

API LNAPL Transmissivity Workbook: A Tool for Baildown Test Analysis

User Guide

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Developed by:

Randall J. Charbeneau, Ph.D., P.E., D. WRE
Civil, Architectural and Environmental Engineering
The University of Texas at Austin
Austin, Texas 78712

Andrew Kirkman, P.E.
AECOM
First National Bank Building
322 Minnesota Street, Suite E1000
St. Paul, Minnesota 55101

Rangaramanujam Muthu, Ph.D., E.I.T.
H2A Environmental Ltd., Inc.
1862 Keller Parkway
Keller, Texas 76248



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PREFACE

LNAPL transmissivity provides a useful measure of potential hydrocarbon liquid mobility within the subsurface environment. The magnitude of LNAPL transmissivity is being accepted as a metric for hydrocarbon recovery system performance and determination of technology-specific endpoints. Baildown tests are a simple method for estimating LNAPL transmissivity. This manuscript describes a spreadsheet tool that can be used to analyze results from baildown tests.

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LIST OF SYMBOLS

b_n	LNAPL thickness in well
b_{nR}	initial LNAPL thickness in well (same as at radius of influence)
b_{nw}	limiting effective LNAPL thickness in well (see Appendix F)
DZ_{12}	depth to top of perching layer
$F()$	Cooper, Bredehoeft and Papadopulos slug test function
$G()$	Jacob-Lohman free-flowing discharge function
h_n	LNAPL head
J	Kirkman J-ratio (see Appendix B)
L_e	initial LNAPL column height (contacting screen) in well
N	number of increments
Q_n	LNAPL discharge
Q_{ni}	LNAPL discharge at time t_i
R	radius of influence
r_c	radius of casing
r_e	effective well radius
$r_{e(i)}$	effective well radius at time t_i (varies with LNAPL column location in well)
r_w	well borehole radius
S	coefficient of storage
s_n	LNAPL drawdown
S_n	LNAPL storage parameter
s_{ni}	LNAPL drawdown at time t_i
S_y	LNAPL specific yield
T	transmissivity
t_i	time epoch
T_n	LNAPL transmissivity
V_n	LNAPL volume
$W()$	Theis well function
z_{an}	elevation of air-LNAPL interface in well
z_{nw}	elevation of LNAPL-water interface in well
Δs_n	LNAPL drawdown correction
Δt_a	time adjustment factor
ρ_r	LNAPL-to-water density ratio

ACRONYMS

BOS	Bottom of Screen
B&R	(generalized) Bouwer and Rice method
CSM	Conceptual Site Model
C&J	Cooper and Jacob method
CB&P	Cooper, Bredehoeft and Papadopoulos method
CV	Coefficient of Variation
DTP	Depth to Product
DTW	Depth to Water
ITRC	Interstate Technology Regulatory Council
LNAPL	Light Non-Aqueous Phase Liquid
SOP	Standard Operating Procedure
SSD	Sum-Square-Difference
TOS	Top of Screen

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1. Introduction

LNAPL transmissivity is a measure of lateral mobility of free-product hydrocarbon liquid within the groundwater environment. The magnitude of LNAPL transmissivity has been suggested as a possible endpoint criterion for LNAPL mass removal using LNAPL hydraulic recovery systems (ASTM E 2531-06 [Tbl X5.1], 2006; ITRC, 2009). Such hydraulic recovery systems include skimmer wells, single-pump wells, dual-pump wells, and trenches. Coupled with the LNAPL CSM, the magnitude of LNAPL transmissivity will assist in the selection of recovery system. As such, methods and their consistent application for estimating LNAPL transmissivity are significant. Perhaps the simplest methods for estimating LNAPL transmissivity are borehole slug test methods, or baildown tests, in which a volume of LNAPL is rapidly removed from a well and the rate of fluid-level recovery (water and LNAPL) is measured and analyzed. Several analytical methods are available to analyze the data from baildown tests to estimate LNAPL transmissivity and described herein. A more general discussion of LNAPL transmissivity measurement is provided by ASTM (2011).

Following a brief description of suggested well configuration, pre-test and test measurements and methods, application of the spreadsheet tool is discussed. Subsequent sections provide a more detailed discussion of significant parameters and basis for the various analysis procedures. A number of example applications are presented. Further details on the different methods are provided in the appendices. Noteworthy is the introduction of the J-ratio (J) described in Appendix A, which appears to render discussions over preference between Lundy and Zimmerman (1996) versus Huntley (2000) methods moot.

2. Well Configuration Data

The following well configuration data should be gathered for baildown test analysis:

1. Elevation of ground surface. This generally serves as the datum with elevations specified as depth below ground surface, bgs. Elevations presented with the geologic log are generally expressed as depth bgs. If data are not conveniently available (or necessary), enter 0 on the spreadsheet.
2. Elevation of top of casing (depths to fluid levels are usually measured from top of casing). If data are not conveniently available (or necessary), enter 0 on the spreadsheet.
3. Well casing radius, r_c (ft).
4. Well borehole radius, r_w (ft).
5. Depth of top of screen (ft bgs). The top of screen can be interpreted to be the top of screen or filter pack, depending on the well construction and gauged fluid levels, and it is

up to professional judgment to correctly select between these. If data are not conveniently available (or necessary), enter 0 on the spreadsheet.

6. Depth of bottom of screen (ft bgs). If data are not conveniently available (or necessary), enter 0 on the spreadsheet.

3. Pre-Test Data

Certain data should be gathered before performance of the baildown test, in order to establish and verify initial conditions. The depth to product (DTP) and depth to water (DTW) should be measured over a period equal to the expected test duration; if the test duration is unknown then use of historic hydrograph data and gauging 8 hours before the test would provide a basic level of understanding for equilibrium conditions. The DTP and DTW should then be measured immediately before start of the test to confirm that fluid levels are stable and in equilibrium. The best practice to confirm equilibrium fluid levels is to gauge the well until it fully recovers as discussed in ASTM E2856-11, Section 6.1.4.16 (2011). Additionally, when conditions allow, it is useful to remove LNAPL from the well during a period before the test (e.g. within one month) to confirm equilibrium contact between formation and well hydrocarbon liquid. This is necessary especially if standing LNAPL is observed or LNAPL has not been recovered from a well for a while. Baildown tests are analyzed by slug test methods modified for two fluids, and it is important that formation and well fluids are in equilibrium. If tidal fluctuations are present the DTP and DTW must be measured regularly for at least a week leading up to the test. In any case it is imperative that the LNAPL/water interface should be positioned across the well screen for confined LNAPL conditions, or the air/LNAPL interface for perched LNAPL conditions, if not both the interfaces.

4. Baildown Test Procedures and Data

In performance of a baildown test a volume of hydrocarbon liquid is rapidly removed from the well and the DTP and DTW are measured as a function of time during the fluid recovery period. Fluid recovery rates generally vary logarithmically, so measurements should be taken more frequently during the initial period following hydrocarbon removal, and the measurement frequency decreases during the later period of the test. The ASTM standard E2856-11 provides a thorough procedure for conducting baildown tests, however, a brief description of significant features are provided below:

- Initial hydrocarbon liquid removal should be rapid. Commercial peristaltic pumps (such as Spill Buddy TM) are preferred since the pump intake can be located to remove only hydrocarbon liquid during the baildown stage. If a bailer is used then additional precautions are necessary to minimize fluid disturbance during LNAPL removal. If removal of larger LNAPL volumes is required, then vacuum trucks can be used, recognizing that significant volumes of water may be removed in addition to LNAPL.

- Following the baildown stage of hydrocarbon liquid removal, the DTP and DTW are measured as a function of time. Measurements can be taken using interface probes (optical and electrical resistivity), and data are recorded as depth (feet) below top of casing.
- In general, the interface depth measurements are taken more frequently during the initial recovery period, and the frequency decreases as recovery proceeds. If recovery rates are too rapid for (near) simultaneous measurement of DTP and DTW, then a pressure transducer can be placed below the LNAPL-water interface and connected to a data-logger. In this case only the DTP need be measured, and such measurements combined with the data-logger record and LNAPL density can be used to calculate the DTW at desired time intervals.
- When possible, recovery monitoring should continue until essentially complete LNAPL recovery is achieved. In low LNAPL transmissivity locations, time requirements might be excessive and early termination will be necessary. Nearly full recovery is especially important for confined and perched LNAPL conditions, to help verify the site conceptual model for the test.
- A record of 20 to 30 measurements (each for DTP and DTW) is generally adequate for data analysis. When possible, these data should be evenly spread in terms of recovery volume. [For example, if the initial LNAPL thickness in a well is 4 ft and the LNAPL thickness after baildown is 0.5 ft, then measurements might be taken when the LNAPL thickness roughly has the following sequence of values: 0.50, 0.52, 0.54, ... 3.90, .. ft.]

5. Post-Test Data

LNAPL transmissivity value from a baildown test is estimated based on measurement of LNAPL drawdown and recharge to the well as a function of time, along with a conceptual site model that can include geologic log and well configuration data to identify possible unconfined, confined, or perched LNAPL conditions. Estimation of formation discharge (well recharge) is based on changes in DTP and DTW values. Changes in fluid levels in the well compared with screen elevations determine the effective storage associated with the well. This storage can include only the casing volume or the casing volume plus some fraction of the pore space of the filter pack that has been drained of LNAPL during the baildown stage of the test. This latter case becomes more complicated, depending on the fluid levels versus the well screen interval, since only part of the LNAPL column in the well may be in contact with the screened interval of the well. These issues are discussed in more detail in Appendix B with regard to estimation of the effective well radius, r_e .

The post-test data that must be calculated include estimation of LNAPL drawdown (s_n) and well discharge (Q_n) as a function of time, and this in turn depends on the effective well radius value along with DTP and DTW measurements.

The LNAPL drawdown is measured based on the DTP, along with any correction that is applied to account for initial non-equilibrium between formation and wellbore LNAPL. Specifically, the drawdown corresponding to time t_i is calculated using

$$(5.1) \quad s_{ni} = DTP_i - DTP_0 - \Delta s_n$$

In Eq. (5.1) DTP_0 is the initial (pre-test) depth to product and Δs_n is a possible LNAPL drawdown correction as discussed below.

The LNAPL discharge from the formation to the well is calculated based on the effective well radius ($r_{e(i)}$) and changes in DTP and DTW over time. Once the effective well radius has been determined, the well discharge from time t_i to time t_{i+1} is calculated using the following equation:

$$(5.2) \quad Q_{ni} = \pi r_{e(i)}^2 (DTP_i - DTP_{i+1} + DTW_{i+1} - DTW_i) / (t_{i+1} - t_i)$$

This equation accounts for the increase in LNAPL storage volume over the time interval, and specifically identifies that the effective well radius might not be constant (such as a change from well casing storage to casing/screen plus filter pack storage).

6. Overview and General Discussion: Analysis of LNAPL Transmissivity Baildown Test Data

This section briefly summarizes methods for analysis of LNAPL transmissivity baildown test data. Additionally, use of time cutoff and time adjustment to eliminate early-time data influenced by filter pack drainage or other factors is discussed, and a default method for estimation of LNAPL storage coefficient is described. Finally, a flowchart that outlines the LNAPL transmissivity estimation process using this workbook is presented.

6.1. Methods for Estimating LNAPL Transmissivity

Among the variety of methods suggested in the literature for analysis of slug test data, three different methods are presented here for analysis of unconfined LNAPL transmissivity baildown tests. These three methods are designated through their original presentation in the literature as follows:

- B&R - Bouwer and Rice (1976)
- C&J - Cooper and Jacob (1946)
- CB&P - Cooper, Bredehoeft and Papadopoulos (1967)

LNAPL baildown tests are inherently transient, meaning that fluid levels and flow rates change with time. Experience with transient aquifer tests suggests that at least two parameters are necessary to describe system performance. With a conventional pumping test one estimates the aquifer transmissivity and storage coefficient. For LNAPL baildown test analysis, both parameters are also necessary, though only the LNAPL transmissivity is of direct interest.

The Bouwer and Rice (B&R) method is conceptually the simplest. The method uses a linear model (Thiem equation) to relate LNAPL discharge to LNAPL drawdown, and is based on continuity of LNAPL volume within the well. LNAPL drawdown versus time data are used to determine the LNAPL transmissivity, based on an estimate of the well radius of influence provided through the empirical analysis presented by Bouwer and Rice (1976). Interesting questions remain in the literature between the applications of the B&R method for LNAPL baildown testing as presented by Lundy and Zimmerman (1996) and Huntley (2000). These approaches differ in terms of assumed fluid levels in the well during recovery. The Huntley method assumes that the water table elevation remains constant during the recovery period. The Lundy method, which proposes removal of a small slug of LNAPL from the well, assumes that the depth to water remains constant during the recovery period. This difference in assumptions results in the Huntley method including an additional factor $1/(1 - \rho_r)$ in the calculation of LNAPL transmissivity, where ρ_r is the LNAPL-water density ratio. For many LNAPL transmissivity baildown tests, neither assumption is observed. For the general case, Andrew Kirkman (personal communication) suggests introduction of the J-ratio parameter that is directly based on measured data to address this issue. The [Kirkman J-ratio](#) is described in Appendix A and the J-ratio method is used herein for both the B&R, and the CB&J methods. The magnitude of the J-ratio is determined by the user using Fig. 4 on the “Figures” worksheet. The B&R method is developed in Appendix C.

The Cooper and Jacob (C&J) method provides an estimate of the LNAPL transmissivity based on the LNAPL discharge to the well and LNAPL drawdown, as a function of time. The method also requires estimation of an LNAPL storage coefficient. Guidance on suggested magnitudes of the LNAPL storage coefficient is provided for the user. The C&J method is developed in Appendix D.

The Cooper, Bredehoeft and Papadopoulos (CB&J) method provides an estimate of the LNAPL transmissivity based on measurements of LNAPL drawdown versus time. The method also requires an estimate of the LNAPL storage coefficient. The CB&P method does not directly use the LNAPL discharge to the well, and it does require an estimate of the effective initial LNAPL drawdown. The CB&P method is developed in Appendix E.

LNAPL can also be found under confined or perched conditions. Methods based on the Bouwer and Rice method of analysis are developed for confined and perched LNAPL in Appendices F and G, respectively.

Discussion

There is no *a priori* preferred method for analysis of LNAPL baildown test data. The B&R method is good for long well purging events, whereas relatively instantaneous events are used with the C&J and CB&P methods because they incorporate transient storage effects. The B&R method is independent of absolute time; rather, just the slope of the log-normalized drawdown versus change in linear time is important. However, if a straight line is not observed with B&R and it concaves upward (as a result of storage effects), then C&J or CB&P are more able to

account for the effects attributed to storage. Absolute time is critical for both C&J and CB&P, and thus it is necessary to adjust the effective time origin when early-time data is eliminated because of filter pack drainage. With the B&R method, the well radius of influence is estimated using well configuration data based on analog simulation analysis described by Bouwer and Rice (1976) for flow of groundwater to a well in an unconfined aquifer. This relationship is assumed to hold for LNAPL. The C&J method is based on an approximate solution describing flow of groundwater to a well under conditions of constant discharge and variable drawdown, and constant drawdown and variable discharge. The relationship is also assumed to apply to flow of LNAPL to a well when both the LNAPL discharge and LNAPL drawdown vary with time. The CB&P method is based on an analytical solution for a slug test in a confined aquifer, and is assumed to apply for LNAPL under unconfined conditions. With the CB&P method, both the effective initial drawdown and LNAPL storage coefficient must be estimated along with the LNAPL transmissivity. Because the CB&P method does not directly consider data regarding LNAPL discharge to the well, it is possibly the most uncertain method of analysis. Nevertheless, when properly applied, the user can often estimate LNAPL transmissivity value with coefficient of variation (ratio of the standard deviation to mean value) of 20 % or less when considering analyses using all three methods.

6.2. Time Cutoff and Time Adjustment

Early-time data from baildown testing may be significantly impacted by filter-pack drainage or other effects that do not reflect LNAPL flow from the formation to the well during recovery. Such data may be eliminated by specifying a cutoff time. Data from times earlier than the cutoff time are not considered in estimation of LNAPL transmissivity. The cut-off time may be used with the B&R, C&J, and CB&P methods. The B&R method does not depend on the time origin, so no further adjustments are necessary. However, both the C&J and CB&P methods include an LNAPL storage coefficient as a parameter, which represents a capacitance factor, and time origin is significant to the theoretical model. For the C&J method a time adjustment of the apparent time origin may be applied. One may think of the Time Adjustment as accounting for the delay in LNAPL flow from the formation to the well associated with the duration of significant filter-pack drainage. Limited experience suggests that the Time Adjustment and Time_{cut} may be related through the following: $\text{Time Adjustment} = (0.6 \text{ or } 2/3) * \text{Time}_{\text{cut}}$. The effects of Time_{cut} and Time Adjustment are shown in Figure 6.1. In this figure, it is desired to eliminate data earlier than 25 minutes because of effects from filter-pack drainage ($\text{Time}_{\text{cut}} = 25$ minutes); for a discussion of how this 25-minute Time_{cut} was selected, see discussion leading to Fig. 7.4 below. A Time Adjustment = 15 minutes is applied for analysis of LNAPL transmissivity using the C&J method, meaning that the apparent time origin for data later than 15 minutes is shifted as shown. For the CB&P method, one simply uses the estimated drawdown at the Time_{cut} as the initial drawdown value.