Learning Objectives

- Basic Baildown Test Analysis (Bouwer-Rice)
- Input Parameter Sensitivity
- Critical Baildown Test Factors

Calculation of LNAPL Tn via Baildown Testing
LNAPL Transmissivity (Tn) for Recoverability/Producibility

- Accounts for magnitude of the mobile interval thickness
- Accounts for soil permeability
- Accounts for LNAPL properties
- Accounts for variability in $k_n$ across the mobile interval

$$T_n = \sum K_n \text{ over } b_n$$

$$K_n = \frac{\rho_n \cdot g \cdot k \cdot k_m}{\mu_n}$$

$k_n(S_n)$ varies the mobile interval
LNAPL Transmissivity, What Are We Measuring?

Recovery Rate versus Drawdown

LNAPL TRANSMISSIVITY TYPE CURVES

LNAPL RECOVERY RATE (GPD)

LNAPL RECOVERY RATE (GPY)

LNAPL DRAWDOWN (FT)

0.01
0.1
1
10
3.7E+00
3.7E+01
3.7E+02
3.7E+03
3.7E+04

0.01
0.1
1
10
3.7E+00
3.7E+01
3.7E+02
3.7E+03
3.7E+04

0.01
0.1
1
10
3.7E+00
3.7E+01
3.7E+02
3.7E+03
3.7E+04

SKIMMING RANGE

VACUUM ENHANCED SKIMMING RANGE

MULTI-PHASE & WATER ENHANCED RECOVERY

10/17/18
What Are We Focused on Measuring?

- **Drawdown** – Measure fluid levels and calculate
  - Gauging Methods
  - Occasionally Transducers
  - Measuring Drawdown is similar for Baildown Tests and Manual Skimming Tests

- **Discharge** – Rate LNAPL flows for a given drawdown
  - Measurement Varies between Manual Skimming and Baildown
  - The intent is to decrease measurement error by moving to manual skimming at low thicknesses
Baildown Test Procedures

- Measure initial Depth to Product (DTP) and Depth to Water (DTW)
- Rapidly remove LNAPL from well (with little water if possible)
- Measure DTP and DTW at different times, rapidly at first and increasing interval later (recovery generally varies logarithmically with time)
- When possible, monitoring of DTP and DTW should continue until complete recovery achieved
- 20 to 30 measurements (DTP and DTW) are generally adequate
- For more information see video at
  - https://www.youtube.com/watch?v=2c8TLQid-bI
Removal of LNAPL

- Bailer – messy, time consuming, disturbance of fluids, water removal (I still use it)

- Peristaltic Pump – can remove only LNAPL – best

- Vacuum Truck – removes all fluids rapidly

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LNAPL Removal Effects

Peristaltic pump – low water removal – steady water table

Vacuum Truck – large fluids removal – large water inflow – unsteady water table
API Baildown Spreadsheet

- Provides tool consistent with ASTM methodology to analyze baildown tests
  - Helps identify and eliminate borehole recharge
  - Includes methodology to analyze constant discharge portions of confined and perched tests
  - Includes multiple graphs for data interpretation

- Analysis Methods
  - Bouwer-Rice
  - Cooper-Jacob
  - CB&P
The Spreadsheet

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<tbody>
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<td>Well Radius, r_w (ft)</td>
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<tr>
<td>LNAPL Density Ratio, p_s</td>
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<tr>
<td>Bottom of Screen (ft bgs)</td>
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<tr>
<td>LNAPL Baldown Vol. (gal)</td>
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| Effective Radius, r_e (ft):  | 0.260 |
| Effective Radius, r_ew (ft): | 0.245 |
| Initial Casing LNAPL Vol. (gal): | 2.10 |
| Initial Filter LNAPL Vol. (gal): | 2.81 |

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<th>Enter Data Here</th>
<th>Water Table Depth (ft)</th>
<th>LNAPL Drawdown s_s (ft)</th>
<th>Average Time (min)</th>
<th>LNAPL Discharge Q_s (ft³/d)</th>
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<th>b_n</th>
<th>r_e</th>
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Data Analysis

10/17/18
Post-Test Diagnostic Tools

- Use Measurement of DTP and DTW to determine
  - LNAPL Discharge to Well - Spreadsheet
    ▪ Requires estimate of filter pack specific yield
  - LNAPL Drawdown – Spreadsheet with user direction

- Diagnostic Tools
  - Plot of LNAPL discharge versus LNAPL drawdown
    ▪ Identify initial non-equilibrium conditions
    ▪ Identify confined/perched LNAPL conditions
  - Plot of LNAPL thickness versus LNAPL drawdown
    ▪ Used to determine the J-factor for data analysis
What are the Key Aspects of the Discharge vs Drawdown Relationship

- Near linear relationship between discharge and drawdown, NOT TIME
- The discharge goes to zero at zero drawdown

Data Analysis

Result: LNAPL Discharge To Well

Result: No LNAPL Flow

Figure 3

LNAPL Drawdown - Discharge Relation
Poor Quality Tests

► Do not exhibit ideal discharge vs drawdown behavior and are difficult to analyze

► Spend 2 hours removing the borehole volume
  • If it recovers fully in thirty minutes, repeat test to be certain
  • Most tests distorted by not knowing filter pack recharge vs formation
  • Slug test still have this issue
Know Equilibrium Fluid Levels

- Wells where periodic bailing occurs are high risk
- Wells screens should not be occluded
- Historical hydrographs and diagnostic gauge plots are useful to take into field for comparison

Provided by A. Kirkman
Figures Are A Key Step in Analysis & Review

Data Analysis

Figure 1

Time (minutes)

Depth (ft)

DTW (blue), Water Table (green), DTP (red)

Figure 2

Time (minutes)

Depth (ft)

DTW (blue), Water Table (green), DTP (red)

Figure 3

LNAPL Discharge (ft³/d)

LNAPL Drawdown - Discharge Relation

Figure 4

LNAPL Drawdown - Discharge Relation

LNAPL Thickness $b_n$ (ft)

Qn (ft³/d) $s_n$ (ft)

0 0 1.53 0

6 0.12 0 0.275

Drawdown Adjust. $\Delta s_n$ (ft) 0.00

J-ratio -0.180

0.6 33.76

64 33.76

0.6 35.39

64 35.39

16.1 #N/A 32.8

16.1 #N/A 0.0
LNAPL Drawdown–Discharge Curve as Diagnostic Tool

- Drawdown-Discharge curve should be linear through the origin
- Residual drawdown at zero discharge implies initial non-equilibrium between formation and well fluids
- Equilibrium fluid levels need to be well supported with data

Residual drawdown = 0.08 ft = 2.4 cm
ASTM and API provide new tools to understand if the data is ideal or what corrections, if any, are appropriate.

Where equilibrium fluid levels are not well understood, equilibrium fluid level inputs can be adjusted to line the discharge versus drawdown trend to intersect the origin (0,0).
Non-Ideal Discharge Versus Drawdown Graphs - 1

- Filter Pack Recharge
- Rapid decrease of discharge but drawdown still remains

LNAPL Drawdown - Discharge Relation

Depth to Product vs. LNAPL Discharge

Discharge (ft³/d)

LNAPL Discharge (ft³/d)

LNAPL Drawdown (ft)

DTP (ft bgs)
J-Factor: $J = \frac{ds_n}{db_n}$

LNAPL column floats on stable water table
$\Rightarrow J = - (1 - \rho_r)$

Huntley Method

LNAPL column grows on stable LNAPL-water interface
$\Rightarrow J = -1$

Lundy Method
LNAPL Drawdown-Thickness as Diagnostic Tool

- Provides significant parameter (J-factor) used in LNAPL transmissivity calculation

J = - 0.223

J = - 1.225
(Generalized) Bouwer and Rice Method

\[ T_n = \frac{r_e^2 \ln(R/r_w) \ln(s_n(0)/s_n(t))}{2(1-J)t} \]

- \( r_e \) = effective well radius including filter pack storage
- \( R/r_w \) = radius of influence ratio determined from initial LNAPL column thickness using Bouwer and Rice’s “C-curve”
- Log-drawdown versus time curve should be linear, slope used to determine \( T_n \)
- Huntley Method: - \( J = (1 - \rho_r) \)
- Lundy Method: - \( J = 1 \)
Bouwer and Rice Worksheet (B&R)

- Only parameter is the cut-off time \((\text{Time}_{\text{cut}})\) to eliminate early-time data impacted by filter pack drainage and/or other factors.

- How do you estimate the cut-off time?

- Look at Fig 3 (drawdown-discharge) \(\rightarrow\) linear relation when \(s_n = 0.25\) ft.

\[
T_n = \frac{r_e^2 \ln\left(\frac{R}{r_e}\right) \ln\left(s_n\left(t_1\right)/s_n\left(t\right)\right)}{2(\text{J}))(t-t_1)}
\]
Use Figures 3 & 10 to find cut-off time

Cut-off time = 25 minutes when $s_n = 0.28$ ft

Useful data

Filter pack drainage – exclude data from analysis
Residual drawdown = 0.08 ft = 2.4 cm

Data Analysis

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Exercise

Discuss in Groups the Test

• Filter Pack Recharge
• Equilibrium Fluid Levels
• Can we Analyze them?
• What portion of the data should be analyzed?
  ▪ Indicate in Period of Time or Consider defining in terms of Drawdown or Discharge Ranges
Example #1

LNAPL Discharge (ft³/d)

LNAPL Drawdown - Discharge Relation

LNAPL Drawdown (ft)
LNAPL Discharge (ft³/d)

LNAPL Thickness bₙ (ft)

Time (minutes)

Depth (ft)

DTW (blue), Water Table (green), DTP (red)
Example #2

Initial Thickness – 1.3 ft
Max Skimming Drawdown – 0.26 ft
No Recovery After 100 minutes
## B-R Type Curve Sheet

Print for Field Use or Use for Post Test Review

<table>
<thead>
<tr>
<th>Type Curve ID</th>
<th>Type Curve Name</th>
<th>Notes</th>
<th>Max Time (min)</th>
<th>Transmissivity (ft²/day)</th>
<th>J-Ratio</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>T=10 ft²/day</td>
<td></td>
<td>150</td>
<td>10</td>
<td>-0.180</td>
</tr>
<tr>
<td>2</td>
<td>T=5 ft²/day</td>
<td></td>
<td>200</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>T=2 ft²/day</td>
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<td>200</td>
<td>2</td>
<td>-0.22</td>
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<tr>
<td>4</td>
<td>T=1 ft²/day</td>
<td></td>
<td>200</td>
<td>1</td>
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<tr>
<td>5</td>
<td>T=0.5 ft²/day</td>
<td></td>
<td>200</td>
<td>0.5</td>
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<tr>
<td>6</td>
<td>T=0.2 ft²/day</td>
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<td>200</td>
<td>0.2</td>
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<tr>
<td>7</td>
<td>T=0.1 ft²/day</td>
<td></td>
<td>200</td>
<td>0.1</td>
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</table>

**B&R Type Curves:** Casing Rad. (ft) = 0.042; Borehole Rad. (ft) = 0.0416666666666667

**Normalized Drawdown (s/s_{initial}) (ft/ft)**

**Time (min)**

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Type Curve (2-inch Well, 8.25- Borehole and Static Potentiometric Surface)

B&R Type Curves: Casing Rad. (ft) = 0.083 ; Borehole Rad. (ft) = 0.344 ; J-Ratio = -0.18

Normalized Drawdown \(s/s_{	ext{initial}}\) (ft/ft)

Time (min)

- \(T=0.05\) ft\(^2\)/day
- \(T=0.15\) ft\(^2\)/day
- \(T=0.3\) ft\(^2\)/day
- \(T=1.0\) ft\(^2\)/day
- \(T=2.0\) ft\(^2\)/day
- \(T=5.0\) ft\(^2\)/day
- \(T=10.0\) ft\(^2\)/day
Transmissivity Testing

- Testing for Tn isn’t as much about as a value but being able to make a decision
- The use of the type curve for the specific scenario can aid in making a decision even if a single value isn’t obtained
- Filter pack recharge can interfere with any test
  - Filter pack recharge induces larger error than long periods of fluid removal
  - No one has defined instantaneous criteria for slug tests
  - Sensible criteria - 1/10th relative to time for a well to recover
DRAWDOWN
Mobile Interval of LNAPL for Unconfined Hydrostatic Conditions
Various Hydrogeologic Scenarios

HydroStatic
Perched Equilibrium

HydroStatic
Confined
LNAPL Drawdown Equations

- LNAPL in contact with mobile interval (unconfined, confined, perched)

\[ s_{n\_unconfined} = Z_{an\_static} - Z_{ao} \]

- Unconfined equilibrium potentiometric surface

\[ s_n = (1 - \rho_r)(b_{n\_static} - b_n) \]

- Confined

  - General for LNAPL/Water above confining contact

\[ s_{n\_confined} = \frac{(Z_{an*} - Z_{cc})\rho_o - (Z_{nw(t)} - Z_{cc})\rho_w - (Z_{an(t)} - Z_{nw(t)})\rho_o}{\rho_o} \]

  - LNAPL water above confining contact and equilibrium potentiometric surface

\[ s_{n\_confined} = b_{nf} \frac{1 - \rho_r}{\rho_r} \]

- Perched

\[ s_{n\_perched} = b_{nf} \]
Rail Car Shops Facility
Perched LNAPL
Confined LNAPL
HOW DO WE CALCULATE DRAWDOWN

CHANGE IN AIR/LNAPL INTERFACE?
Consider The Pressure Difference in the Mobile Interval

EQUILIBRIUM FLUID LEVELS

BAILDOWN TEST INITIATED $t_0$

BAILDOWN TEST $t_1$

BAILDOWN TEST $t_2$

Declining Discharge Period $t_2$

$Z_{AO}(t)$

$Z_{AO}^{(*)}$

$Z_{POT}(t)$

$Z_{POT}^{(*)}$

$Z_{CC}$

$Z_{OW}(t)$

$Z_{OW}^{(*)}$

COARSE GRAINED LAYER WITH LOW ENTRY PRESSURE HEAD

FINE GRAINED LAYER WITH HIGH ENTRY PRESSURE HEAD

Mobile LNAPL Interval

Constant Discharge Periods $t_0$ & $t_1$
Confined LNAPL Baildown Test Scenarios

- Confined baildown tests can exhibit up to 3 periods of different drawdown calculation methods.
- Drawdown during time period t1 needs to consider changes in water head above the LNAPL layer in the formation as well as changes in LNAPL.
- Time period t1 can result in decreasing and constant discharge trends.
- Drawdown can be calculated using the difference in air/LNAPL interface for time periods similar to $t_2$ and $t_0$.

$$s[t_0&t_2] = Z_{ao*} - Z_{ao(t)}$$
Calculation of LNAPL drawdown for $t_1$:

- Applicable to equilibrium or non-equilibrium potentiometric surface
- Represents the LNAPL head difference at the confining contact between equilibrium conditions and a given point in time

### Equilibrium Pressure

$$P_{LNAPL}[Z_{cc}] = g(Z_{an} - Z_{cc})\rho_o$$

### Non-Equilibrium Pressure

$$P_{LNAPL}[Z_{cc}] = g(Z_{nw} - Z_{cc})\rho_w + g(Z_{an} - Z_{nw})\rho_o$$

Resulting Drawdown

$$s[Z_{cc}] = \frac{(Z_{ao^*} - Z_{cc})\rho_o - (Z_{ow(t)} - Z_{cc})\rho_w - (Z_{ao(t)} - Z_{ow(t)})\rho_o}{\rho_o}$$
Questions?