Constant Potentiometric Surface



DTP (ft bgs)	DTW (ft bgs)	LNAPL Volume (gallons)	
		0	
41.46	41.84	0.04	
41.45	41.88	0.06	0
41.45	41.90	0.07	–0.2
41.44	41.90	0.07	–1
41.43	41.93	0.12	–0.25
41.41	42.00	0.17	–0.1765
41.39	42.06	0.22	–0.25
41.37	42.11	0.26	–0.2857
41.35	42.17	0.32	–0.2667
41.33	42.23	0.37	–0.2353
41.31	42.29	0.41	–0.25
41.30	42.35	0.45	–0.2143
41.28	42.39	0.49	–0.25
41.26	42.45	0.55	–0.2667
41.24	42.51	0.59	–0.25
41.22	42.57	0.65	–0.2353
41.20	42.64	0.69	–0.2353
41.19	42.69	0.73	–0.2308
41.17	42.73	0.76	–0.2727
41.16	42.76	0.79	–0.3333
41.15	42.81	0.84	–0.0833
41.15	42.84	0.82	0
41.15	42.84	0.84	–1
41.14	42.86	0.85	–0.25
41.17	42.90	0.85	3
41.19	42.93	0.87	1.33333

FIG. X2.4 Data Page 3—Constant Potentiometric Surface

Example 1

Q_n (ft^3/d)	S_n (ft)
0	0
4	0.3

t (min)	S_n (ft)
0	0.3
100	0

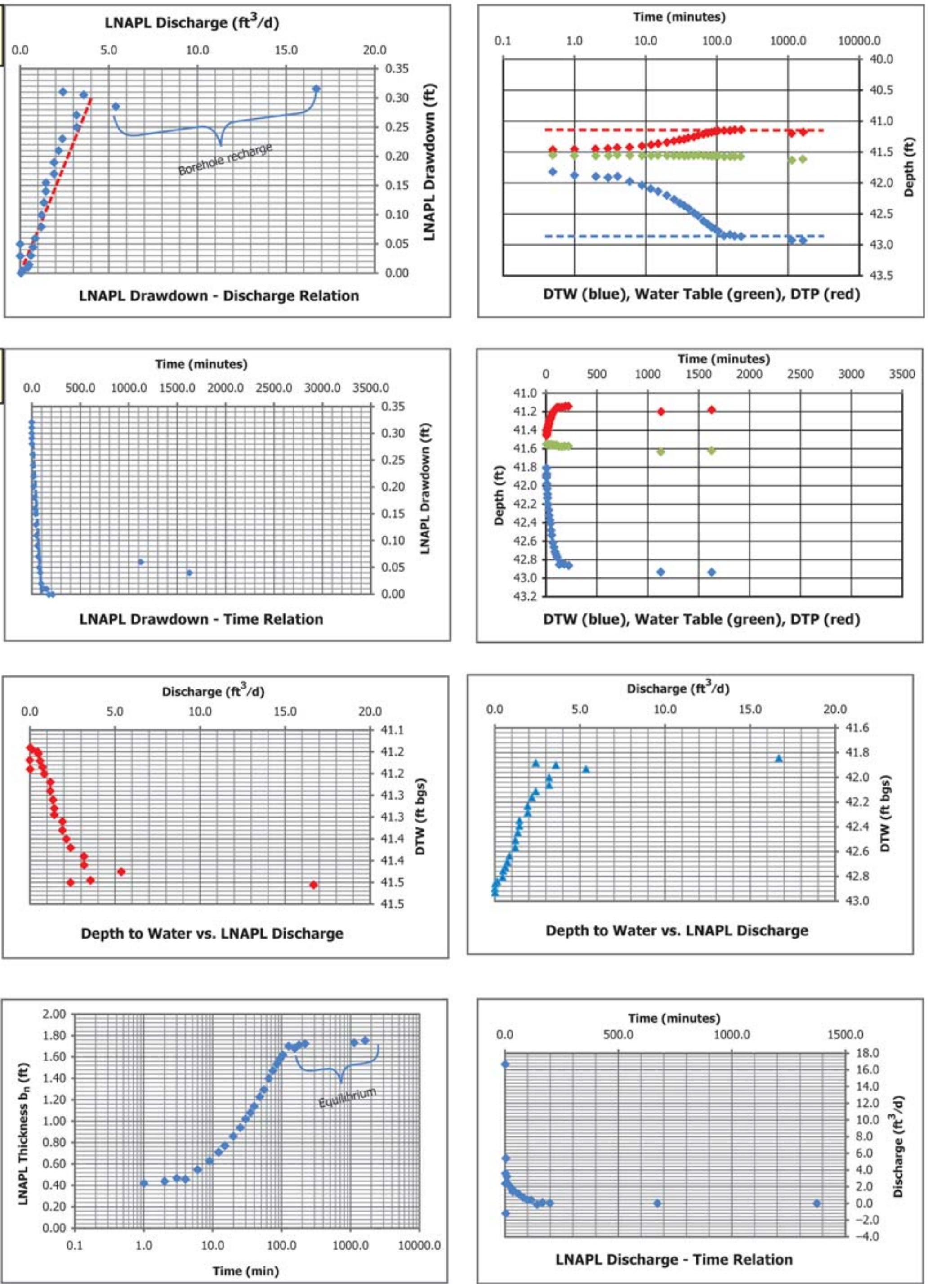


FIG. X2.5 Figures Page 1—Constant Potentiometric Surface

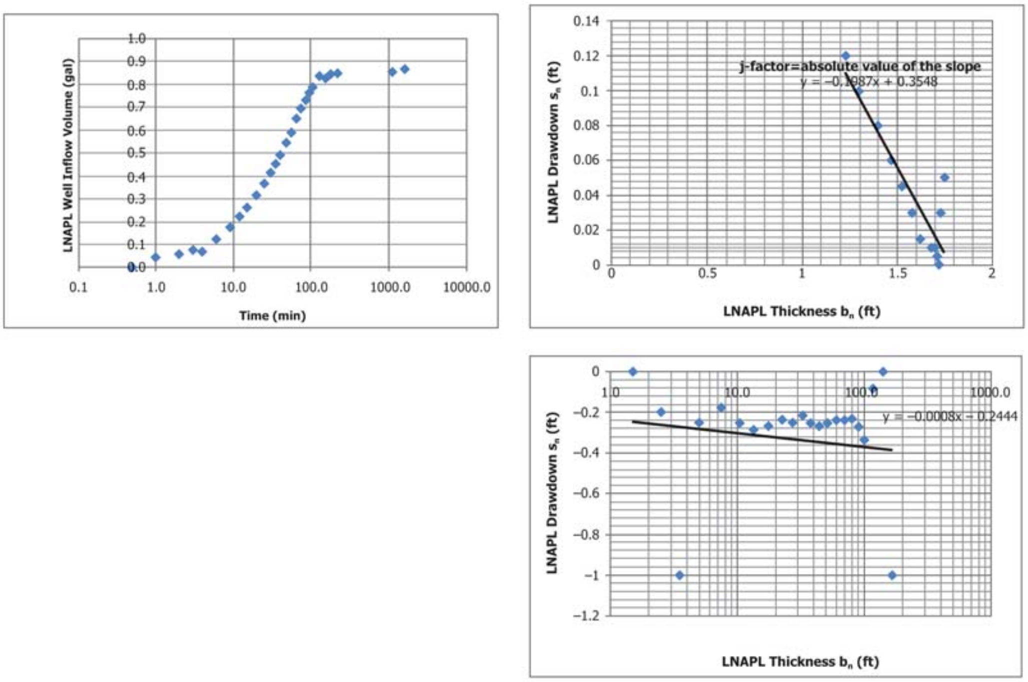
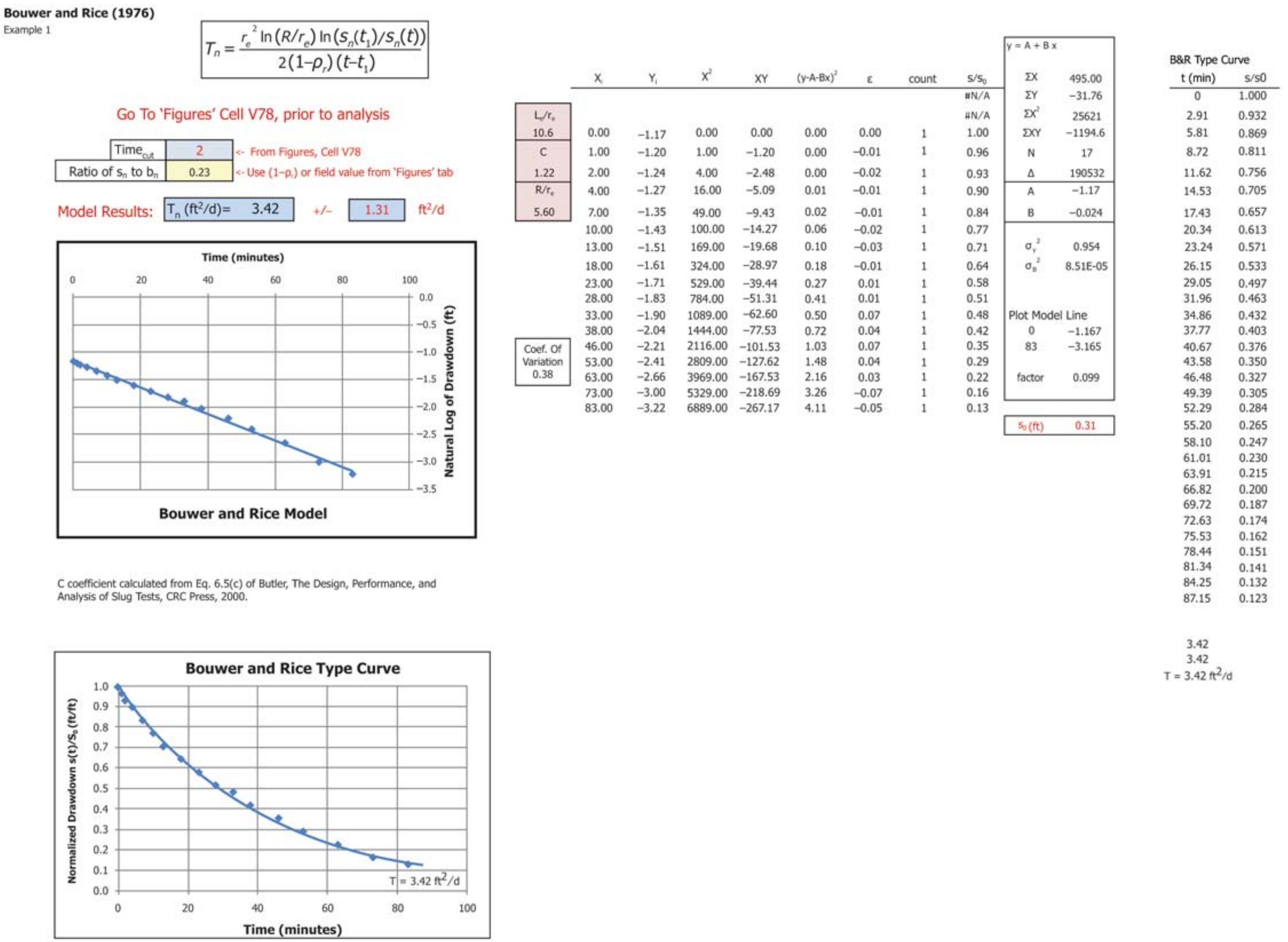


FIG. X2.5 Figures Page 2—Constant Potentiometric Surface *(continued)*



Bouwer and Rice (1976)

Example 1

$$T_n = \frac{r_e^{\,2}\ln(R/r_e)\ln(s_n(t_1)/s_n(t))}{2(1-\rho_r)(t-t_1)}$$

Go To 'Figures' Cell V78, prior to analysis

Time_{cut}	2	<- From Figures, Cell V78
Ratio of s_n to b_n	0.23	<- Use $(1-\rho_r)$ or field value from 'Figures' tab

Model Results: T_n (ft²/d)= 3.42 +/− 1.31 ft²/d

L_e/r_e
10.6
C
1.22
R/r_e
5.60

Coef. Of Variation 0.38

X_i	Y_i	X^2	XY	$(y\text{-}A\text{-}Bx)^2$	ε	count	s/s_0
							#N/A
							#N/A
0.00	−1.17	0.00	0.00	0.00	0.00	1	1.00
1.00	−1.20	1.00	−1.20	0.00	−0.01	1	0.96
2.00	−1.24	4.00	−2.48	0.00	−0.02	1	0.93
4.00	−1.27	16.00	−5.09	0.01	−0.01	1	0.90
7.00	−1.35	49.00	−9.43	0.02	−0.01	1	0.84
10.00	−1.43	100.00	−14.27	0.06	−0.02	1	0.77
13.00	−1.51	169.00	−19.68	0.10	−0.03	1	0.71
18.00	−1.61	324.00	−28.97	0.18	−0.01	1	0.64
23.00	−1.71	529.00	−39.44	0.27	0.01	1	0.58
28.00	−1.83	784.00	−51.31	0.41	0.01	1	0.51
33.00	−1.90	1089.00	−62.60	0.50	0.07	1	0.48
38.00	−2.04	1444.00	−77.53	0.72	0.04	1	0.42
46.00	−2.21	2116.00	−101.53	1.03	0.07	1	0.35
53.00	−2.41	2809.00	−127.62	1.48	0.04	1	0.29
63.00	−2.66	3969.00	−167.53	2.16	0.03	1	0.22
73.00	−3.00	5329.00	−218.69	3.26	−0.07	1	0.16
83.00	−3.22	6889.00	−267.17	4.11	−0.05	1	0.13

y = A + B x

ΣX	495.00
ΣY	−31.76
ΣX^2	25621
ΣXY	−1194.6
N	17
Δ	190532
A	−1.17
B	−0.024
$\sigma_y^{\,2}$	0.954
$\sigma_B^{\,2}$	8.51E-05
Plot Model Line	
0	−1.167
83	−3.165
factor	0.099

s_0 (ft) 0.31

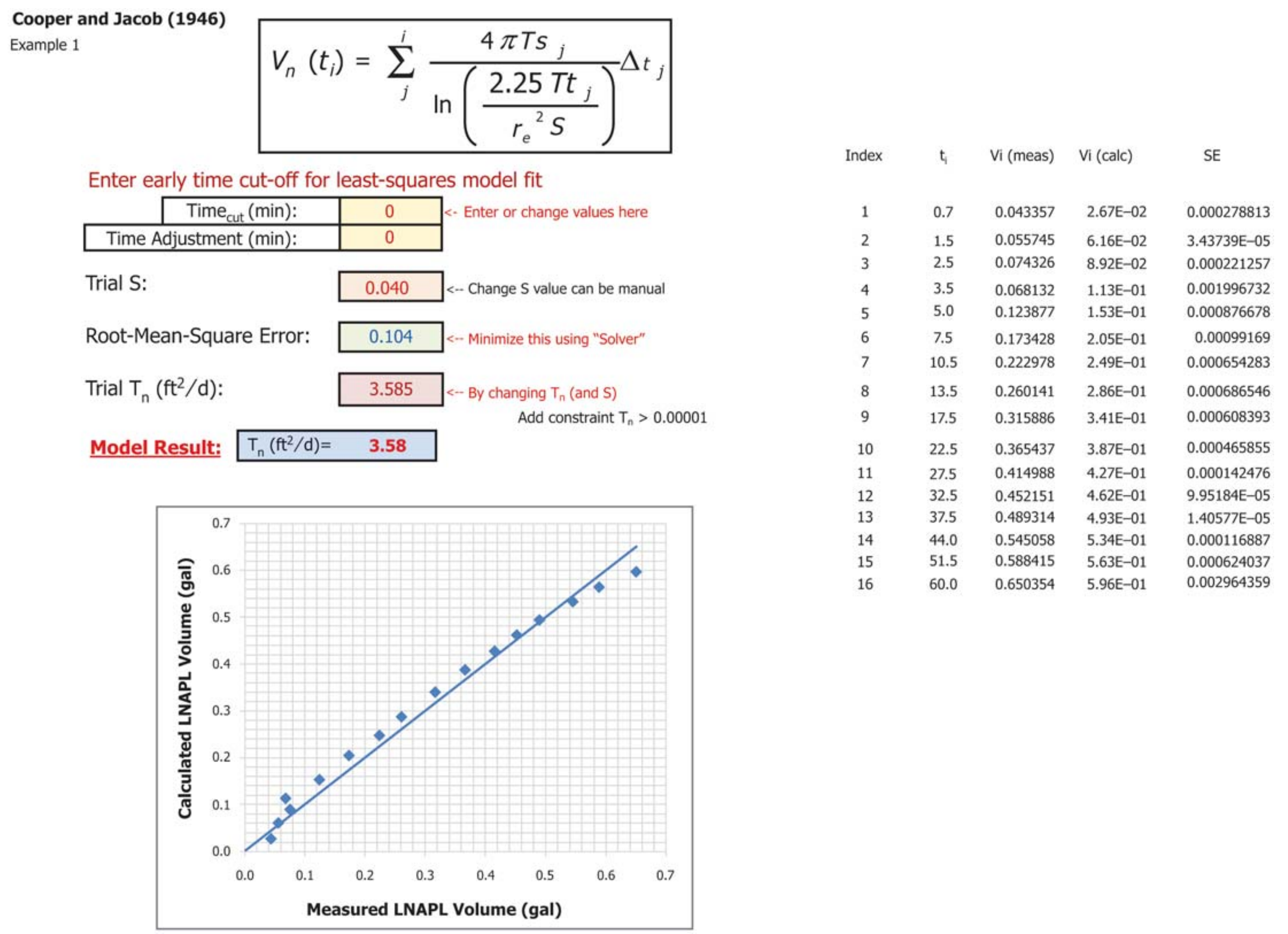
B&R Type Curve

t (min)	s/s0
0	1.000
2.91	0.932
5.81	0.869
8.72	0.811
11.62	0.756
14.53	0.705
17.43	0.657
20.34	0.613
23.24	0.571
26.15	0.533
29.05	0.497
31.96	0.463
34.86	0.432
37.77	0.403
40.67	0.376
43.58	0.350
46.48	0.327
49.39	0.305
52.29	0.284
55.20	0.265
58.10	0.247
61.01	0.230
63.91	0.215
66.82	0.200
69.72	0.187
72.63	0.174
75.53	0.162
78.44	0.151
81.34	0.141
84.25	0.132
87.15	0.123

3.42
3.42
T = 3.42 ft²/d

C coefficient calculated from Eq. 6.5(c) of Butler, The Design, Performance, and Analysis of Slug Tests, CRC Press, 2000.

FIG. X2.6 Bouwer-Rice Worksheet—Constant Potentiometric Surface



Cooper and Jacob (1946)
Example 1

$$V_n\ (t_i) = \sum_{j}^{i} \frac{4\pi T s_j}{\ln\left(\dfrac{2.25\, T t_j}{r_e^{\,2} S}\right)} \Delta t_j$$

Enter early time cut-off for least-squares model fit

Time$_{cut}$ (min):	0	<-- Enter or change values here
Time Adjustment (min):	0	
Trial S:	0.040	<-- Change S value can be manual
Root-Mean-Square Error:	0.104	<-- Minimize this using "Solver"
Trial T_n (ft^2/d):	3.585	<-- By changing T_n (and S) Add constraint T_n > 0.00001

Model Result: T_n (ft^2/d)= **3.58**

Index	t_i	Vi (meas)	Vi (calc)	SE
1	0.7	0.043357	2.67E−02	0.000278813
2	1.5	0.055745	6.16E−02	3.43739E−05
3	2.5	0.074326	8.92E−02	0.000221257
4	3.5	0.068132	1.13E−01	0.001996732
5	5.0	0.123877	1.53E−01	0.000876678
6	7.5	0.173428	2.05E−01	0.00099169
7	10.5	0.222978	2.49E−01	0.000654283
8	13.5	0.260141	2.86E−01	0.000686546
9	17.5	0.315886	3.41E−01	0.000608393
10	22.5	0.365437	3.87E−01	0.000465855
11	27.5	0.414988	4.27E−01	0.000142476
12	32.5	0.452151	4.62E−01	9.95184E−05
13	37.5	0.489314	4.93E−01	1.40577E−05
14	44.0	0.545058	5.34E−01	0.000116887
15	51.5	0.588415	5.63E−01	0.000624037
16	60.0	0.650354	5.96E−01	0.002964359

FIG. X2.7 Cooper and Jacob Worksheet—Constant Potentiometric Surface

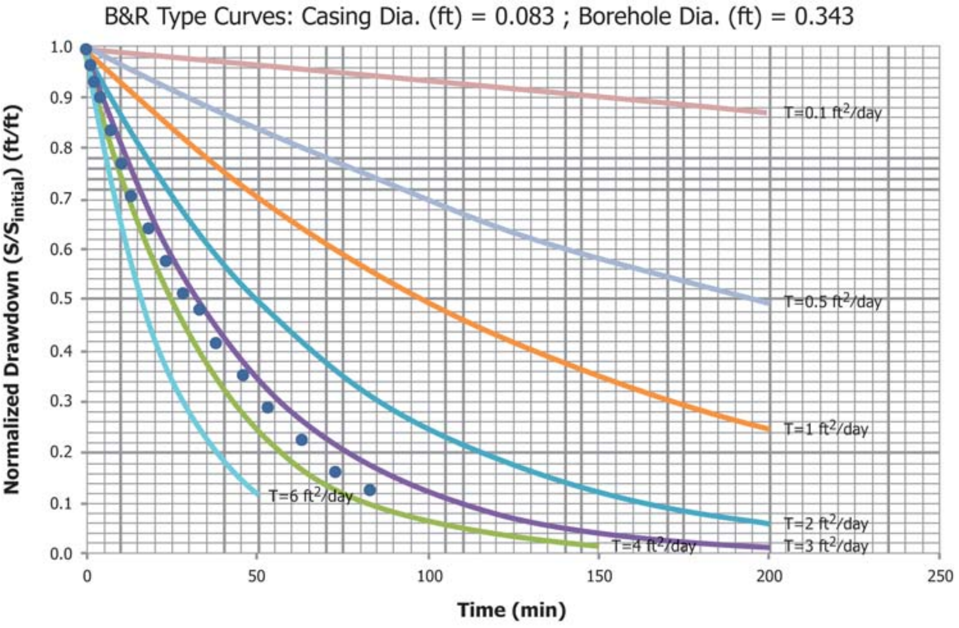
Bouwer and Rice Short Term LNAPL Mobility Test Type Curves

B&R Type Curves: Casing Dia. (ft) = 0.083; Borehole Dia. (ft) = 0.343

Example 1

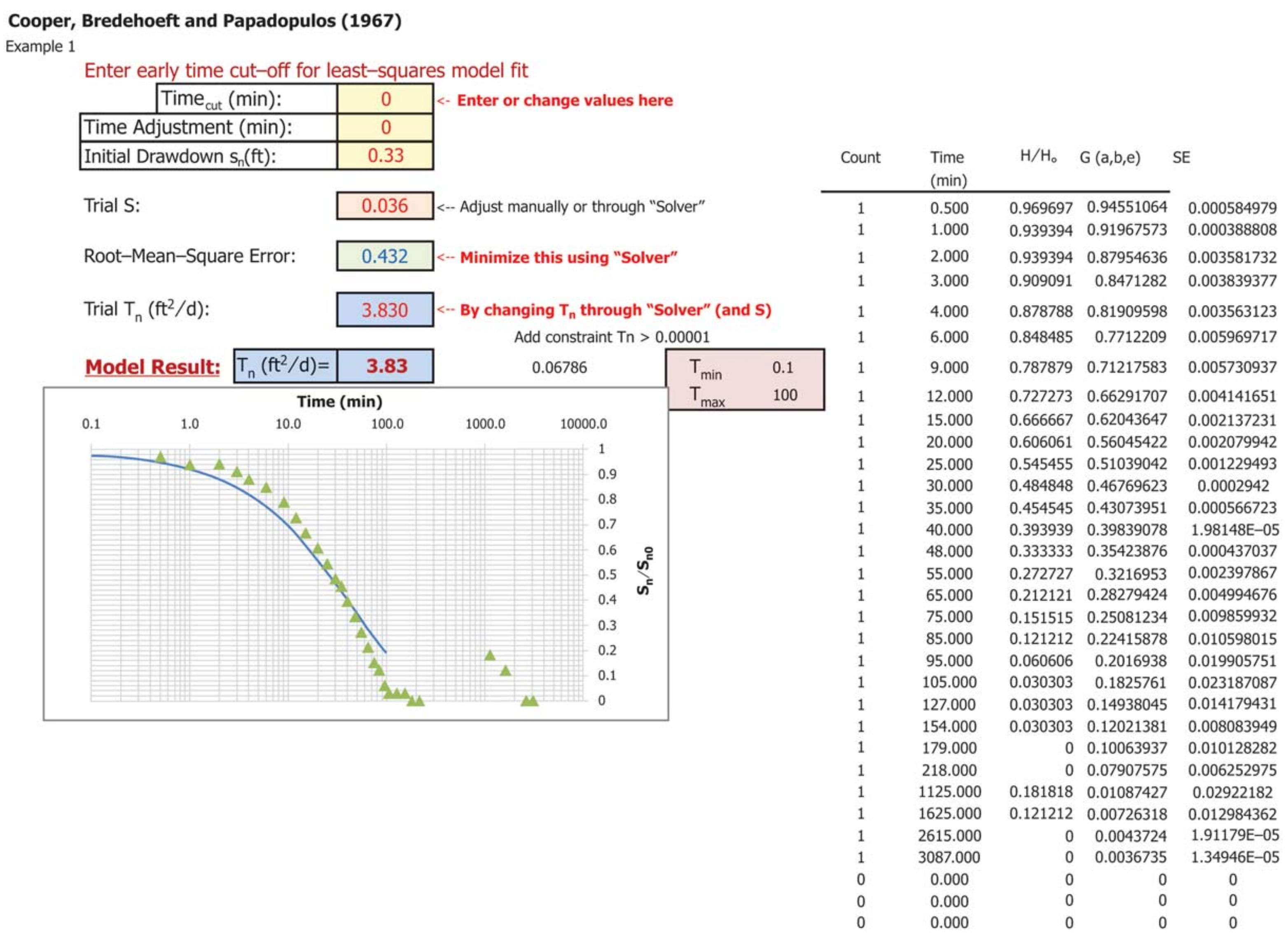
Enter these values

Type Curve ID	Type Curve Name	Notes	Max Time (min)	Transmissivity (ft^2/day)
1	T=6 ft^2/day		50	6
2	T=4 ft^2/day		150	4
3	T=3 ft^2/day		200	3
4	T=2 ft^2/day		200	2
5	T=1 ft^2/day		200	1
6	T=0.5 ft^2/day		200	0.5
7	T=0.1 ft^2/day		200	0.1



Field Data								
Record Data in Fields Below						Calculate and Plot Fields Below		
Well ID		Well Dia. (ft)		Total Depth (ft)				
Notes	Date	Time	Elapsed Time (min)	Depth To Product (TOC)	Depth To Water (TOC)	Product Thickness (ft)	Drawdown(s) DTP-DTP-(initial) (ft)	Normalized Drawdown ($S/S_{initial}$)
Intial Measurment								
Stopped Boiling/Start Gauging			0					
Well Starts recovering								

FIG. X2.8 Bouwer-Rice Type Curve Worksheet—Constant Potentiometric Surface



Cooper, Bredehoeft and Papadopulos (1967)

Example 1

Enter early time cut–off for least–squares model fit

Time_{cut} (min):	0	<- **Enter or change values here**
Time Adjustment (min):	0	
Initial Drawdown s_n(ft):	0.33	

Trial S: 0.036 <-- Adjust manually or through "Solver"

Root–Mean–Square Error: 0.432 <-- **Minimize this using "Solver"**

Trial T_n (ft^2/d): 3.830 <-- **By changing T_n through "Solver" (and S)**

Add constraint Tn > 0.00001

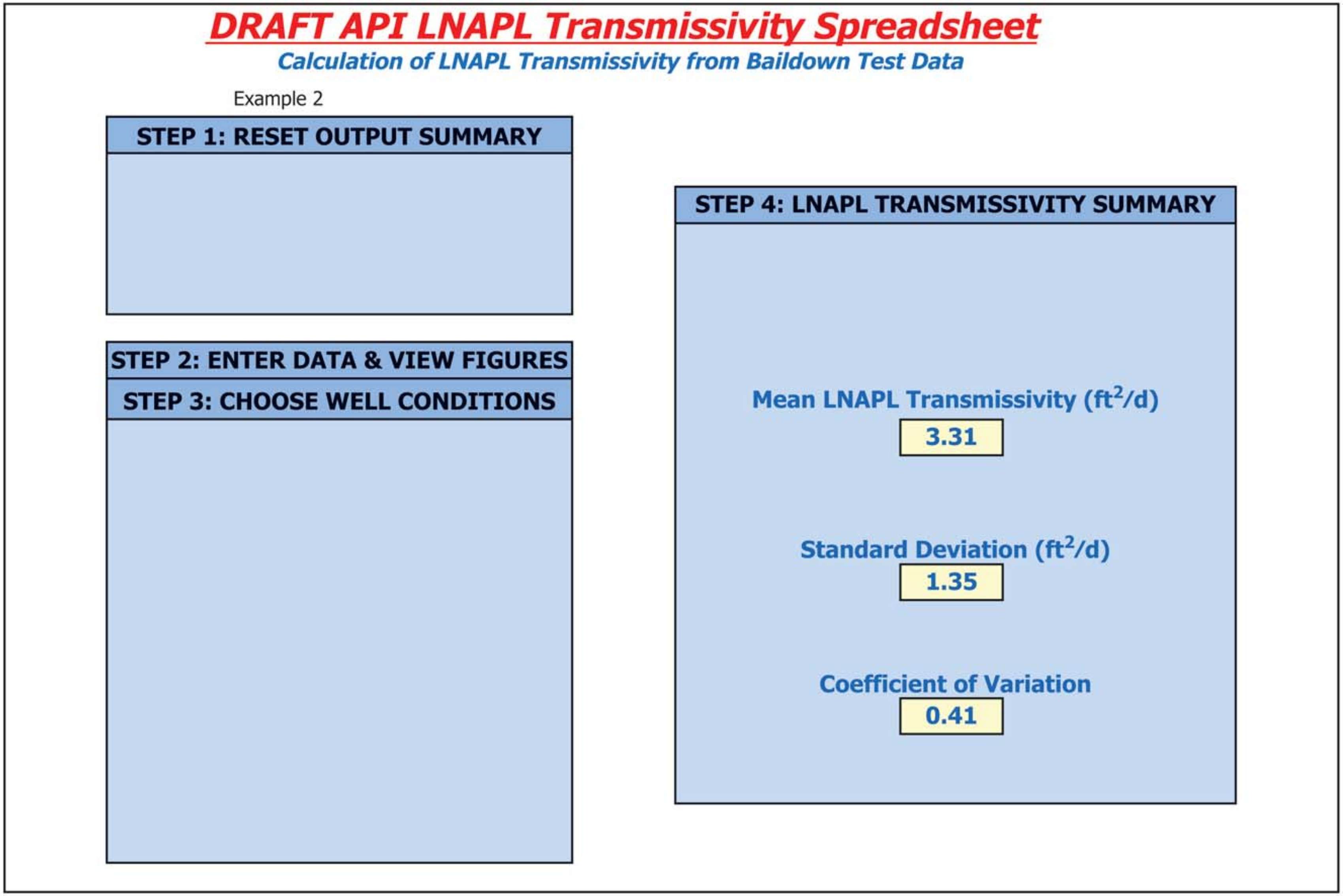
Model Result: T_n (ft^2/d)= **3.83**

0.06786

T_{min}	0.1
T_{max}	100

Count	Time (min)	H/H₀	G (a,b,e)	SE
1	0.500	0.969697	0.94551064	0.000584979
1	1.000	0.939394	0.91967573	0.000388808
1	2.000	0.939394	0.87954636	0.003581732
1	3.000	0.909091	0.8471282	0.003839377
1	4.000	0.878788	0.81909598	0.003563123
1	6.000	0.848485	0.7712209	0.005969717
1	9.000	0.787879	0.71217583	0.005730937
1	12.000	0.727273	0.66291707	0.004141651
1	15.000	0.666667	0.62043647	0.002137231
1	20.000	0.606061	0.56045422	0.002079942
1	25.000	0.545455	0.51039042	0.001229493
1	30.000	0.484848	0.46769623	0.0002942
1	35.000	0.454545	0.43073951	0.000566723
1	40.000	0.393939	0.39839078	1.98148E–05
1	48.000	0.333333	0.35423876	0.000437037
1	55.000	0.272727	0.3216953	0.002397867
1	65.000	0.212121	0.28279424	0.004994676
1	75.000	0.151515	0.25081234	0.009859932
1	85.000	0.121212	0.22415878	0.010598015
1	95.000	0.060606	0.2016938	0.019905751
1	105.000	0.030303	0.1825761	0.023187087
1	127.000	0.030303	0.14938045	0.014179431
1	154.000	0.030303	0.12021381	0.008083949
1	179.000	0	0.10063937	0.010128282
1	218.000	0	0.07907575	0.006252975
1	1125.000	0.181818	0.01087427	0.02922182
1	1625.000	0.121212	0.00726318	0.012984362
1	2615.000	0	0.0043724	1.91179E–05
1	3087.000	0	0.0036735	1.34946E–05
0	0.000	0	0	0
0	0.000	0	0	0
0	0.000	0	0	0

FIG. X2.9 Cooper, Bredehoeft and Papadopulos Worksheet—Constant Potentiometric Surface



DRAFT API LNAPL Transmissivity Spreadsheet

Calculation of LNAPL Transmissivity from Baildown Test Data

Example 2

Mean LNAPL Transmissivity (ft^2/d): 3.31

Standard Deviation (ft^2/d): 1.35

Coefficient of Variation: 0.41

FIG. X2.10 Results Page—Constant LNAPL/water Interface

Example 2
Well Designation: Relatively constant O-W interface
Date:

Ground Surface Elev (ft msl)	20.1	Enter These Data
Top of Casing Elev (ft msl)	20.1	
Well Casing Radius, r_c (ft):	0.167	r_{e1}
Well Radius, r_w (ft):	0.5000	
LNAPL Specific Yield, S_y:	0.105	
LNAPL Density Ratio, ρ_r:	0.87	
Top of Screen (ft bgs):	8.0	
Bottom of Screen (ft bgs):	28.0	
LNAPL Baildown Vol. (gal.):	8.0	
Effective Radius, r_{e3} (ft):	0.226	Calculated Parameters
Effective Radius, r_{e2} (ft):	0.219	
Initial Casing LNAPL Vol. (gal.):	4.76	
Initial Filter LNAPL Vol. (gal.):	4.00	

Drawdown Adjustment (ft)
0

	Enter Data Here					Water Table Depth (ft)	LNAPL Drawdown s_n (ft)	Index	Average Time (min)	LNAPL Discharge Q_n (ft^3/d)	s_n (ft)	b_n (ft)	r_e (ft)
	Time (min)	DTP (ft btoc)	DTW (ft btoc)	DTP (ft bgs)	DTW (ft bgs)								
Initial Fluid Levels:	0	19.85	27.14	19.85	27.14	20.80	0.95					7.29	
Test Starts:	1.0	26.45	27.27	26.45	27.27	26.56	6.60	1.0					
	3.0	25.73	27.21	25.73	27.21	25.92	5.88	2.0	2.0	76.303	6.24	1.48	0.226
	5.0	25.25	27.18	25.25	27.18	25.50	5.40	3.0	4.0	52.025	5.64	1.93	0.226
	7.0	24.80	27.12	24.80	27.12	25.10	4.95	4.0	6.0	45.088	5.18	2.32	0.226
	9.0	24.30	27.08	24.30	27.08	24.66	4.45	5.0	8.0	53.181	4.70	2.78	0.226
	11.0	23.91	27.04	23.91	27.04	24.32	4.06	6.0	10.0	40.464	4.26	3.13	0.226
	15.0	23.15	26.95	23.15	26.95	23.64	3.30	7.0	13.0	38.730	3.68	3.80	0.226
	20.0	22.40	26.88	22.40	26.88	22.98	2.55	8.0	17.5	31.446	2.93	4.48	0.226
	25.0	21.85	26.82	21.85	26.82	22.50	2.00	9.0	22.5	22.660	2.28	4.97	0.226
	30.0	21.42	26.80	21.42	26.80	22.12	1.57	10.0	27.5	18.960	1.79	5.38	0.226
	36.0	21.08	26.77	21.08	26.77	21.82	1.23	11.0	33.0	11.946	1.40	5.69	0.226
	40.0	20.90	26.78	20.90	26.78	21.66	1.05	12.0	38.0	10.983	1.14	5.88	0.226
	44.0	20.78	26.77	20.78	26.77	21.56	0.93	13.0	42.0	6.359	0.99	5.99	0.226
	50.0	20.61	26.75	20.61	26.75	21.41	0.76	14.0	47.0	5.781	0.85	6.14	0.226
	55.0	20.54	26.76	20.54	26.76	21.35	0.69	15.0	52.5	3.700	0.73	6.22	0.226
	60.0	20.47	26.75	20.47	26.75	21.29	0.62	16.0	57.5	2.775	0.66	6.28	0.226
	70.0	20.34	26.76	20.34	26.76	21.17	0.49	17.0	65.0	3.237	0.56	6.42	0.226
	80.0	20.28	26.76	20.28	26.76	21.12	0.43	18.0	75.0	1.387	0.46	6.48	0.226
	90.0	20.22	26.77	20.22	26.77	21.07	0.37	19.0	85.0	1.619	0.40	6.55	0.226
	100.0	20.20	26.76	20.20	26.76	21.05	0.35	20.0	95.0	0.231	0.36	6.56	0.226
	110.0	20.17	26.81	20.17	26.81	21.03	0.32	21.0	105.0	1.850	0.34	6.64	0.226
	120.0	20.14	26.82	20.14	26.82	21.01	0.29	22.0	115.0	0.925	0.31	6.68	0.226
	150.0	20.08	26.88	20.08	26.88	20.96	0.23	23.0	135.0	0.925	0.26	6.80	0.226
	180.0	20.03	26.91	20.03	26.91	20.92	0.18	24.0	165.0	0.617	0.21	6.88	0.226
	240.0	19.96	27.00	19.96	27.00	20.88	0.11	25.0	210.0	0.617	0.15	7.04	0.226
	300.0	19.91	27.06	19.91	27.06	20.84	0.06	26.0	270.0	0.424	0.09	7.15	0.226

FIG. X2.11 Data Page—Constant LNAPL/water Interface

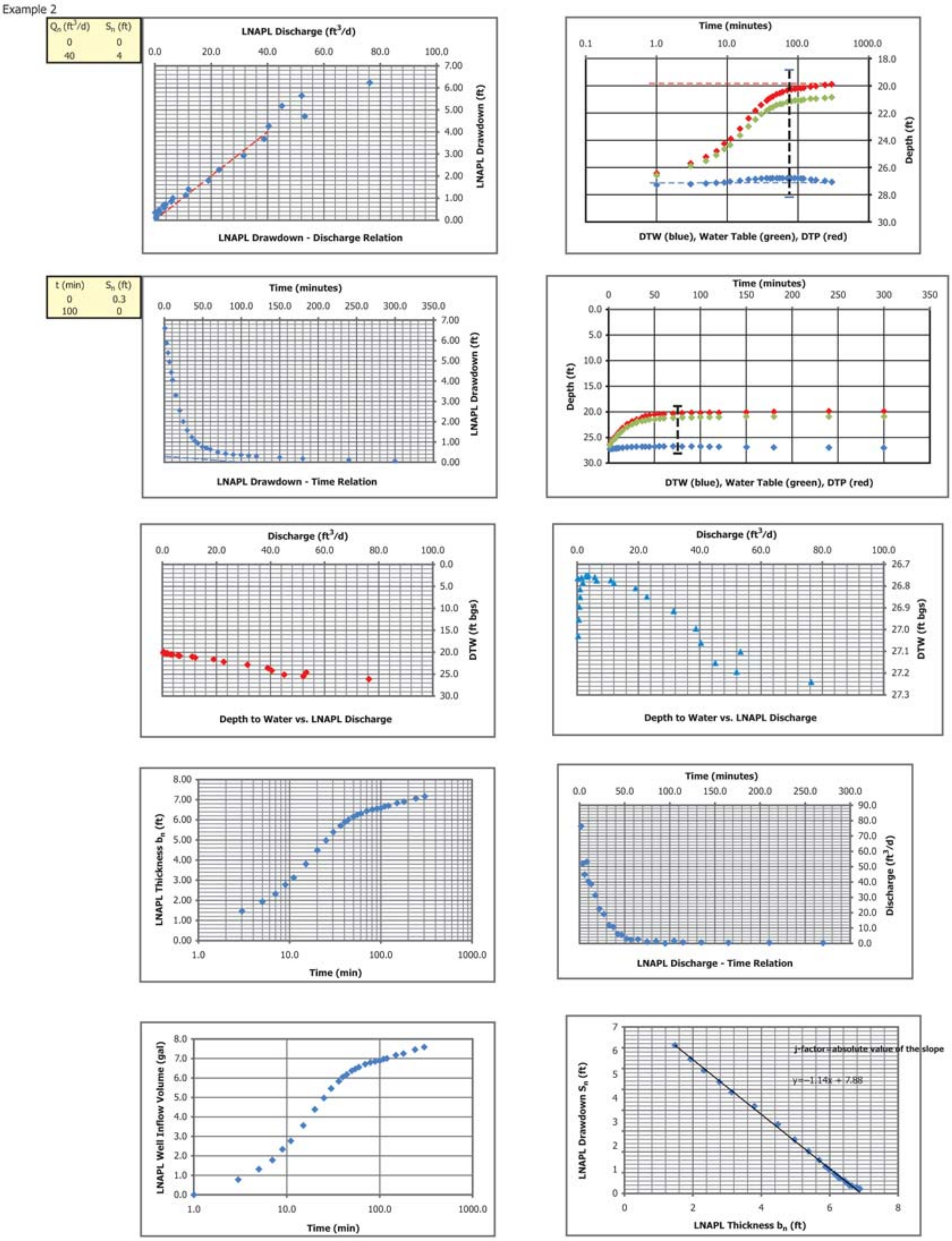
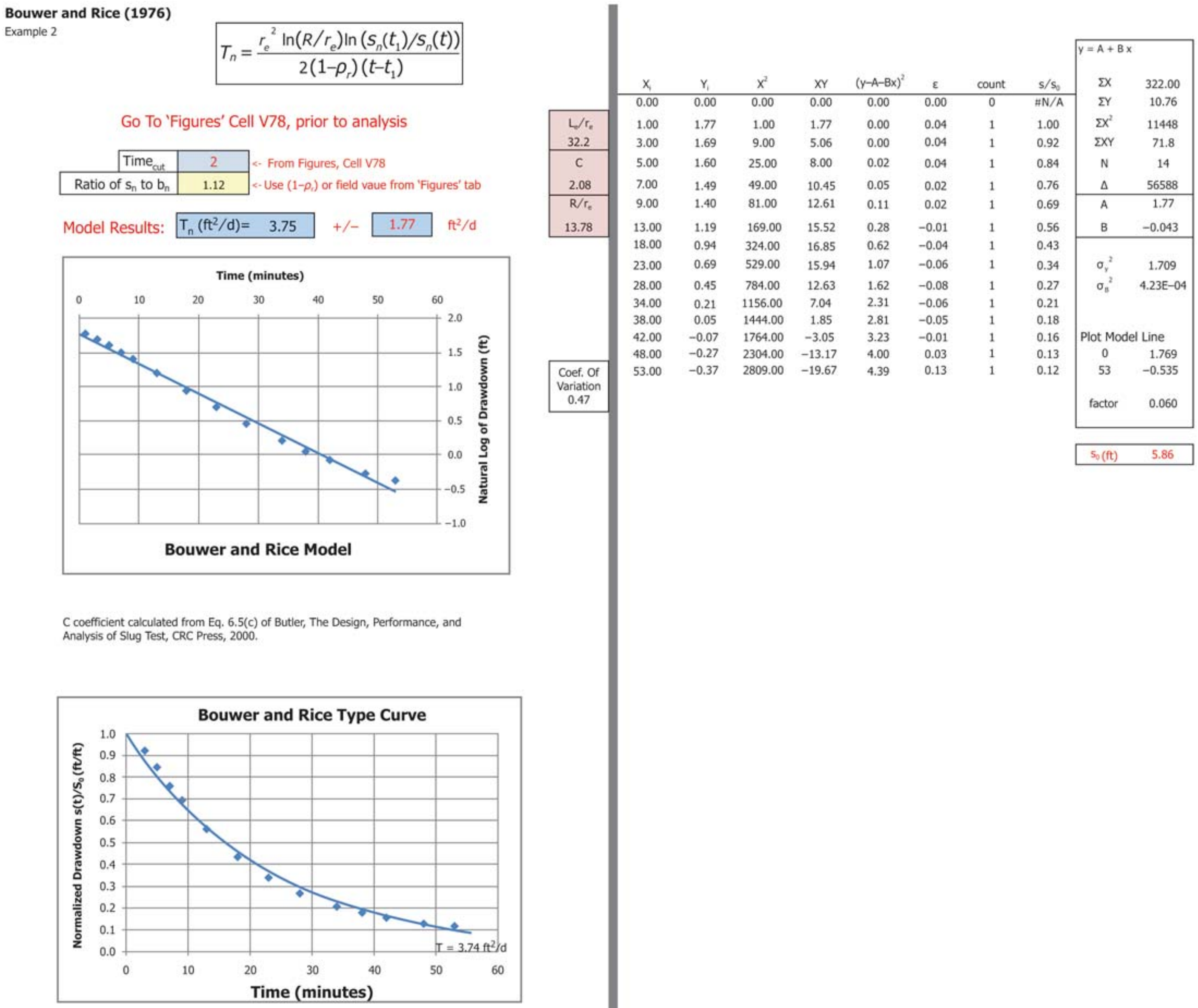


FIG. X2.12 Figures Page—Constant LNAPL/water Interface



Bouwer and Rice (1976)

Example 2

$$T_n = \frac{r_e^2 \ln(R/r_e)\ln(s_n(t_1)/s_n(t))}{2(1-\rho_r)(t-t_1)}$$

Go To 'Figures' Cell V78, prior to analysis

Time_{cut}	2	<- From Figures, Cell V78
Ratio of s_n to b_n	1.12	<- Use $(1-\rho_r)$ or field vaue from 'Figures' tab

Model Results: T_n (ft²/d)= 3.75 +/− 1.77 ft²/d

L_e/r_e	32.2
C	2.08
R/r_e	13.78

Coef. Of Variation 0.47

X_i	Y_i	X^2	XY	$(y-A-Bx)^2$	ε	count	s/s_0
0.00	0.00	0.00	0.00	0.00	0.00	0	#N/A
1.00	1.77	1.00	1.77	0.00	0.04	1	1.00
3.00	1.69	9.00	5.06	0.00	0.04	1	0.92
5.00	1.60	25.00	8.00	0.02	0.04	1	0.84
7.00	1.49	49.00	10.45	0.05	0.02	1	0.76
9.00	1.40	81.00	12.61	0.11	0.02	1	0.69
13.00	1.19	169.00	15.52	0.28	−0.01	1	0.56
18.00	0.94	324.00	16.85	0.62	−0.04	1	0.43
23.00	0.69	529.00	15.94	1.07	−0.06	1	0.34
28.00	0.45	784.00	12.63	1.62	−0.08	1	0.27
34.00	0.21	1156.00	7.04	2.31	−0.06	1	0.21
38.00	0.05	1444.00	1.85	2.81	−0.05	1	0.18
42.00	−0.07	1764.00	−3.05	3.23	−0.01	1	0.16
48.00	−0.27	2304.00	−13.17	4.00	0.03	1	0.13
53.00	−0.37	2809.00	−19.67	4.39	0.13	1	0.12

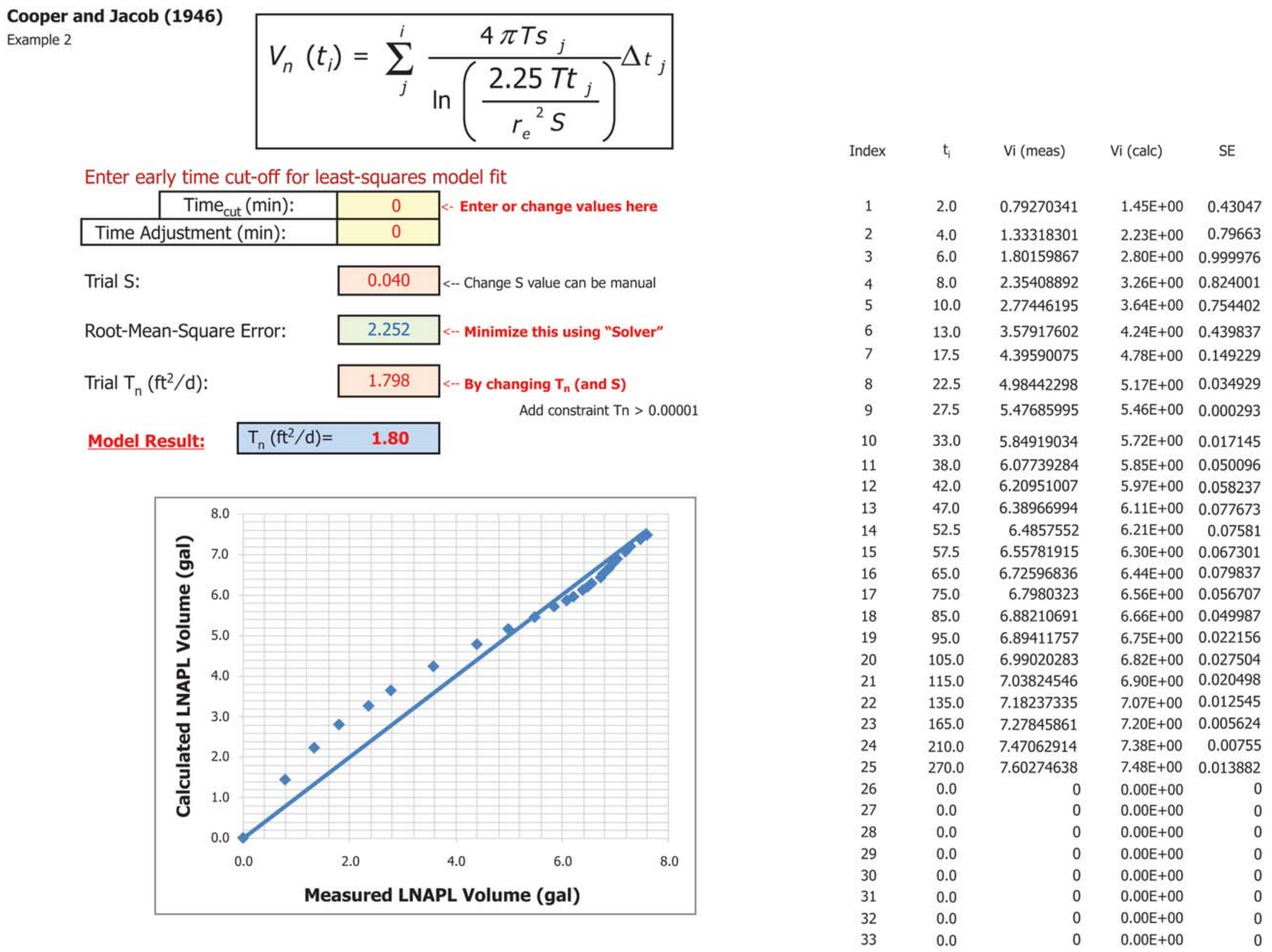
y = A + B x

ΣX	322.00
ΣY	10.76
ΣX^2	11448
ΣXY	71.8
N	14
Δ	56588
A	1.77
B	−0.043
σ_y^2	1.709
σ_B^2	4.23E−04
Plot Model Line	
0	1.769
53	−0.535
factor	0.060

s_0 (ft) 5.86

C coefficient calculated from Eq. 6.5(c) of Butler, The Design, Performance, and Analysis of Slug Test, CRC Press, 2000.

FIG. X2.13 Bouwer-Rice Worksheet—Constant LNAPL/water Interface



Cooper and Jacob (1946)

Example 2

$$V_n\ (t_i) = \sum_{j}^{i} \frac{4\pi T s_j}{\ln\left(\frac{2.25\ T t_j}{r_e^{\ 2} S}\right)} \Delta t_j$$

Enter early time cut-off for least-squares model fit

Time_{cut} (min):	0	<- **Enter or change values here**
Time Adjustment (min):	0	
Trial S:	0.040	<-- Change S value can be manual
Root-Mean-Square Error:	2.252	<-- **Minimize this using "Solver"**
Trial T_n (ft^2/d):	1.798	<-- **By changing T_n (and S)**

Add constraint Tn > 0.00001

Model Result: T_n (ft^2/d)= **1.80**

Index	t_i	Vi (meas)	Vi (calc)	SE
1	2.0	0.79270341	1.45E+00	0.43047
2	4.0	1.33318301	2.23E+00	0.79663
3	6.0	1.80159867	2.80E+00	0.999976
4	8.0	2.35408892	3.26E+00	0.824001
5	10.0	2.77446195	3.64E+00	0.754402
6	13.0	3.57917602	4.24E+00	0.439837
7	17.5	4.39590075	4.78E+00	0.149229
8	22.5	4.98442298	5.17E+00	0.034929
9	27.5	5.47685995	5.46E+00	0.000293
10	33.0	5.84919034	5.72E+00	0.017145
11	38.0	6.07739284	5.85E+00	0.050096
12	42.0	6.20951007	5.97E+00	0.058237
13	47.0	6.38966994	6.11E+00	0.077673
14	52.5	6.4857552	6.21E+00	0.07581
15	57.5	6.55781915	6.30E+00	0.067301
16	65.0	6.72596836	6.44E+00	0.079837
17	75.0	6.7980323	6.56E+00	0.056707
18	85.0	6.88210691	6.66E+00	0.049987
19	95.0	6.89411757	6.75E+00	0.022156
20	105.0	6.99020283	6.82E+00	0.027504
21	115.0	7.03824546	6.90E+00	0.020498
22	135.0	7.18237335	7.07E+00	0.012545
23	165.0	7.27845861	7.20E+00	0.005624
24	210.0	7.47062914	7.38E+00	0.00755
25	270.0	7.60274638	7.48E+00	0.013882
26	0.0	0	0.00E+00	0
27	0.0	0	0.00E+00	0
28	0.0	0	0.00E+00	0
29	0.0	0	0.00E+00	0
30	0.0	0	0.00E+00	0
31	0.0	0	0.00E+00	0
32	0.0	0	0.00E+00	0
33	0.0	0	0.00E+00	0

FIG. X2.14 Cooper and Jacob Worksheet—Constant LNAPL/water Interface

Cooper, Bredehoeft and Papadopulos (1967)

Example 2

Enter early time cut-off for least-squares model fit

$Time_{cut}$ (min):	0	<- **Enter or change values here**
Time Adjustment (min):	0	
Initial Drawdown s_n (ft):	6.2	

Trial S: 0.005 <-- Adjust manually or through "Solver"

Root-Mean-Square Error: 0.341 <-- **Minimize this using "Solver"**

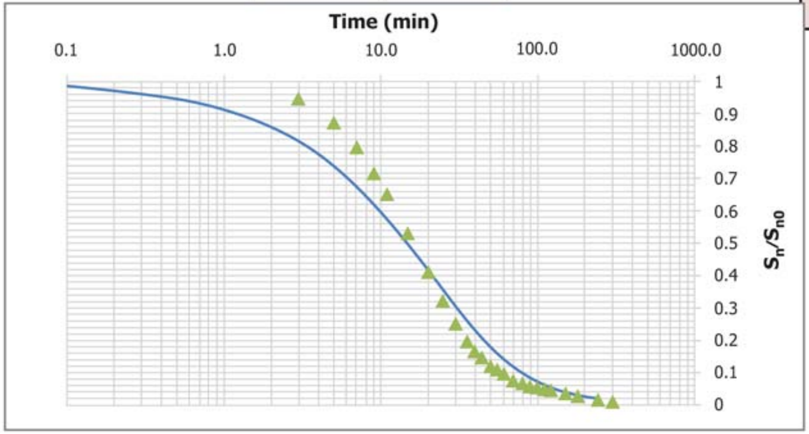
Trial T_n (ft^2/d): 4.393 <-- **By changing T_n through "Solver" (and S)**

Add constraint Tn > 0.00001

Model Result: T_n (ft^2/d)= **4.39**

0.077842

T_{min}	0.1
T_{max}	250



Count	Time (min)	H/H₀	G (a,b,e)	SE
1	1.000	1.064516	0.9138387	0.022704
1	3.000	0.948387	0.81586235	0.017563
1	5.000	0.870968	0.74060068	0.016996
1	7.000	0.798387	0.67784769	0.01453
1	9.000	0.717742	0.62384676	0.008816
1	11.000	0.654839	0.57655128	0.006129
1	15.000	0.532258	0.49720815	0.001228
1	20.000	0.41129	0.41898496	5.92E-05
1	25.000	0.322581	0.35736551	0.00121
1	30.000	0.253226	0.30787019	0.002986
1	36.000	0.198387	0.26036763	0.003842
1	40.000	0.169355	0.23426983	0.004214
1	44.000	0.15	0.21172819	0.00381
1	50.000	0.122581	0.18332371	0.00369
1	55.000	0.11129	0.16365351	0.002742
1	60.000	0.1	0.14690143	0.0022
1	70.000	0.079032	0.1201752	0.001693
1	80.000	0.069355	0.10012386	0.000947
1	90.000	0.059677	0.08478382	0.00063
1	100.000	0.056452	0.07284058	0.000269
1	110.000	0.051613	0.06339255	0.000139
1	120.000	0.046774	0.0558084	8.16E-05
1	150.000	0.037097	0.0403192	1.04E-05
1	180.000	0.029032	0.03111429	4.33E-06
1	240.000	0.017742	0.02106869	1.11E-05
1	300.000	0.009677	0.01584122	3.8E-05
0	0.000	0	0	0
0	0.000	0	0	0

FIG. X2.15 Cooper, Bredehoeft and Papadopulos Worksheet—Constant LNAPL/water Interface

Bouwer and Rice Short Term LNAPL Mobility Test Type Curves

B&R Type Curves: Casing Dia. (ft) = 0.167 ; Borehole Dia. (ft) = 0.5

Example 2

Enter these values

Type Curve ID	Type Curve Name	Notes	Max Time (min)	Transmissivity (ft^2/day)
1	T = 6 ft2/day		50	6
2	T = 4 ft2/day		150	4
3	T = 3 ft2/day		200	3
4	T = 2 ft2/day		200	2
5	T = 1 ft2/day		200	1
6	T = 0.5 ft2/day		200	0.5
7	T = 0.1 ft2/day		200	0.1

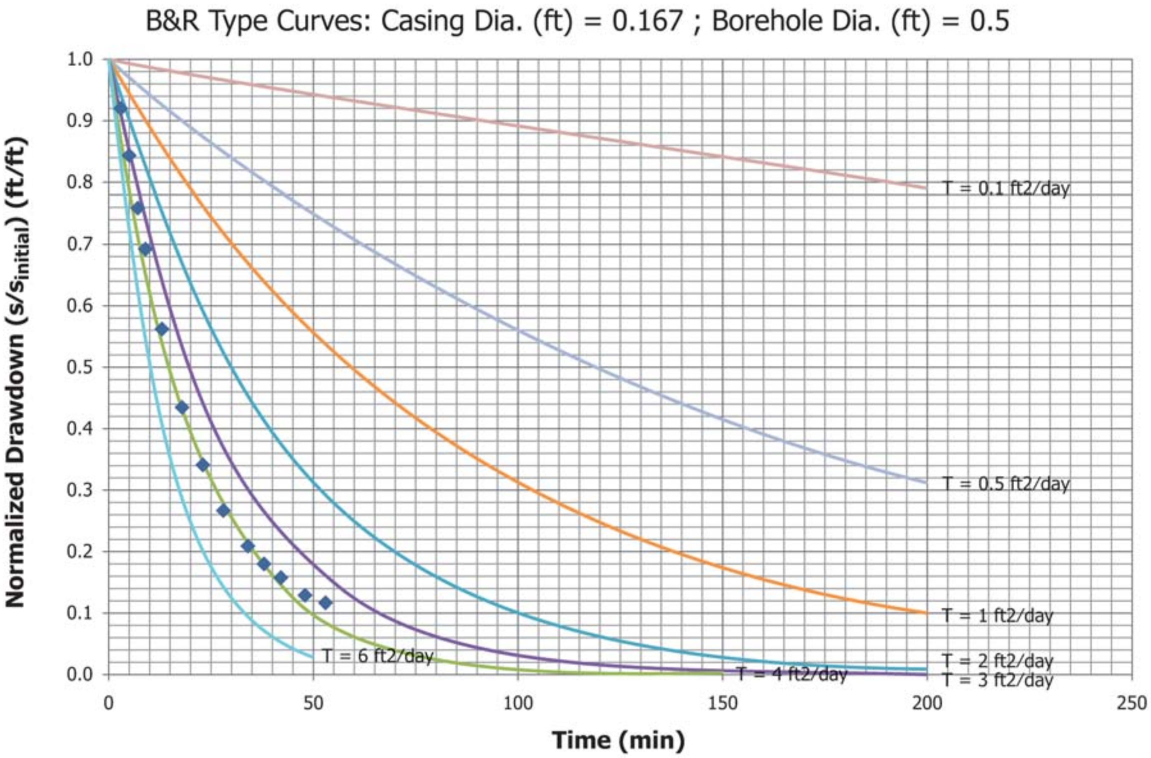
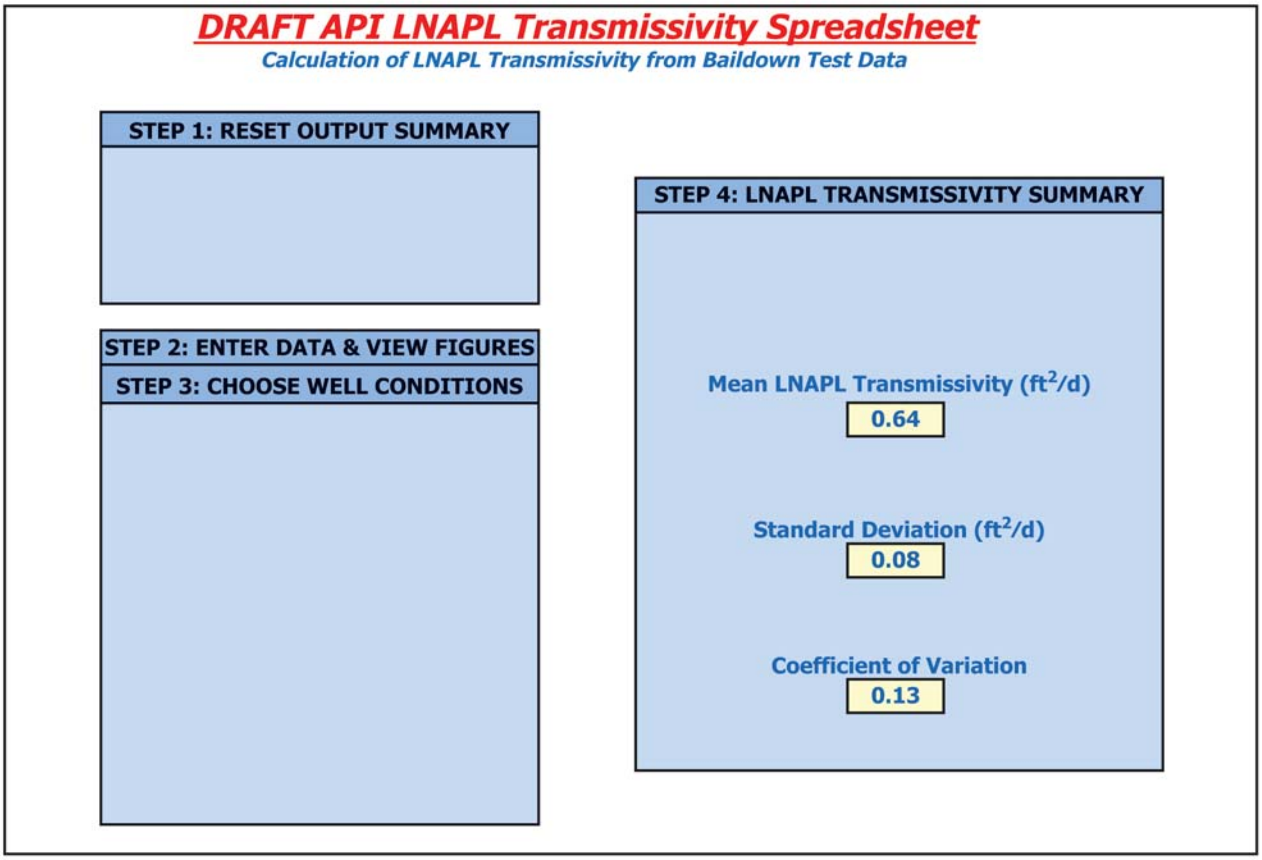


FIG. X2.16 Bouwer-Rice Type Curve Worksheet—Constant LNAPL/water Interface



DRAFT API LNAPL Transmissivity Spreadsheet

Calculation of LNAPL Transmissivity from Baildown Test Data

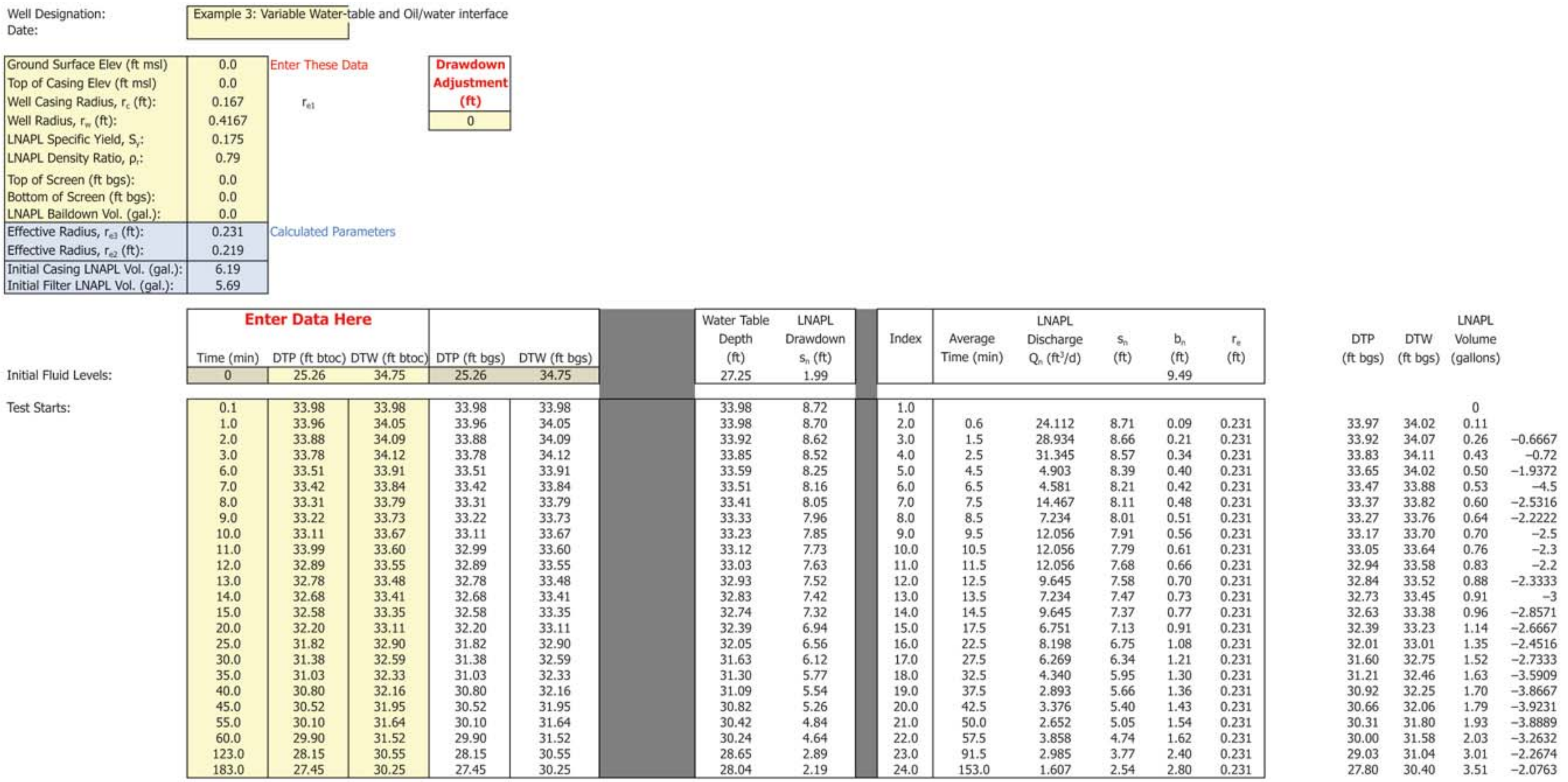
STEP 4: LNAPL TRANSMISSIVITY SUMMARY

Mean LNAPL Transmissivity (ft^2/d): 0.64

Standard Deviation (ft^2/d): 0.08

Coefficient of Variation: 0.13

FIG. X2.17 Results Page—Variable LNAPL/Water Interface



Well Designation: Example 3: Variable Water-table and Oil/water interface
Date:

Ground Surface Elev (ft msl)	0.0	Enter These Data
Top of Casing Elev (ft msl)	0.0	
Well Casing Radius, r_c (ft):	0.167	r_{e1}
Well Radius, r_w (ft):	0.4167	
LNAPL Specific Yield, S_y:	0.175	
LNAPL Density Ratio, ρ_r:	0.79	
Top of Screen (ft bgs):	0.0	
Bottom of Screen (ft bgs):	0.0	
LNAPL Baildown Vol. (gal.):	0.0	
Effective Radius, r_{e3} (ft):	0.231	Calculated Parameters
Effective Radius, r_{e2} (ft):	0.219	
Initial Casing LNAPL Vol. (gal.):	6.19	
Initial Filter LNAPL Vol. (gal.):	5.69	

Drawdown Adjustment (ft)
0

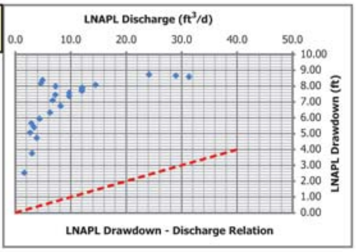
Enter Data Here

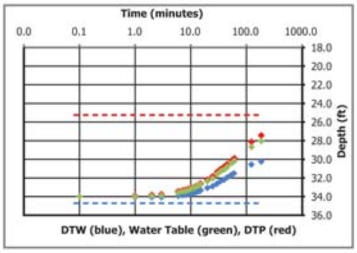
	Time (min)	DTP (ft btoc)	DTW (ft btoc)	DTP (ft bgs)	DTW (ft bgs)	Water Table Depth (ft)	LNAPL Drawdown s_n (ft)	Index	Average Time (min)	LNAPL Discharge Q_n (ft^3/d)	s_n (ft)	b_n (ft)	r_e (ft)	DTP (ft bgs)	DTW (ft bgs)	LNAPL Volume (gallons)	
Initial Fluid Levels:	0	25.26	34.75	25.26	34.75	27.25	1.99					9.49					
Test Starts:	0.1	33.98	33.98	33.98	33.98	33.98	8.72	1.0								0	
	1.0	33.96	34.05	33.96	34.05	33.98	8.70	2.0	0.6	24.112	8.71	0.09	0.231	33.97	34.02	0.11	
	2.0	33.88	34.09	33.88	34.09	33.92	8.62	3.0	1.5	28.934	8.66	0.21	0.231	33.92	34.07	0.26	−0.6667
	3.0	33.78	34.12	33.78	34.12	33.85	8.52	4.0	2.5	31.345	8.57	0.34	0.231	33.83	34.11	0.43	−0.72
	6.0	33.51	33.91	33.51	33.91	33.59	8.25	5.0	4.5	4.903	8.39	0.40	0.231	33.65	34.02	0.50	−1.9372
	7.0	33.42	33.84	33.42	33.84	33.51	8.16	6.0	6.5	4.581	8.21	0.42	0.231	33.47	33.88	0.53	−4.5
	8.0	33.31	33.79	33.31	33.79	33.41	8.05	7.0	7.5	14.467	8.11	0.48	0.231	33.37	33.82	0.60	−2.5316
	9.0	33.22	33.73	33.22	33.73	33.33	7.96	8.0	8.5	7.234	8.01	0.51	0.231	33.27	33.76	0.64	−2.2222
	10.0	33.11	33.67	33.11	33.67	33.23	7.85	9.0	9.5	12.056	7.91	0.56	0.231	33.17	33.70	0.70	−2.5
	11.0	33.99	33.60	32.99	33.60	33.12	7.73	10.0	10.5	12.056	7.79	0.61	0.231	33.05	33.64	0.76	−2.3
	12.0	32.89	33.55	32.89	33.55	33.03	7.63	11.0	11.5	12.056	7.68	0.66	0.231	32.94	33.58	0.83	−2.2
	13.0	32.78	33.48	32.78	33.48	32.93	7.52	12.0	12.5	9.645	7.58	0.70	0.231	32.84	33.52	0.88	−2.3333
	14.0	32.68	33.41	32.68	33.41	32.83	7.42	13.0	13.5	7.234	7.47	0.73	0.231	32.73	33.45	0.91	−3
	15.0	32.58	33.35	32.58	33.35	32.74	7.32	14.0	14.5	9.645	7.37	0.77	0.231	32.63	33.38	0.96	−2.8571
	20.0	32.20	33.11	32.20	33.11	32.39	6.94	15.0	17.5	6.751	7.13	0.91	0.231	32.39	33.23	1.14	−2.6667
	25.0	31.82	32.90	31.82	32.90	32.05	6.56	16.0	22.5	8.198	6.75	1.08	0.231	32.01	33.01	1.35	−2.4516
	30.0	31.38	32.59	31.38	32.59	31.63	6.12	17.0	27.5	6.269	6.34	1.21	0.231	31.60	32.75	1.52	−2.7333
	35.0	31.03	32.33	31.03	32.33	31.30	5.77	18.0	32.5	4.340	5.95	1.30	0.231	31.21	32.46	1.63	−3.5909
	40.0	30.80	32.16	30.80	32.16	31.09	5.54	19.0	37.5	2.893	5.66	1.36	0.231	30.92	32.25	1.70	−3.8667
	45.0	30.52	31.95	30.52	31.95	30.82	5.26	20.0	42.5	3.376	5.40	1.43	0.231	30.66	32.06	1.79	−3.9231
	55.0	30.10	31.64	30.10	31.64	30.42	4.84	21.0	50.0	2.652	5.05	1.54	0.231	30.31	31.80	1.93	−3.8889
	60.0	29.90	31.52	29.90	31.52	30.24	4.64	22.0	57.5	3.858	4.74	1.62	0.231	30.00	31.58	2.03	−3.2632
	123.0	28.15	30.55	28.15	30.55	28.65	2.89	23.0	91.5	2.985	3.77	2.40	0.231	29.03	31.04	3.01	−2.2674
	183.0	27.45	30.25	27.45	30.25	28.04	2.19	24.0	153.0	1.607	2.54	2.80	0.231	27.80	30.40	3.51	−2.0763

FIG. X2.18 Data Page—Variable LNAPL/Water Interface

Example 3

Q_n(ft^3/d)	S_n (ft)
0	0
40	4

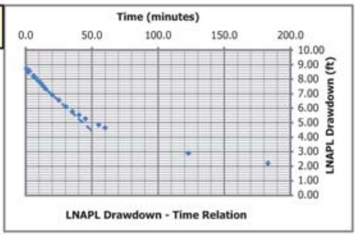


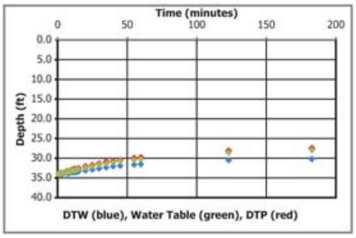


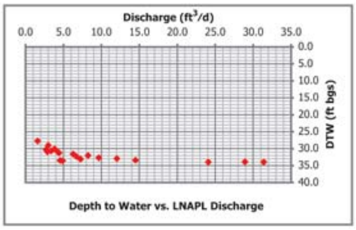
0.1	25.26
183	25.26
0.1	34.75
183	34.75

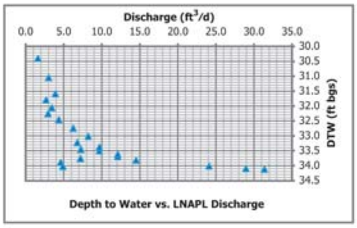
45.8	#N/A	24.3
45.8	#N/A	0.0

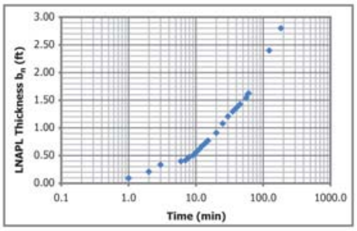
t (min)	S_n (ft)
0	8.5
50	4.5

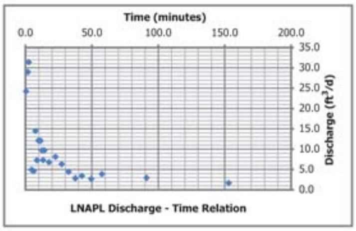






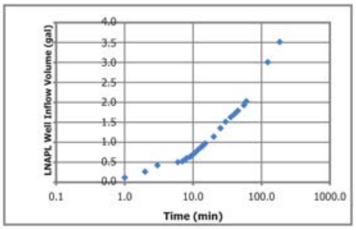


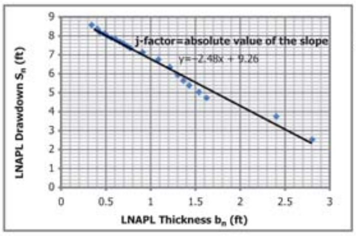




Enter early time cut-off for least-squares model fit
Absolute Value of the Resulting Trend-line Slope,
Represents Actual Ration of s_n to b_n

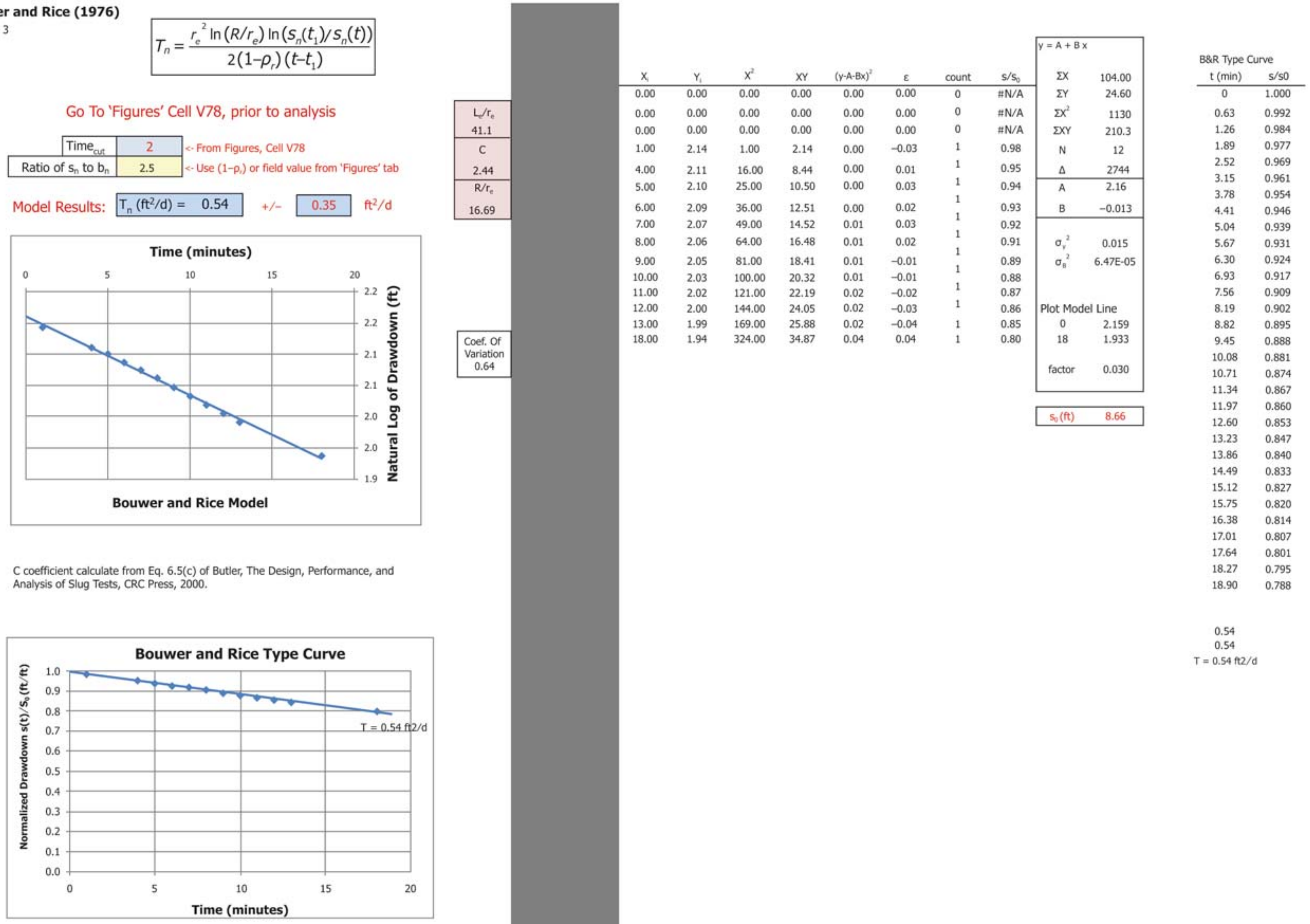
B-R Time Cut (min)= 2
B-R Max Time Fit (min)= 200





Index	S_n (ft)	b_n (ft)
3		
4	8.57	0.34
5	8.385	0.401
6	8.205	0.42
7	8.105	0.48
8	8.005	0.51
9	7.905	0.56
10	7.79	0.61
11	7.68	0.66
12	7.575	0.7
13	7.47	0.73
14	7.37	0.77
15	7.13	0.91
16	6.75	1.08
17	6.34	1.21
18	5.945	1.3
19	5.655	1.36
20	5.4	1.43
21	5.05	1.54
22	4.74	1.62
23	3.765	2.4
24	2.54	2.8

FIG. X2.19 Figure Page—Variable LNAPL/Water Interface



Bouwer and Rice (1976)
Example 3

$$T_n = \frac{r_e^{\,2}\ln(R/r_e)\ln(s_n(t_1)/s_n(t))}{2(1-\rho_r)(t-t_1)}$$

Go To 'Figures' Cell V78, prior to analysis

Time_{cut}	2	<- From Figures, Cell V78
Ratio of s_n to b_n	2.5	<- Use $(1-\rho_r)$ or field value from 'Figures' tab

Model Results: T_n (ft²/d) = 0.54 +/- 0.35 ft²/d

L_e/r_e
41.1
C
2.44
R/r_e
16.69

Coef. Of Variation
0.64

C coefficient calculate from Eq. 6.5(c) of Butler, The Design, Performance, and Analysis of Slug Tests, CRC Press, 2000.

X_i	Y_i	X^2	XY	$(y\text{-}A\text{-}Bx)^2$	ε	count	s/s_0
0.00	0.00	0.00	0.00	0.00	0.00	0	#N/A
0.00	0.00	0.00	0.00	0.00	0.00	0	#N/A
0.00	0.00	0.00	0.00	0.00	0.00	0	#N/A
1.00	2.14	1.00	2.14	0.00	−0.03	1	0.98
4.00	2.11	16.00	8.44	0.00	0.01	1	0.95
5.00	2.10	25.00	10.50	0.00	0.03	1	0.94
6.00	2.09	36.00	12.51	0.00	0.02	1	0.93
7.00	2.07	49.00	14.52	0.01	0.03	1	0.92
8.00	2.06	64.00	16.48	0.01	0.02	1	0.91
9.00	2.05	81.00	18.41	0.01	−0.01	1	0.89
10.00	2.03	100.00	20.32	0.01	−0.01	1	0.88
11.00	2.02	121.00	22.19	0.02	−0.02	1	0.87
12.00	2.00	144.00	24.05	0.02	−0.03	1	0.86
13.00	1.99	169.00	25.88	0.02	−0.04	1	0.85
18.00	1.94	324.00	34.87	0.04	0.04	1	0.80

y = A + B x

ΣX	104.00
ΣY	24.60
ΣX^2	1130
ΣXY	210.3
N	12
Δ	2744
A	2.16
B	−0.013
σ_y^2	0.015
σ_B^2	6.47E-05
Plot Model Line	
0	2.159
18	1.933
factor	0.030

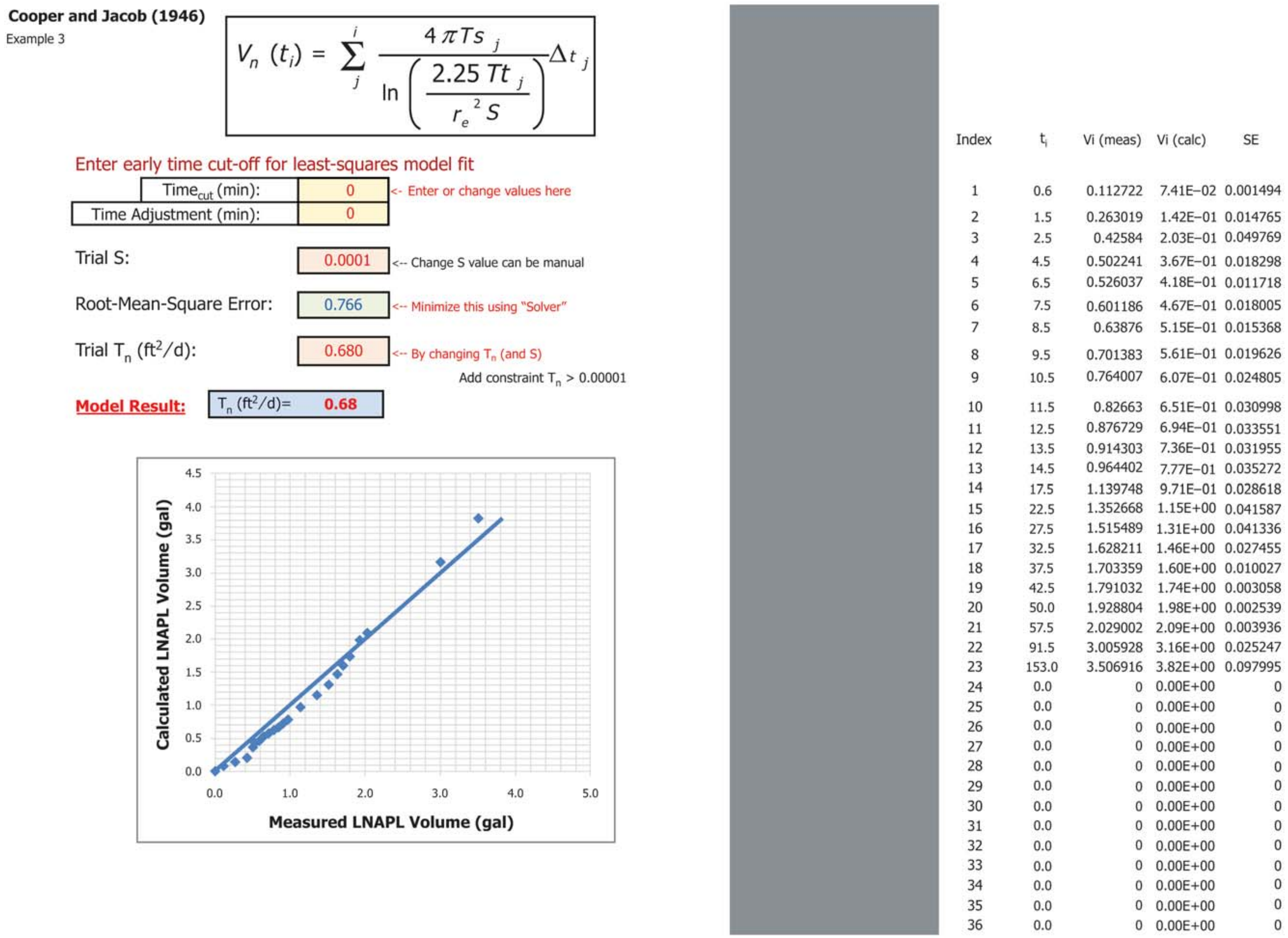
s_0 (ft) 8.66

B&R Type Curve

t (min)	s/s0
0	1.000
0.63	0.992
1.26	0.984
1.89	0.977
2.52	0.969
3.15	0.961
3.78	0.954
4.41	0.946
5.04	0.939
5.67	0.931
6.30	0.924
6.93	0.917
7.56	0.909
8.19	0.902
8.82	0.895
9.45	0.888
10.08	0.881
10.71	0.874
11.34	0.867
11.97	0.860
12.60	0.853
13.23	0.847
13.86	0.840
14.49	0.833
15.12	0.827
15.75	0.820
16.38	0.814
17.01	0.807
17.64	0.801
18.27	0.795
18.90	0.788

0.54
0.54
T = 0.54 ft2/d

FIG. X2.20 Bouwer-Rice Worksheet—Variable LNAPL/Water Interface



Cooper and Jacob (1946)

Example 3

$$V_n\ (t_i) = \sum_j^i \frac{4\pi T s_j}{\ln\left(\dfrac{2.25\, T t_j}{r_e^{\,2} S}\right)} \Delta t_j$$

Enter early time cut-off for least-squares model fit

Time$_{cut}$ (min):	0	<- Enter or change values here
Time Adjustment (min):	0	

Trial S: 0.0001 <-- Change S value can be manual

Root-Mean-Square Error: 0.766 <-- Minimize this using "Solver"

Trial T$_n$ (ft^2/d): 0.680 <-- By changing T$_n$ (and S)

Add constraint T$_n$ > 0.00001

Model Result: T$_n$ (ft^2/d)= **0.68**

Index	t$_i$	Vi (meas)	Vi (calc)	SE
1	0.6	0.112722	7.41E-02	0.001494
2	1.5	0.263019	1.42E-01	0.014765
3	2.5	0.42584	2.03E-01	0.049769
4	4.5	0.502241	3.67E-01	0.018298
5	6.5	0.526037	4.18E-01	0.011718
6	7.5	0.601186	4.67E-01	0.018005
7	8.5	0.63876	5.15E-01	0.015368
8	9.5	0.701383	5.61E-01	0.019626
9	10.5	0.764007	6.07E-01	0.024805
10	11.5	0.82663	6.51E-01	0.030998
11	12.5	0.876729	6.94E-01	0.033551
12	13.5	0.914303	7.36E-01	0.031955
13	14.5	0.964402	7.77E-01	0.035272
14	17.5	1.139748	9.71E-01	0.028618
15	22.5	1.352668	1.15E+00	0.041587
16	27.5	1.515489	1.31E+00	0.041336
17	32.5	1.628211	1.46E+00	0.027455
18	37.5	1.703359	1.60E+00	0.010027
19	42.5	1.791032	1.74E+00	0.003058
20	50.0	1.928804	1.98E+00	0.002539
21	57.5	2.029002	2.09E+00	0.003936
22	91.5	3.005928	3.16E+00	0.025247
23	153.0	3.506916	3.82E+00	0.097995
24	0.0	0	0.00E+00	0
25	0.0	0	0.00E+00	0
26	0.0	0	0.00E+00	0
27	0.0	0	0.00E+00	0
28	0.0	0	0.00E+00	0
29	0.0	0	0.00E+00	0
30	0.0	0	0.00E+00	0
31	0.0	0	0.00E+00	0
32	0.0	0	0.00E+00	0
33	0.0	0	0.00E+00	0
34	0.0	0	0.00E+00	0
35	0.0	0	0.00E+00	0
36	0.0	0	0.00E+00	0

FIG. X2.21 Cooper and Jacob Worksheet—Variable LNAPL/Water Interface

Cooper, Bredehoeft and Papadopulos (1967)

Example 3

Enter early time cut-off for least-squares model fit

Time$_{cut}$ (min):	0	<- Enter or change values here
Time Adjustment (min):	0	
Initial Drawdown s_n (ft):	8.5	

Trial S: 0.000 <-- Adjust manually or through "Solver"

Root-Mean-Square Error: 0.146 <-- Minimize this using "Solver"

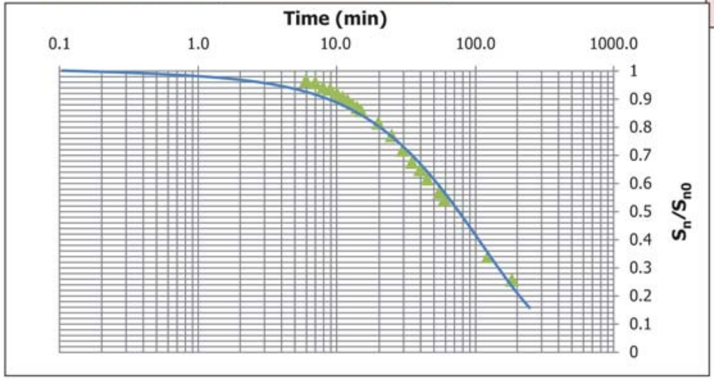
Trial T_n (ft^2/d): 0.699 <-- By changing T_n through "Solver" (and S)

Add constraint T_n > 0.00001

Model Result: T_n (ft^2/d) = **0.70**

0.012391

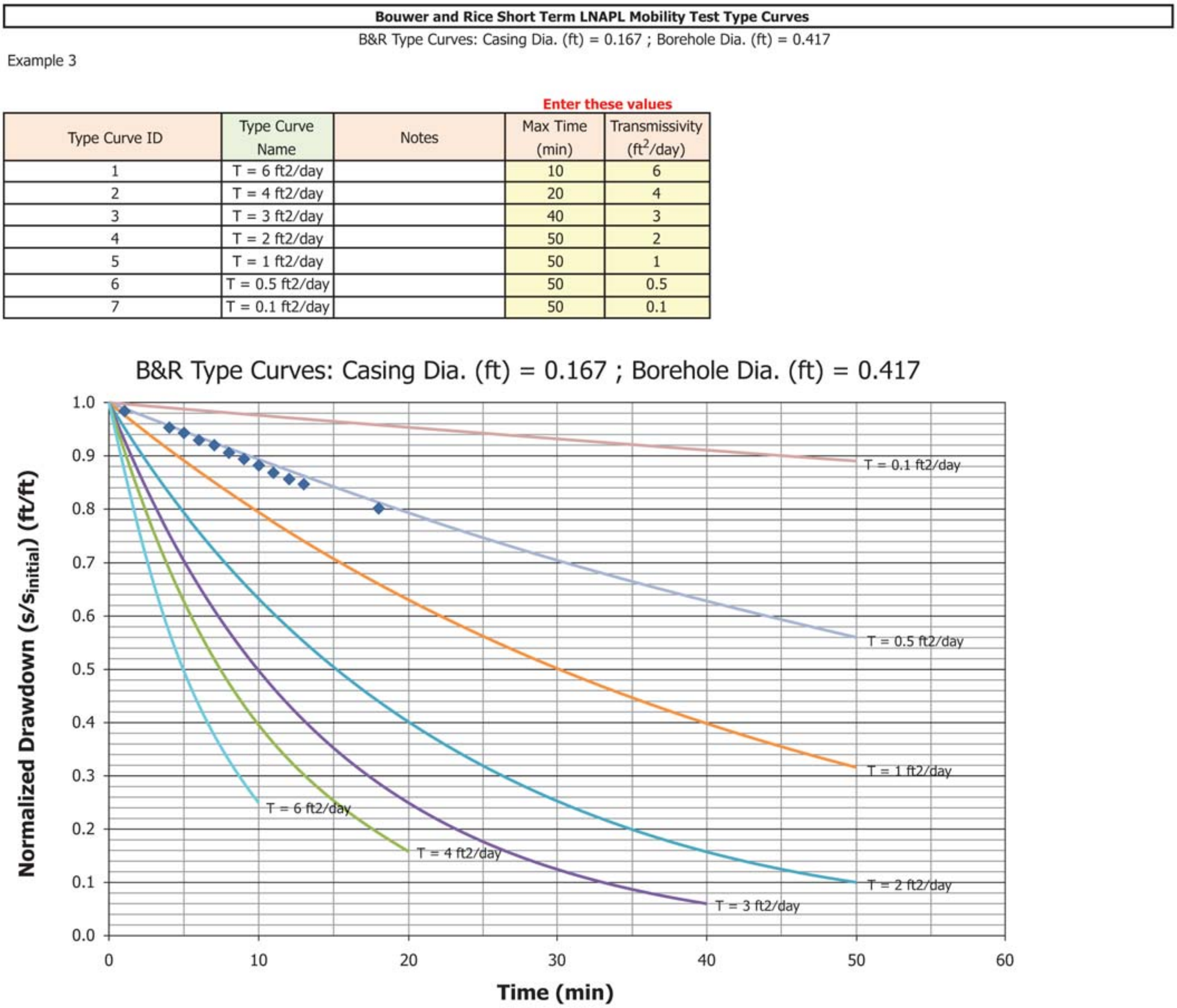
T_{min}	0.1
T_{max}	250



e 0.000001

Count	Time (min)	H/H$_o$	G (a,b,e)	SE
1	0.100	1.025882	0.997288	0.000818
1	1.000	1.023529	0.98334	0.001615
1	2.000	1.014118	0.970525	0.0019
1	3.000	1.002353	0.958749	0.001901
1	6.000	0.970588	0.926704	0.001926
1	7.000	0.96	0.916758	0.00187
1	8.000	0.947059	0.907092	0.001597
1	9.000	0.936471	0.897675	0.001505
1	10.000	0.923529	0.888481	0.001228
1	11.000	0.909412	0.879493	0.000895
1	12.000	0.897647	0.870694	0.000726
1	13.000	0.884706	0.862072	0.000512
1	14.000	0.872941	0.853616	0.000373
1	15.000	0.861176	0.845315	0.000252
1	20.000	0.816471	0.805898	0.000112
1	25.000	0.771765	0.769465	5.29E–06
1	30.000	0.72	0.735546	0.000242
1	35.000	0.678824	0.703812	0.000624
1	40.000	0.651765	0.674015	0.000495
1	45.000	0.618824	0.64596	0.000736
1	55.000	0.569412	0.59446	0.000627
1	60.000	0.545882	0.570766	0.000619
1	123.000	0.34	0.3549	0.000222
1	183.000	0.257647	0.237138	0.000421

FIG. X2.22 Cooper, Bredehoeft and Papadopulos—Worksheet Variable LNAPL/Water Interface



Bouwer and Rice Short Term LNAPL Mobility Test Type Curves

B&R Type Curves: Casing Dia. (ft) = 0.167 ; Borehole Dia. (ft) = 0.417

Example 3

Enter these values

Type Curve ID	Type Curve Name	Notes	Max Time (min)	Transmissivity (ft^2/day)
1	T = 6 ft2/day		10	6
2	T = 4 ft2/day		20	4
3	T = 3 ft2/day		40	3
4	T = 2 ft2/day		50	2
5	T = 1 ft2/day		50	1
6	T = 0.5 ft2/day		50	0.5
7	T = 0.1 ft2/day		50	0.1

FIG. X2.23 Bouwer-Rice Type Curve Worksheet—Variable LNAPL/Water Interface

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