LNAPL Transmissivity ASTM Training Course Outline

- 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

Theory

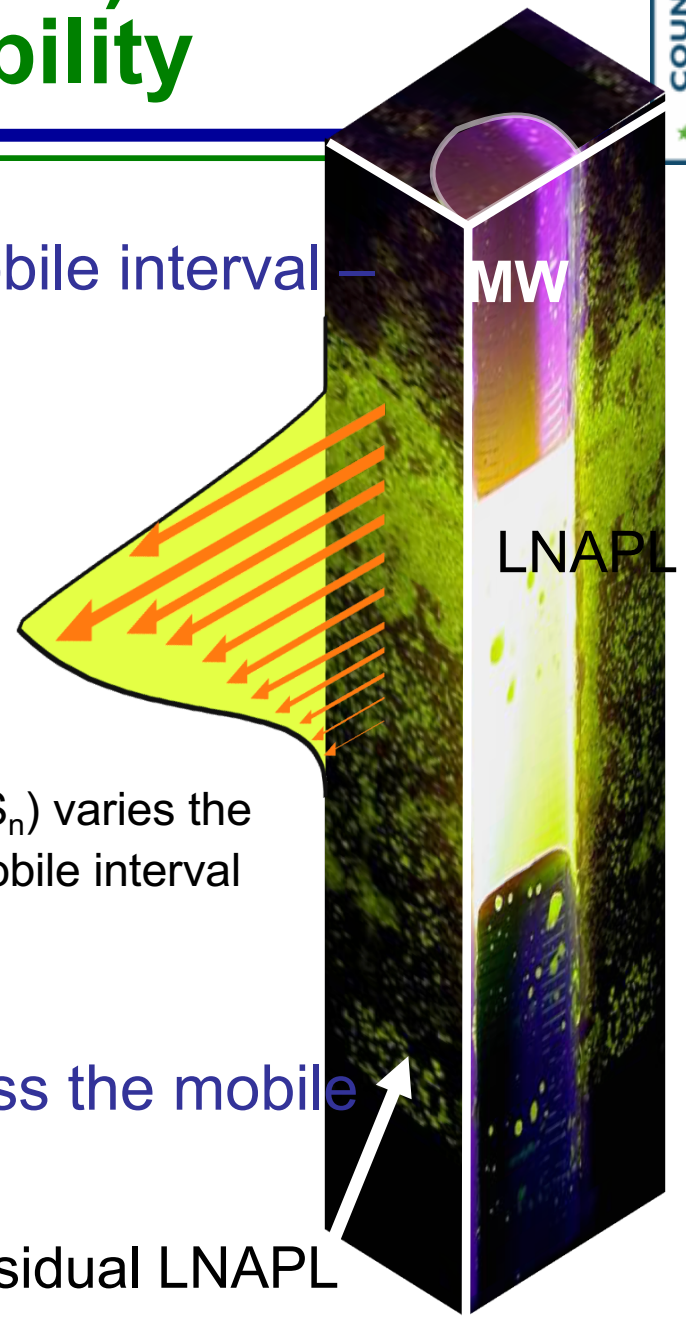
- Accounts for magnitude of the mobile interval – thickness
- Accounts for soil permeability

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

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

$k_n(S_n)$ varies the mobile interval

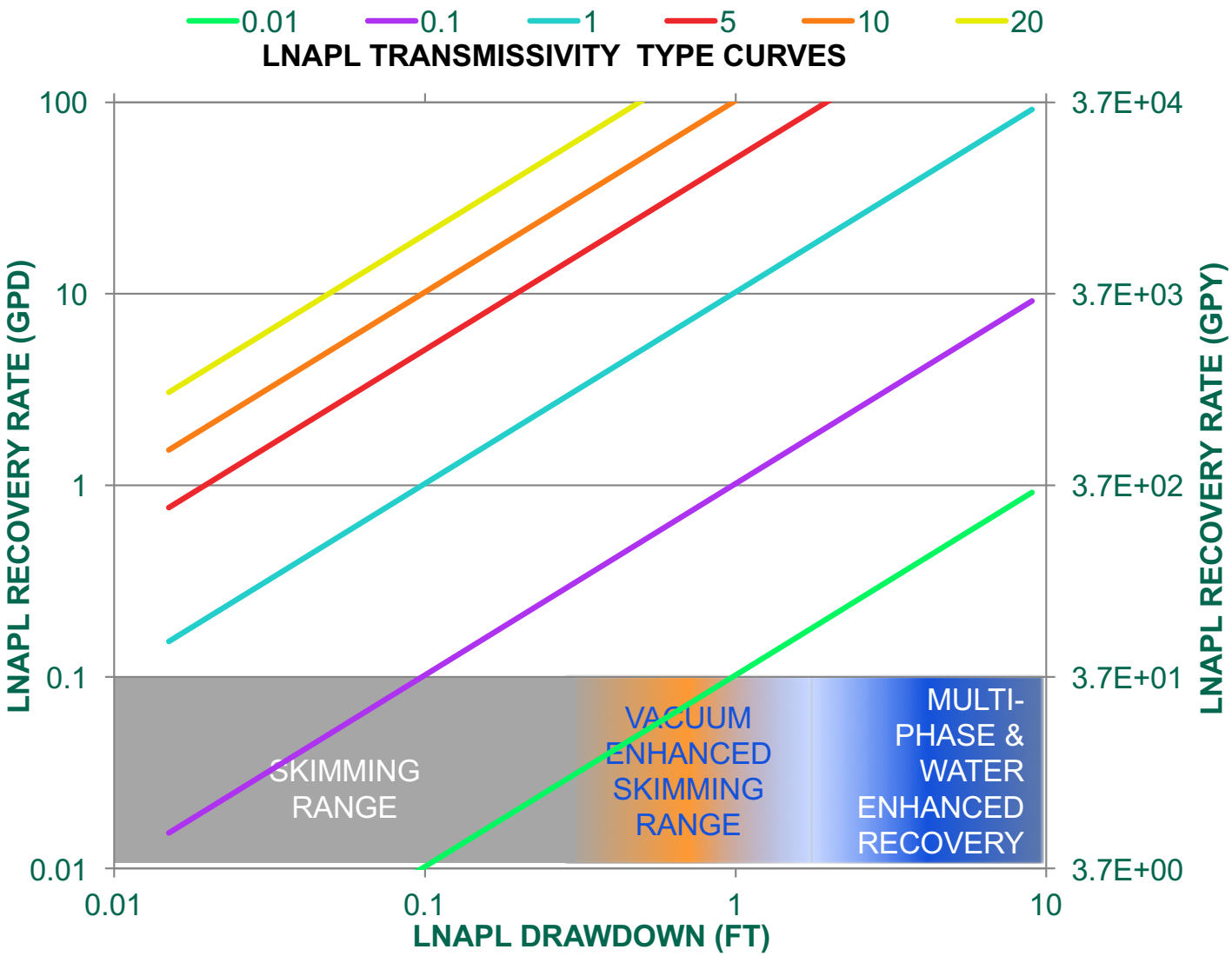
- Accounts for LNAPL properties
- Accounts for variability in k_n across the mobile interval



LNAPL Transmissivity, What Are We Measuring?

Recovery Rate versus Drawdown

Theory



What Are We Focused on Measuring?

Theory

- 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

Field Testing

- 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)

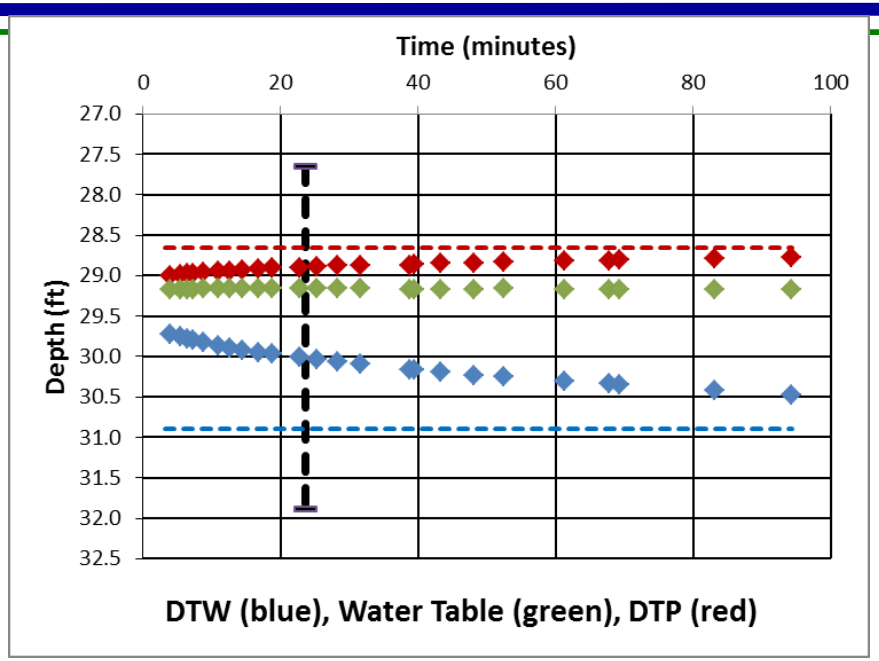
Spill Buddy ™

- Peristaltic Pump – can remove only LNAPL – best

- Vacuum Truck – removes all fluids rapidly

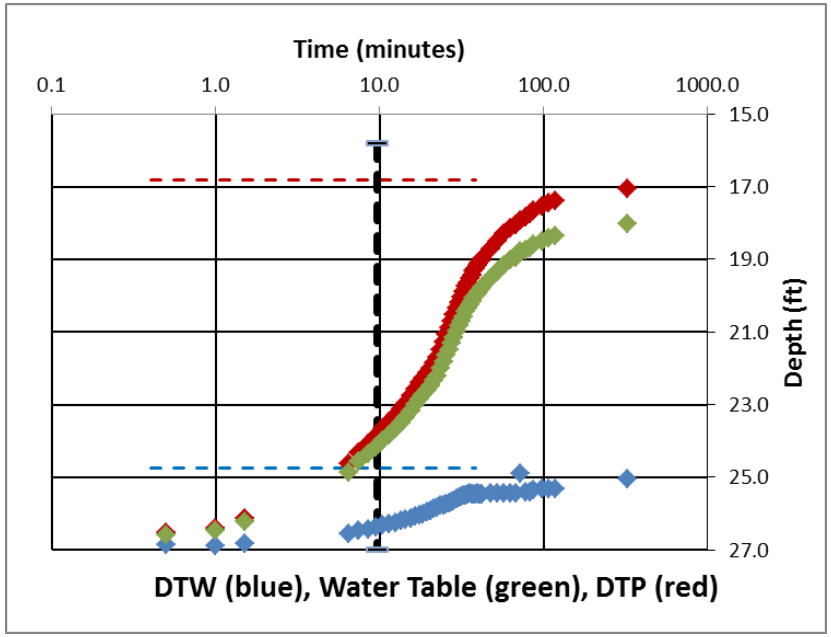
LNAPL Removal Effects

Field Testing



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

Data Analysis

Well Designation:	YYY	Beckett and Lyverse (2002)	
Date:	date		
Ground Surface Elev (ft msl)	0.0	Enter These Data	**Drawdown Adjustment (ft)**
Top of Casing Elev (ft msl)	0.0		
Well Casing Radius, r_c (ft):	0.170	r_{e1}	
Well Radius, r_w (ft):	0.500		0.08
LNAPL Specific Yield, S_y:	0.175		
LNAPL Density Ratio, ρ_r:	0.780		
Top of Screen (ft bgs):	0.0		
Bottom of Screen (ft bgs):	0.0		
LNAPL Baildown Vol. (gal.):			
Effective Radius, r_{e3} (ft):	0.260	Calculated Parameters	
Effective Radius, r_{e2} (ft):	0.245		
Initial Casing LNAPL Vol. (gal.	2.10		
Initial Filter LNAPL Vol. (gal.):	2.81		

	Enter Data Here					Water Table Depth (ft)	LNAPL Drawdown s_n (ft)	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	22.29	25.38	22.29	25.38	22.97					3.09	
Enter Test Data:	1.0	22.80	23.30	22.80	23.30	22.91	0.43				0.50	
	1.5	22.79	23.38	22.79	23.38	22.92	0.42	1.3	55.041	0.43	0.59	0.260
	2.0	22.74	23.41	22.74	23.41	22.89	0.37	1.8	48.925	0.40	0.67	0.260
	3.0	22.73	23.50	22.73	23.50	22.90	0.36	2.5	30.578	0.37	0.77	0.260
	4.0	22.72	23.54	22.72	23.54	22.90	0.35	3.5	15.289	0.36	0.82	0.260
	5.0	22.72	23.59	22.72	23.59	22.91	0.35	4.5	15.289	0.35	0.87	0.260
	7.5	22.69	23.66	22.69	23.66	22.90	0.32	6.3	12.231	0.34	0.97	0.260
	12.0	22.67	23.89	22.67	23.89	22.94	0.30	9.8	16.988	0.31	1.22	0.260
	15.0	22.67	23.90	22.67	23.90	22.94	0.30	13.5	1.019	0.30	1.23	0.260
	20.0	22.64	23.98	22.64	23.98	22.93	0.27	17.5	6.727	0.29	1.34	0.260
	25.0	22.62	24.04	22.62	24.04	22.93	0.25	22.5	4.893	0.26	1.42	0.260
	30.0	22.61	24.07	22.61	24.07	22.93	0.24	27.5	2.446	0.25	1.46	0.260
	40.0	22.6	24.15	22.60	24.15	22.94	0.23	35.0	2.752	0.24	1.55	0.260
	52.0	22.58	24.22	22.58	24.22	22.94	0.21	46.0	2.293	0.22	1.64	0.260

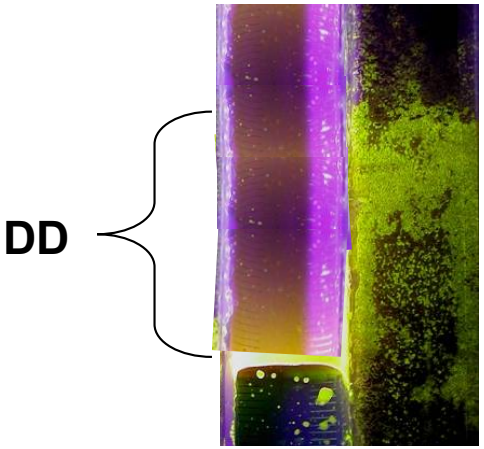
Post-Test Diagnostic Tools

- 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

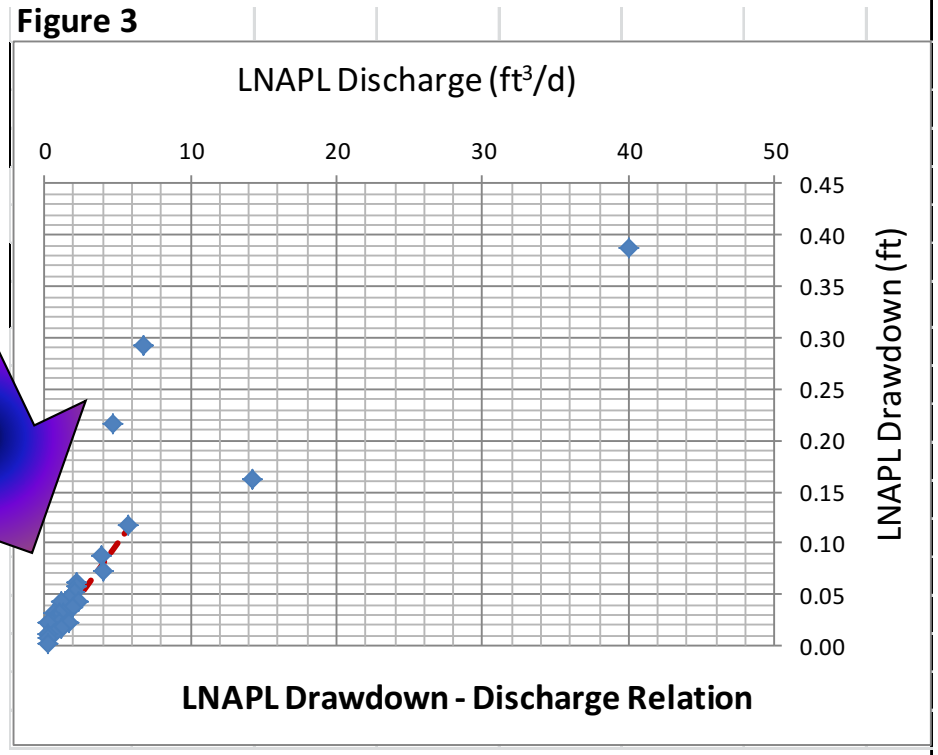
Drawdown >0



Result: LNAPL Discharge To Well

Drawdown =0

Result: No LNAPL Flow



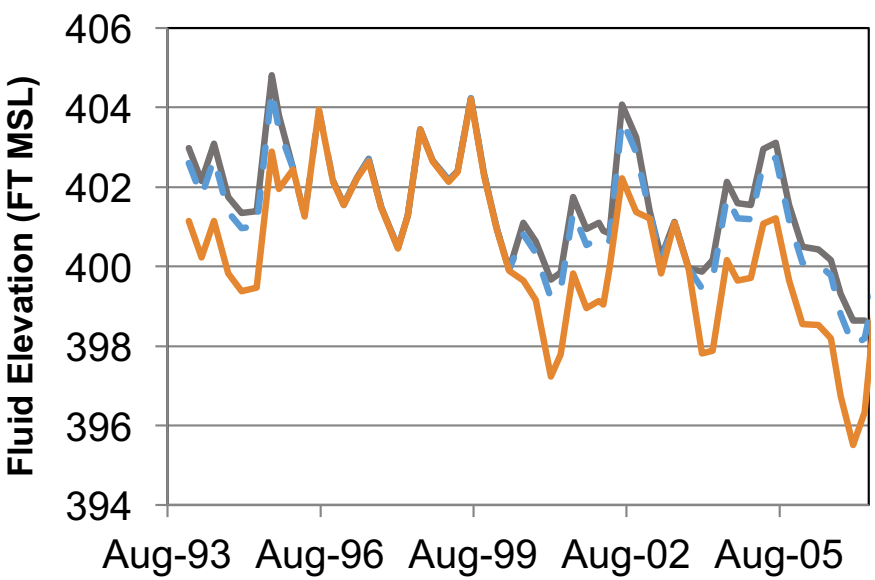
Poor Quality Tests

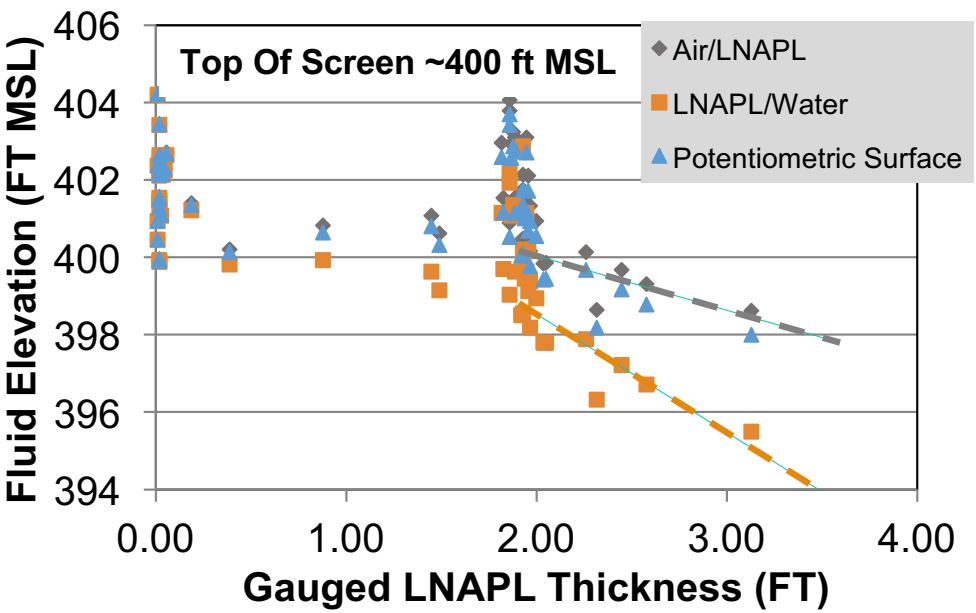
- Do not exhibit ideal discharge vs drawdown behavior and are difficult to analyze
- Spend 2 hours removing the borehole volume
  - If it recovers fully in thirty minutes, repeat test to be certain
  - Most tests distorted by not knowing filter pack recharge vs formation
  - Slug test still have this issue

Know Equilibrium Fluid Levels

Data Analysis

- 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

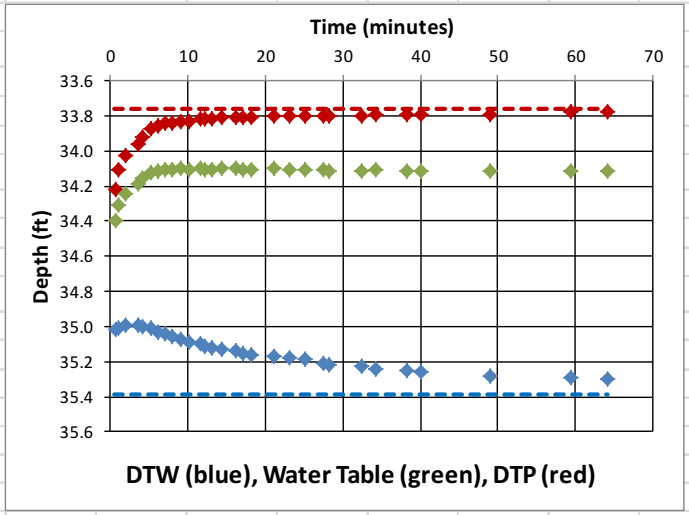
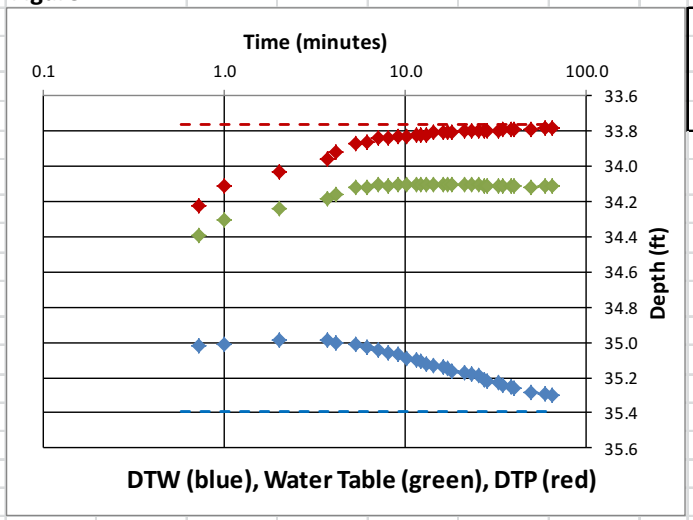


Figure 2



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

Figure 3

Q_n (ft^3/d)	s_n (ft)
0	0
6	0.12

Drawdown Adjust.	
Δs_n (ft)	0.00

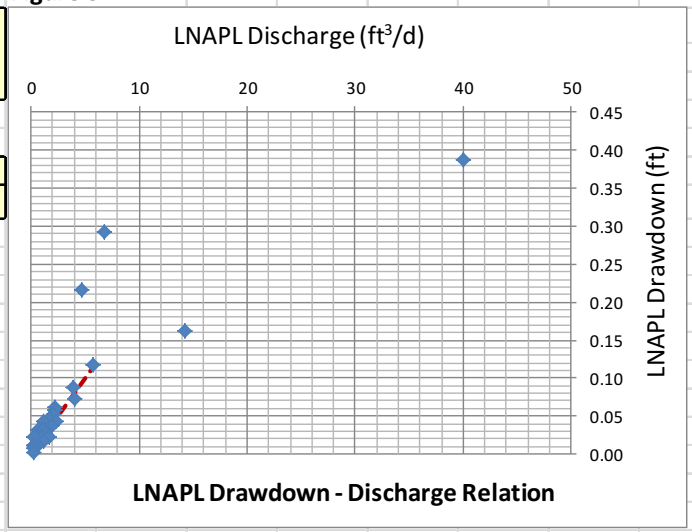
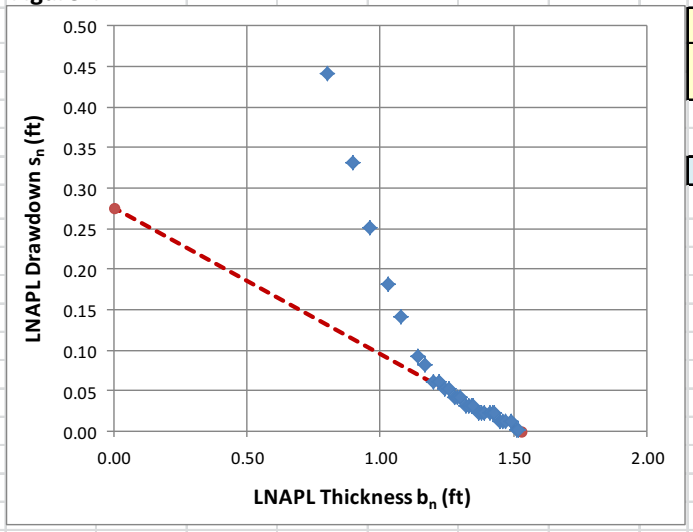


Figure 4



b_n	s_n
1.53	0
0	0.275

J-ratio	-0.180

Figure 5

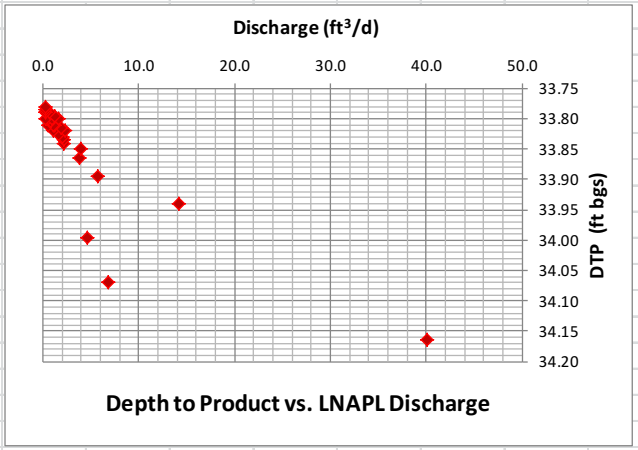


Figure 6

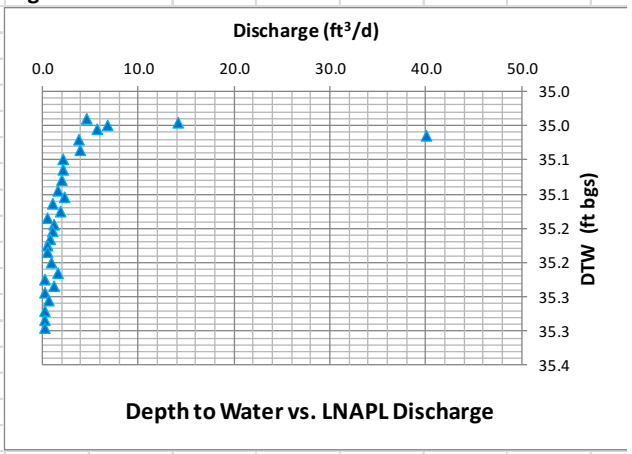


Figure 7

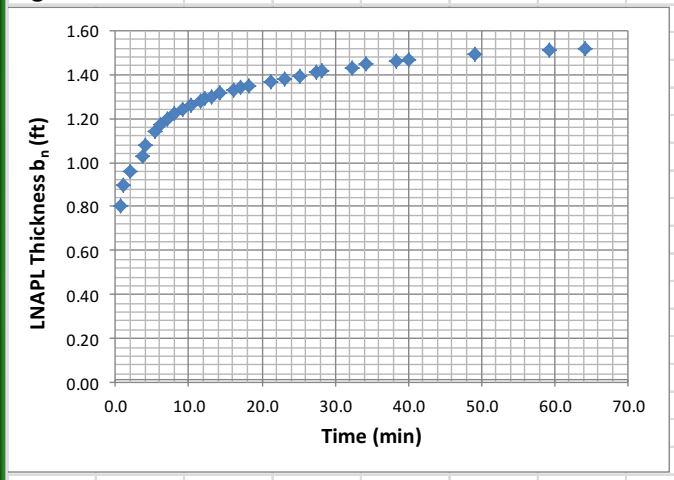


Figure 7

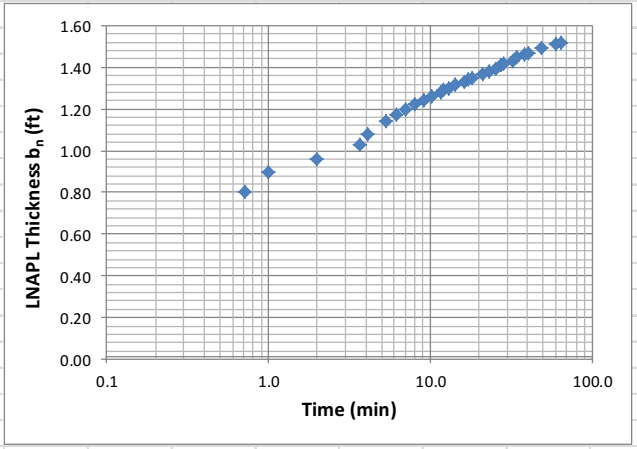


Figure 8

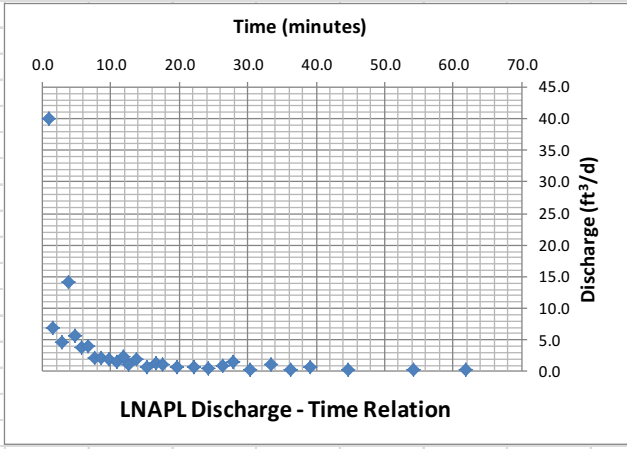


Figure 9

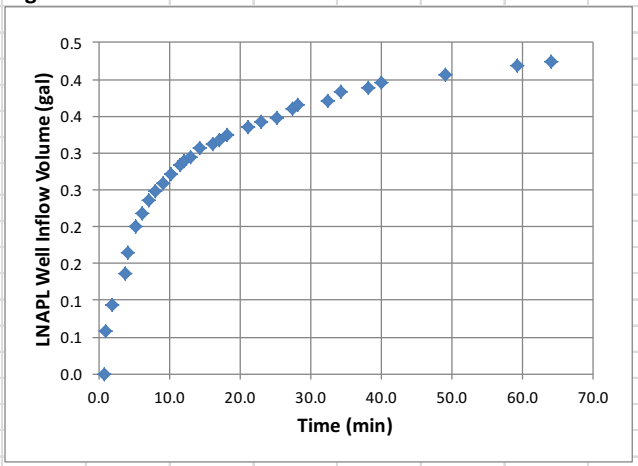
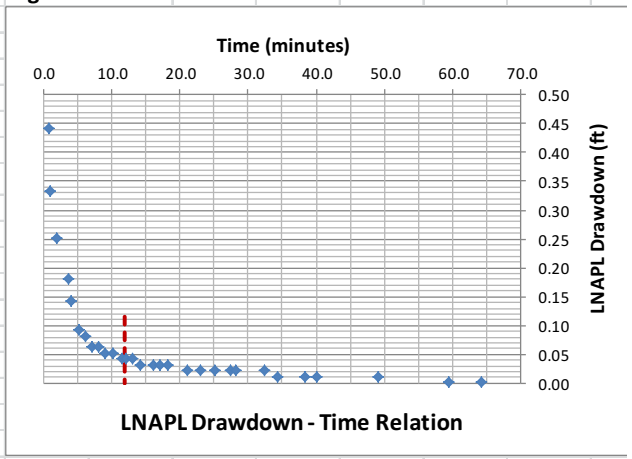


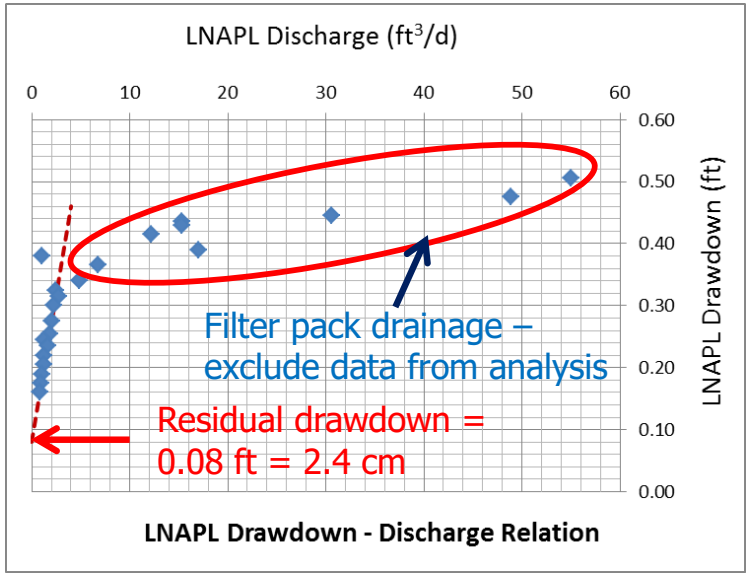
Figure 10



LNAPL Drawdown–Discharge Curve as Diagnostic Tool

Data Analysis

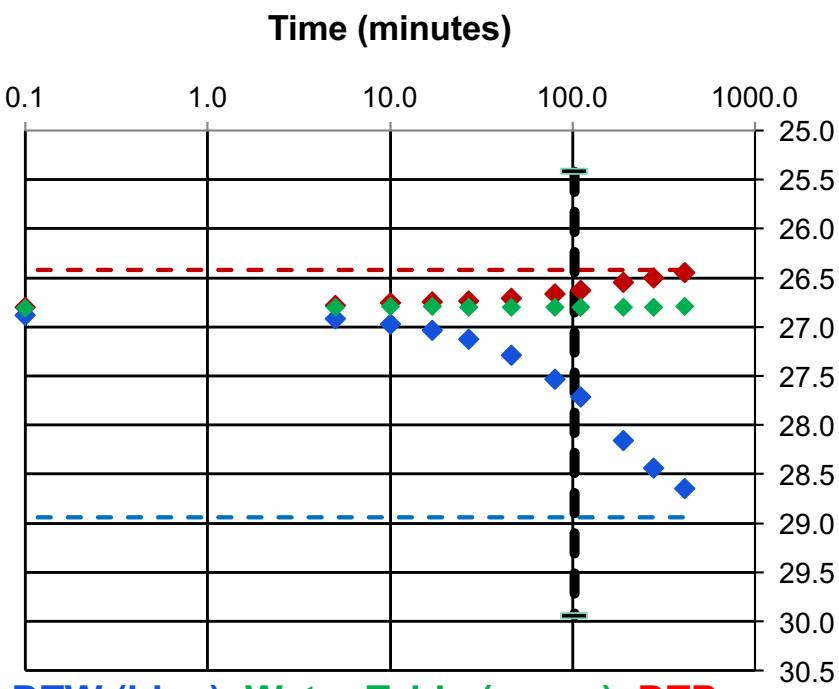
- Drawdown-Discharge curve should be linear through the origin
- Residual drawdown at zero discharge implies initial non-equilibrium between formation and well fluids
- Equilibrium fluid levels need to be well supported with data



Ideal LNAPL Baildown Test Example and Initial Data Review Tools

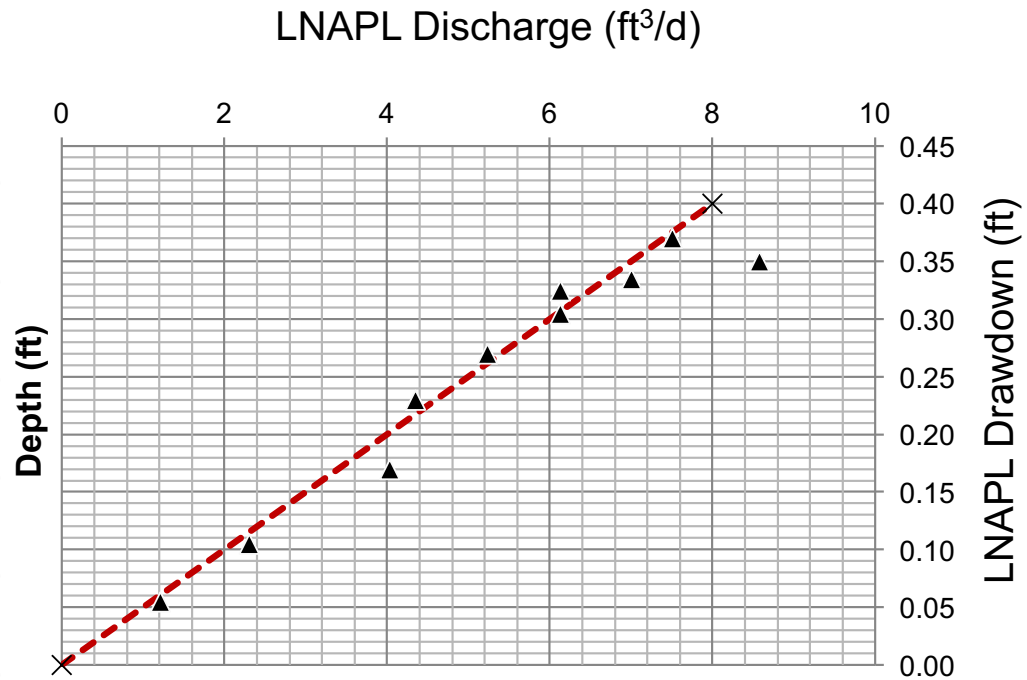
Data Analysis

- ASTM and API provide new tools to understand if the data is ideal or what corrections, if any, are appropriate



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

Hydrograph data help understand variability in the water-table and consistency of LNAPL recovery trends

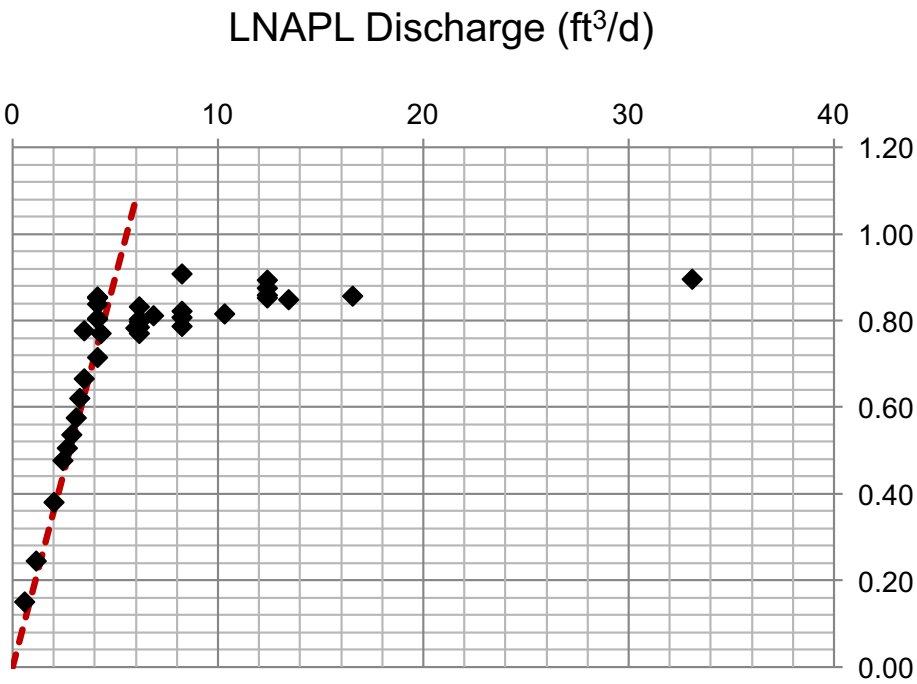


LNAPL Drawdown - Discharge Relation

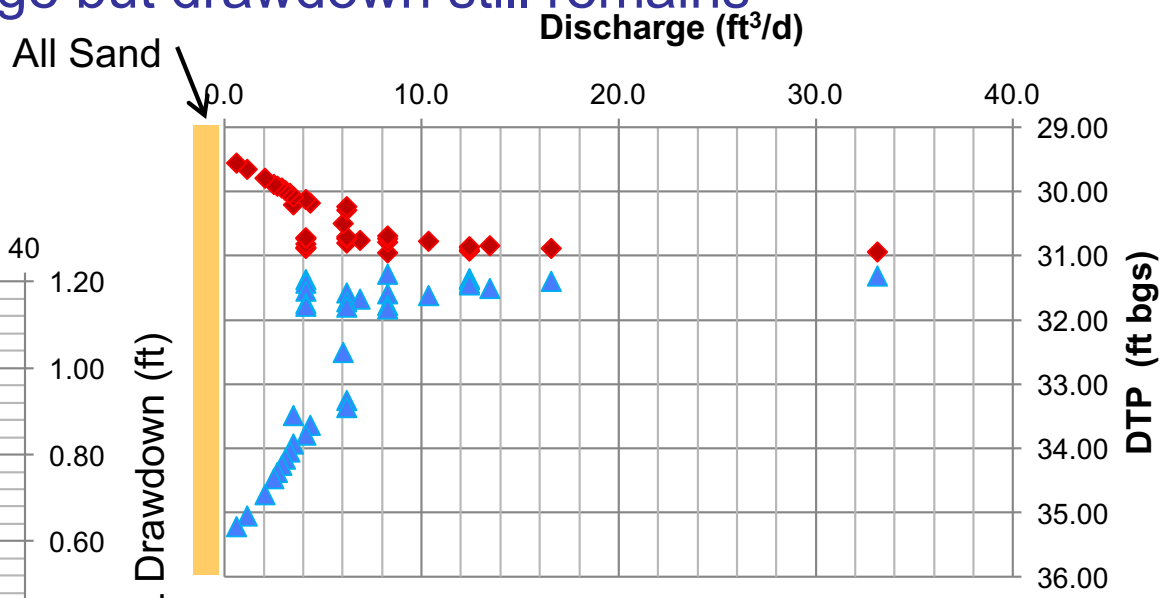
Where equilibrium fluid levels are not well understood, equilibrium fluid level inputs can be adjusted to line the discharge versus drawdown trend to intersect the origin (0,0)

Non-Ideal Discharge Versus Drawdown Graphs - 1

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

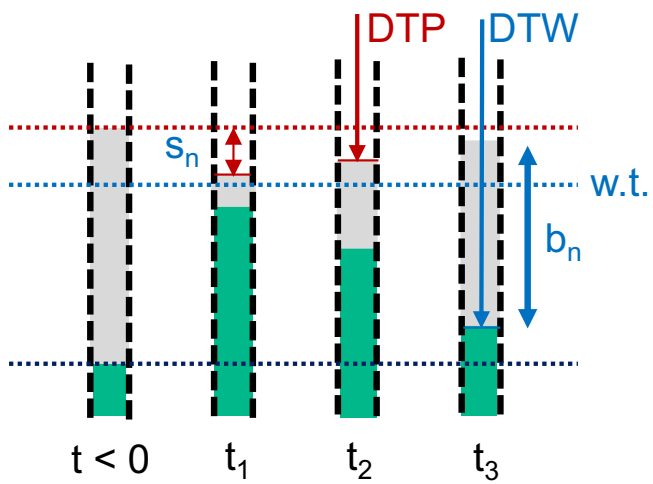


LNAPL Drawdown - Discharge Relation



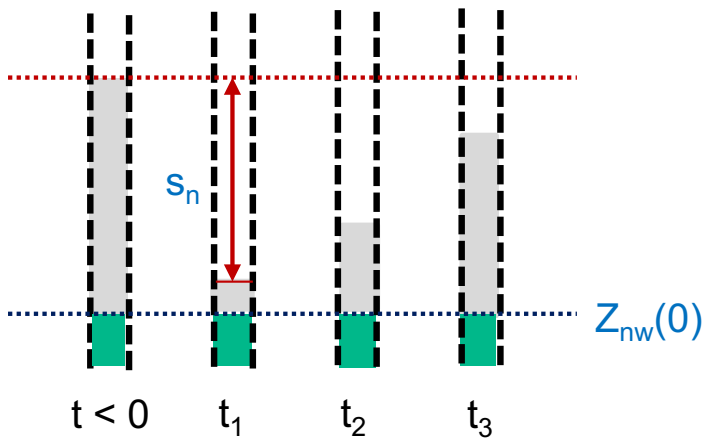
Depth to Product vs. LNAPL Discharge

J-Factor: $J = ds_n/db_n$



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

Huntley Method



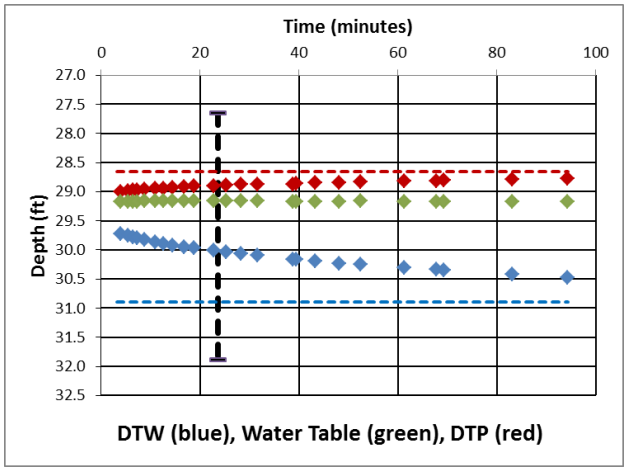
LNAPL column grows on stable LNAPL-water interface
→ $J = -1$

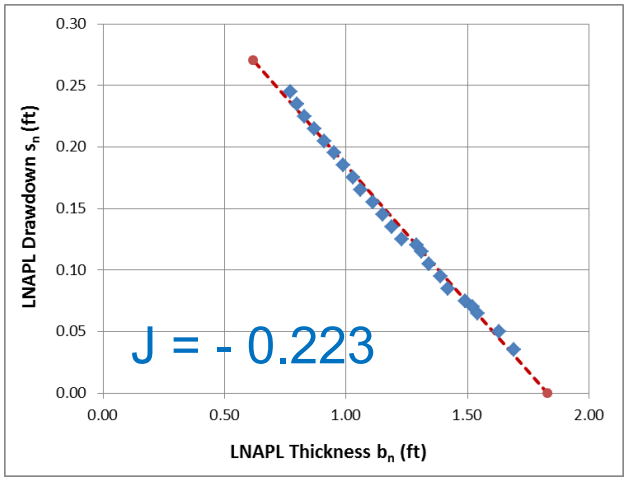
Lundy Method

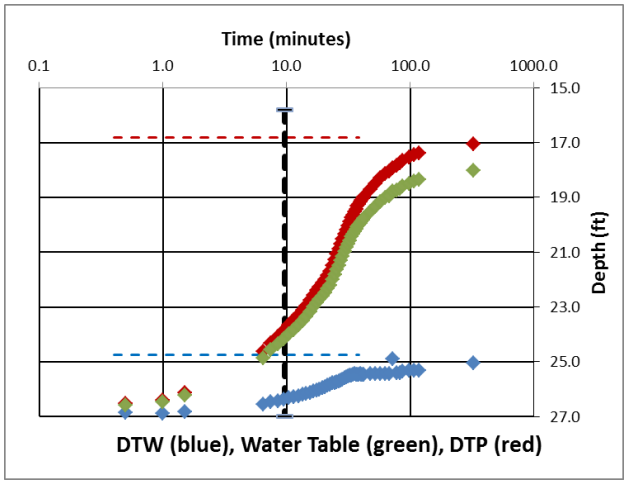
LNAPL Drawdown-Thickness as Diagnostic Tool

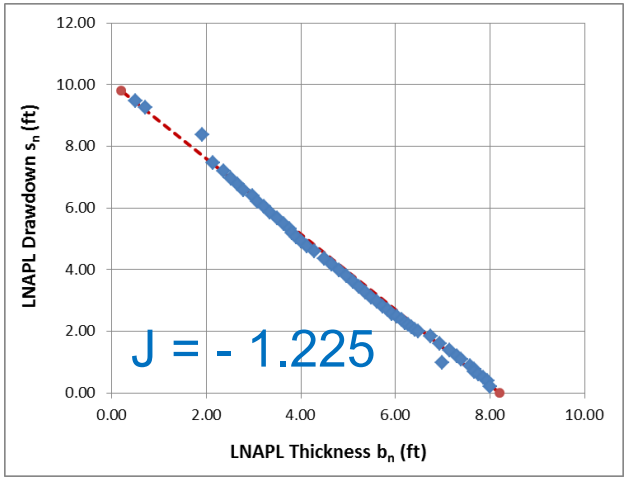
Data Analysis

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





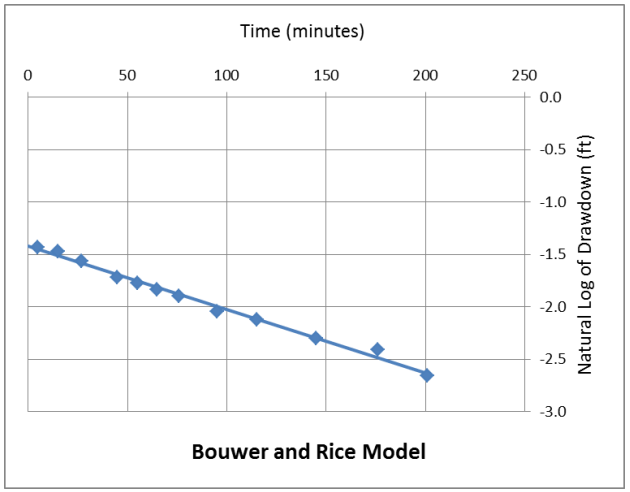




(Generalized) Bouwer and Rice Method

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

- 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)

Data Analysis

- Only parameter is the cut-off time ($Time_{cut}$) 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) → linear relation when s_n = 0.25 ft

Generalized Bouwer and Rice (1976)

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

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

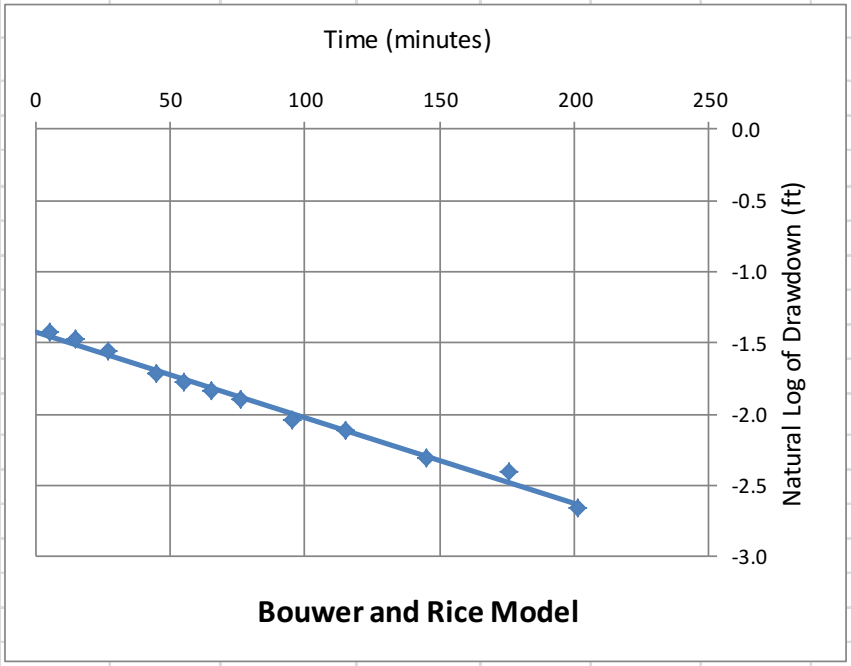
$Time_{cut}$	25	<- Enter or change value here

Model Results: T_n (ft^2/d) : 2.79 +/- 0.08 ft^2/d

L_e/r_e
11.9
C
1.27
R/r_e
6.14

J-Ratio
-0.192

Coef. Of Variation
0.03



Use Figures 3 & 10 to find cut-off time

Data Analysis

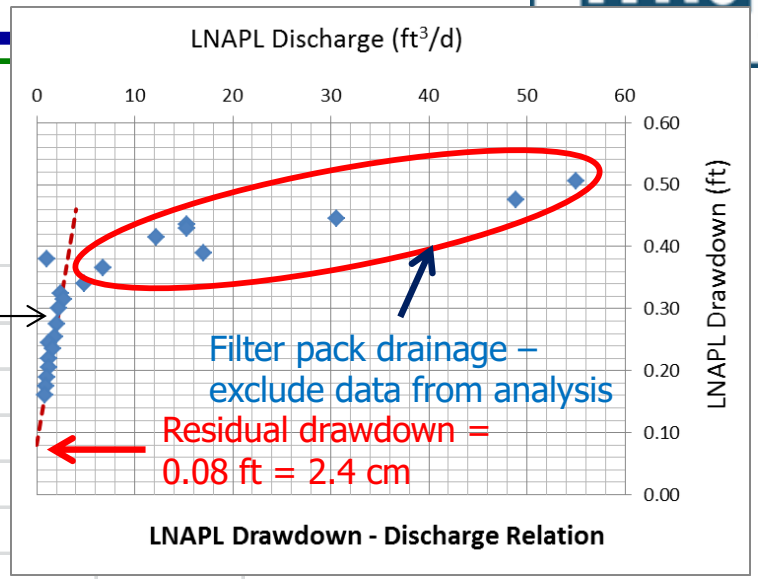
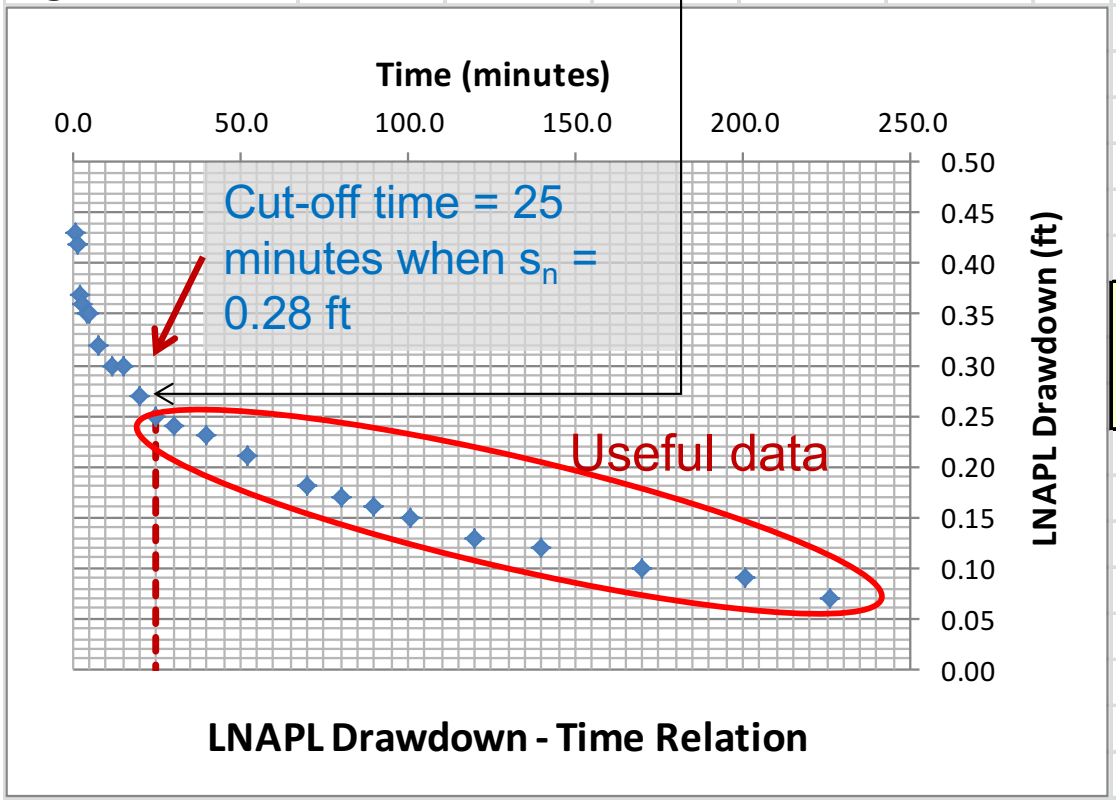


Figure 10

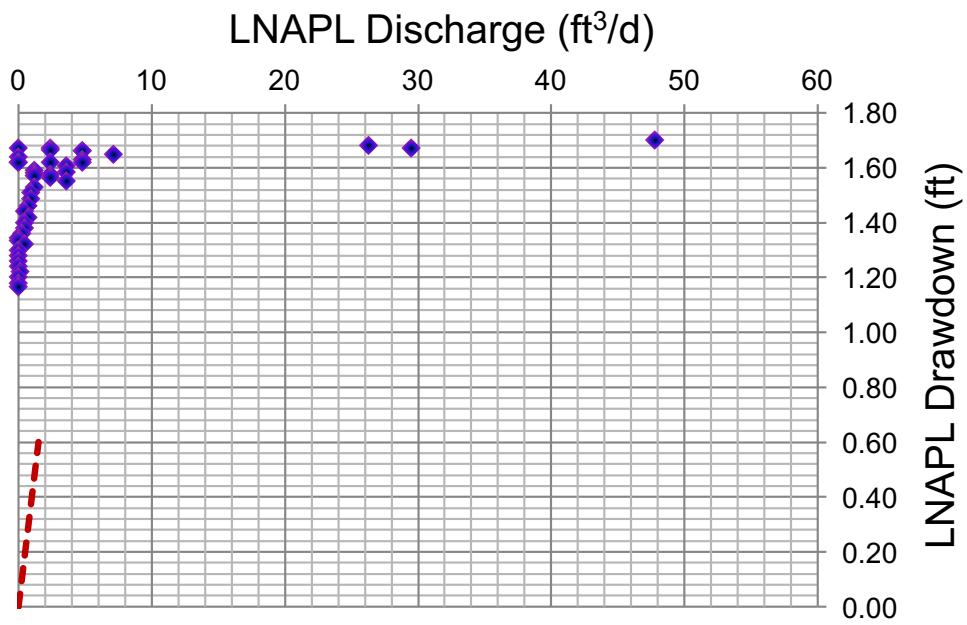


t (min)	s_n (ft)
25	0.25
25	0

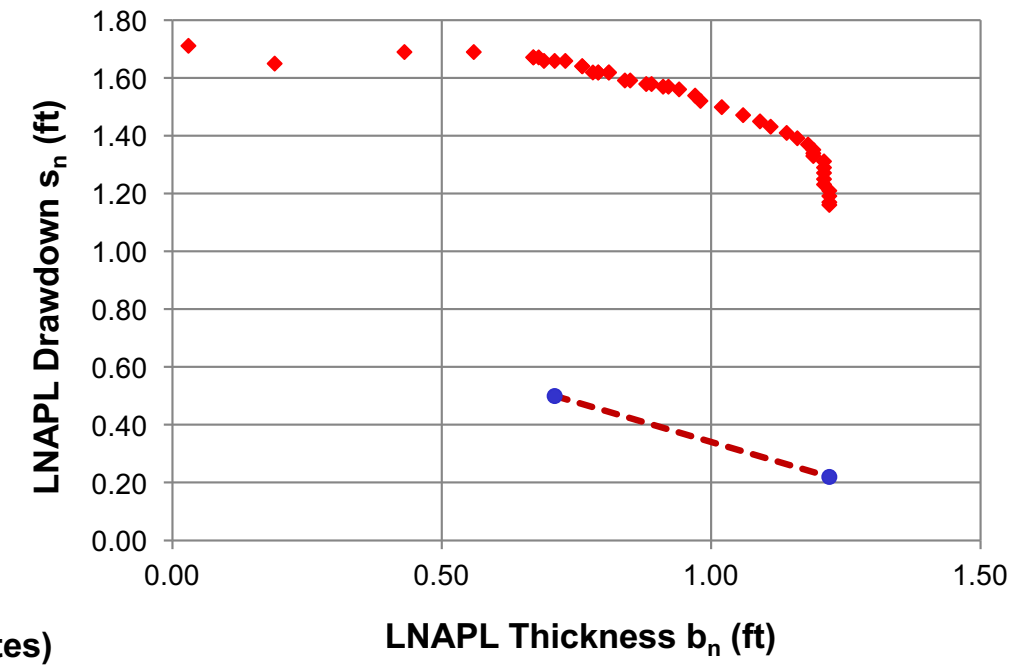
Exercise

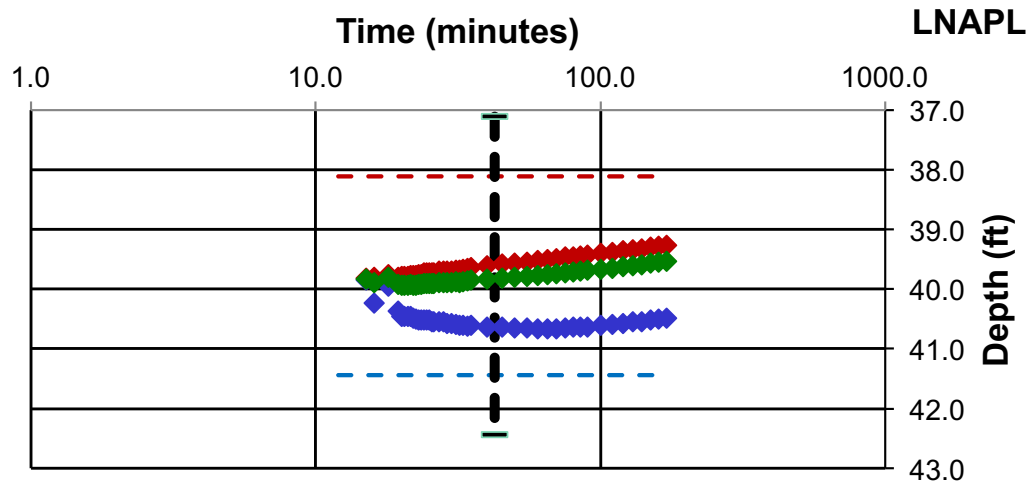
- Discuss in Groups the Test
  - Filter Pack Recharge
  - Equilibrium Fluid Levels
  - Can we Analyze them?
  - What portion of the data should be analyzed?
    - Indicate in Period of Time or Consider defining in terms of Drawdown or Discharge Ranges

Example #1



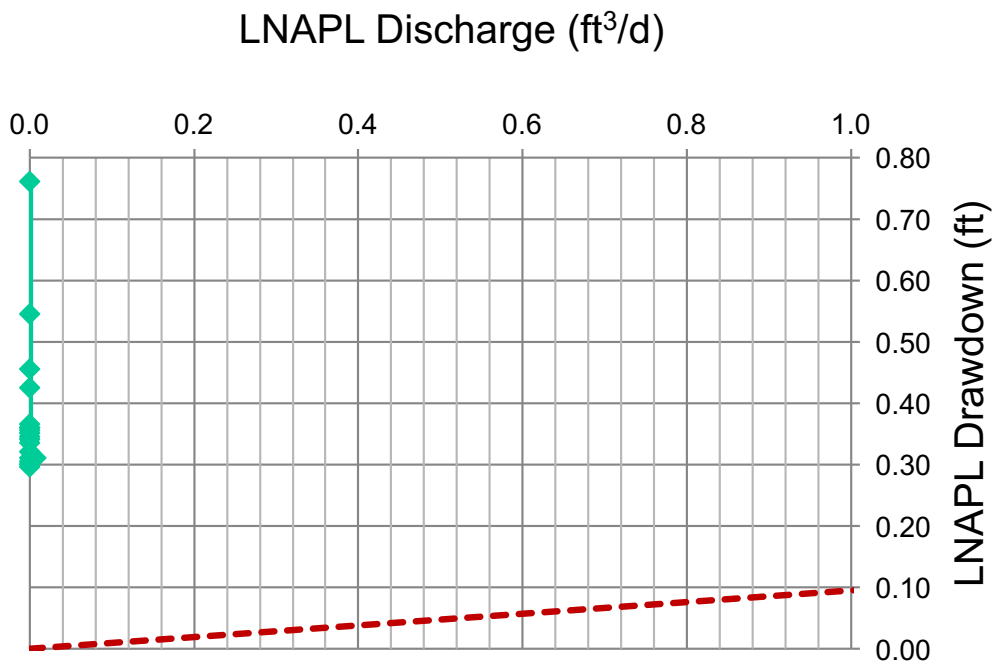
LNAPL Drawdown - Discharge Relation



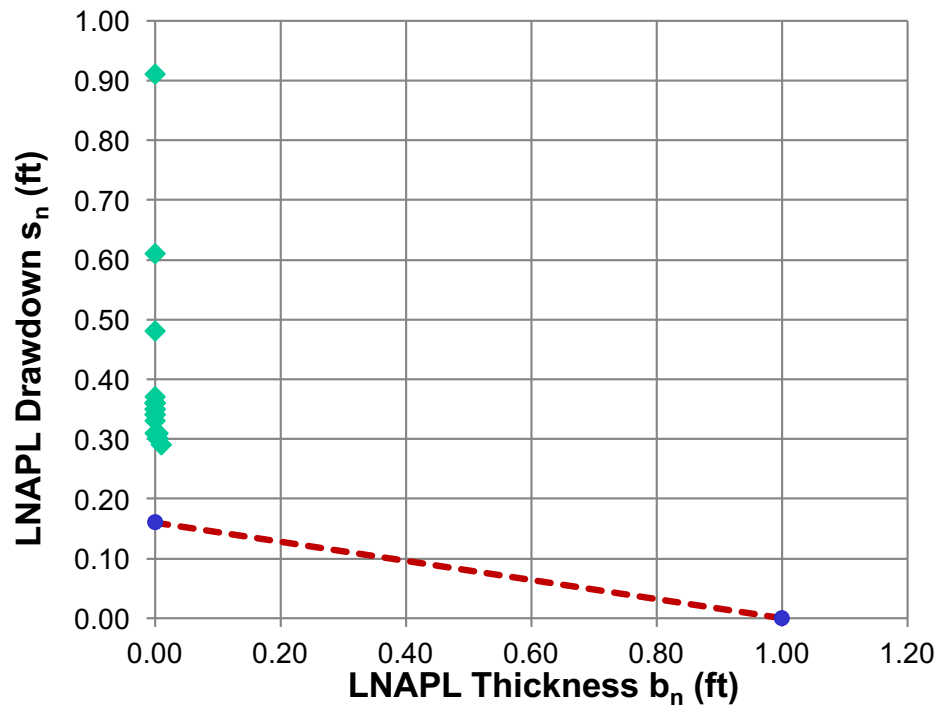


DTW (blue), Water Table (green), DTP (red)

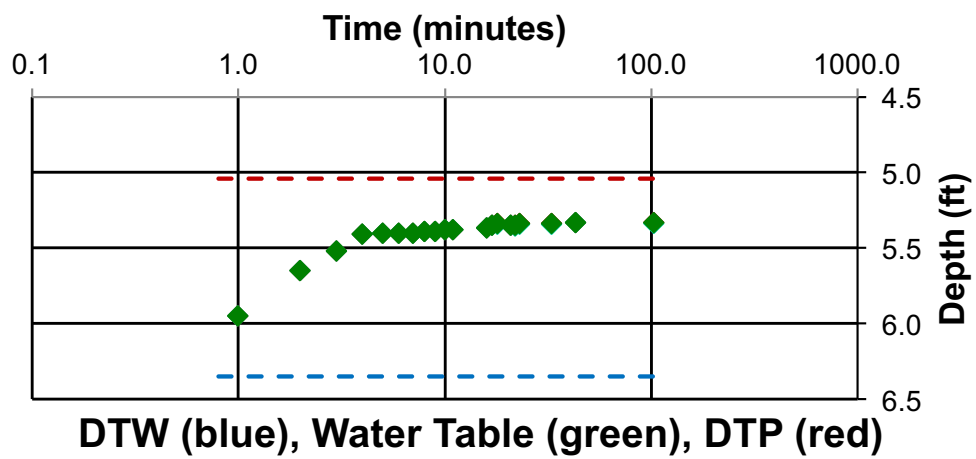
Example #2



LNAPL Drawdown - Discharge Relation



Initial Thickness – 1.3 ft
Max Skimming Drawdown – 0.26 ft
No Recovery After 100 minutes



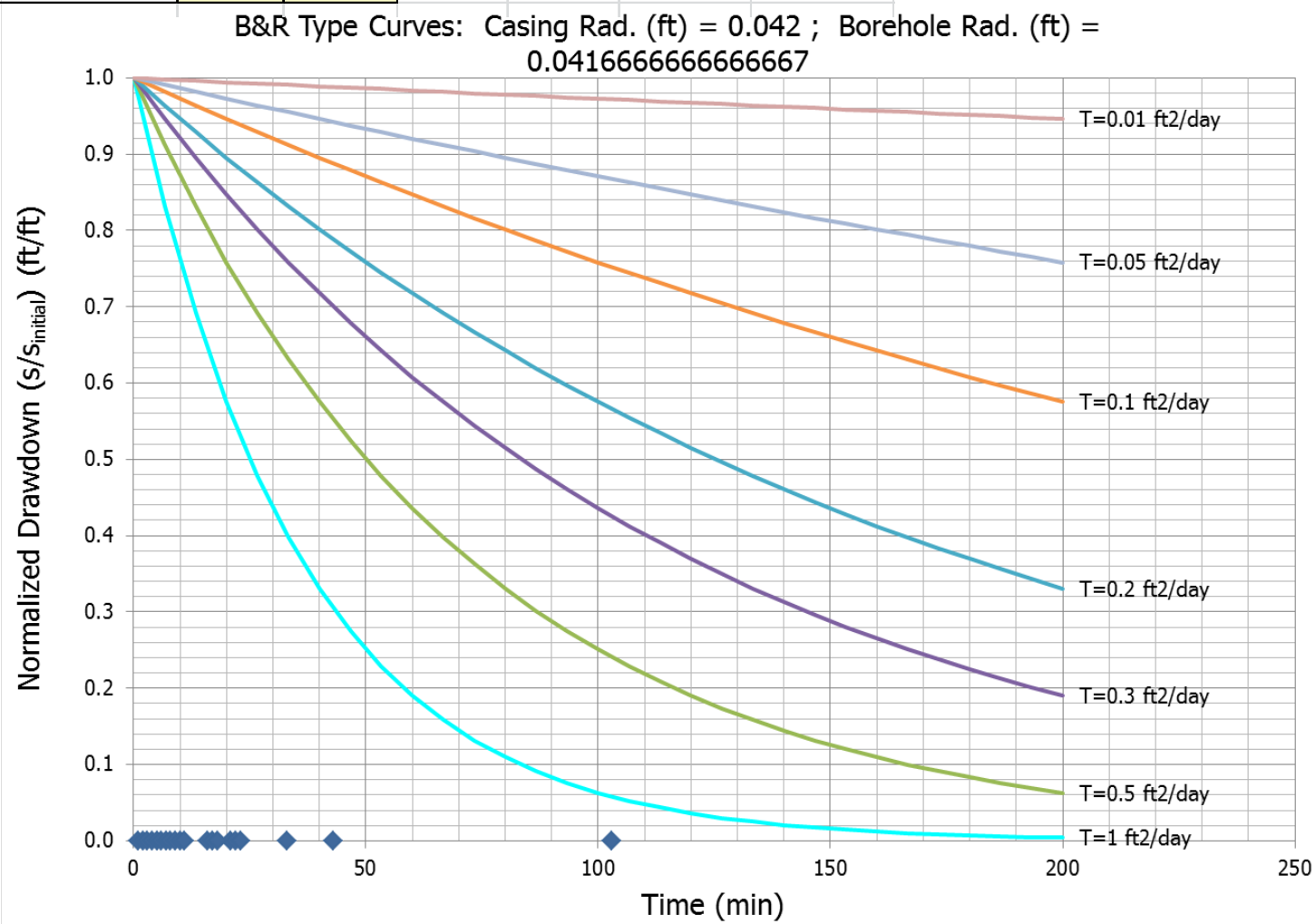
B-R Type Curve Sheet

Print for Field Use or Use for Post Test Review

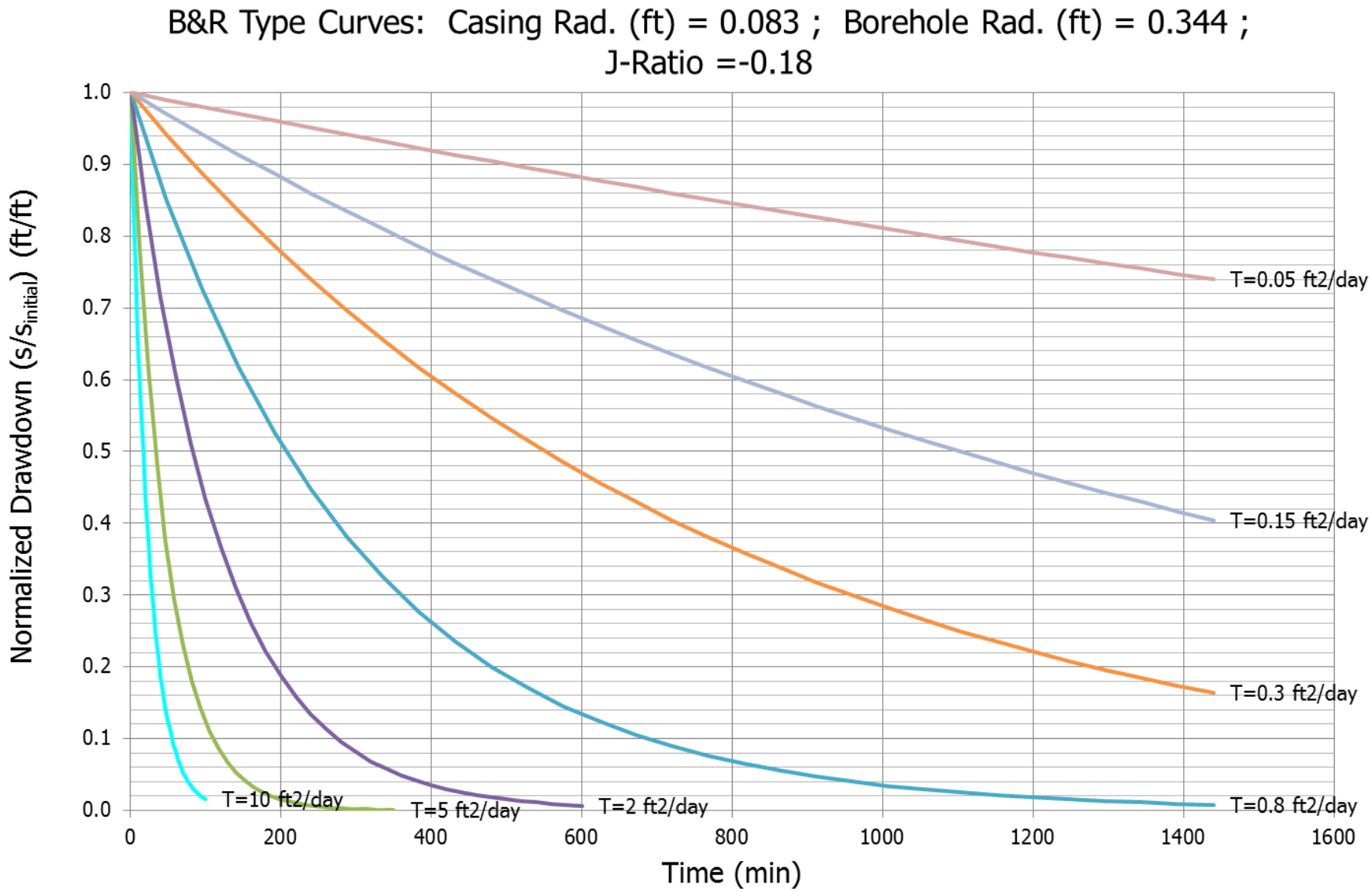
Enter these values

Type Curve ID	Type Curve Name	Notes	Max Time (min)	Transmissivity (ft^2/day)
1	T=10 ft2/day		150	10
2	T=5 ft2/day		200	5
3	T=2 ft2/day		200	2
4	T=1 ft2/day		200	1
5	T=0.5 ft2/day		200	0.5
6	T=0.2 ft2/day		200	0.2
7	T=0.1 ft2/day		200	0.1

J-Ratio	
-0.180	<-- If uncertain use
	-0.22



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

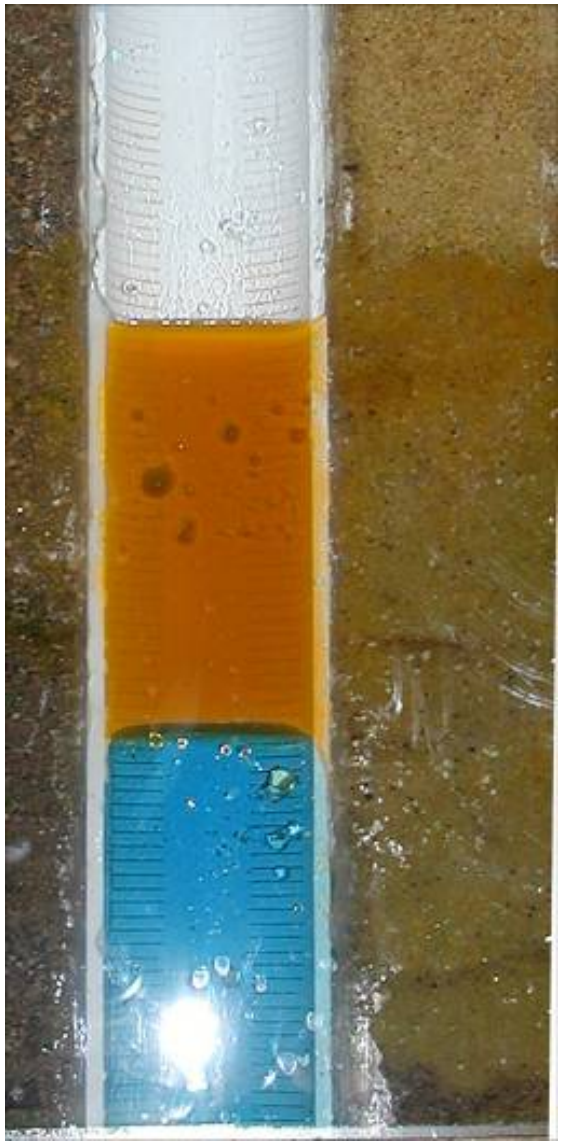


Transmissivity Testing

- 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

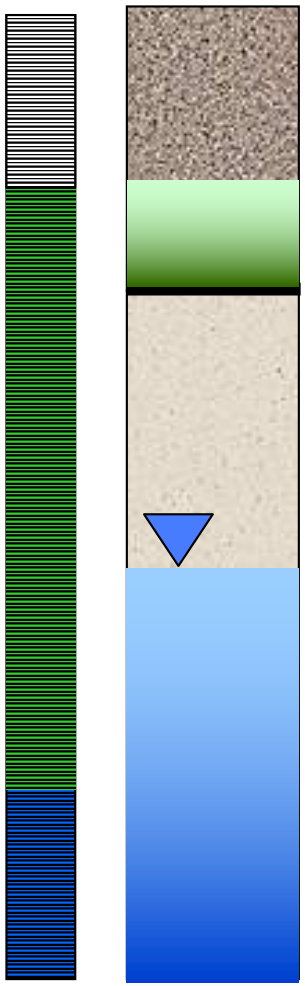
DRAWDOWN

Mobile Interval of LNAPL for Unconfined Hydrostatic Conditions

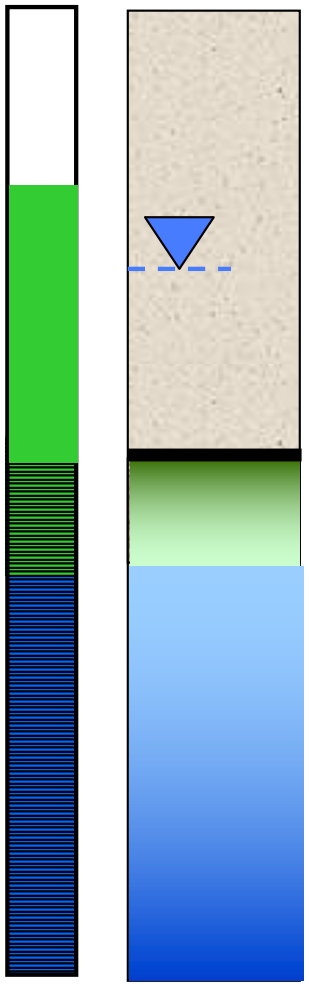


Various Hydrogeologic Scenarios

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

$$s_n = (1 - \rho_r)\left(b_{n\_static} - b_n\right)$$

- Confined
  - General for LNAPL/Water above confining contact

$$s_{n\_confined} = \frac{(Z_{an*} - Z_{cc})\rho_o - \left(Z_{nw(t)} - Z_{cc}\right)\rho_w - \left(Z_{an(t)} - Z_{nw(t)}\right)\rho_o}{\rho_o}$$

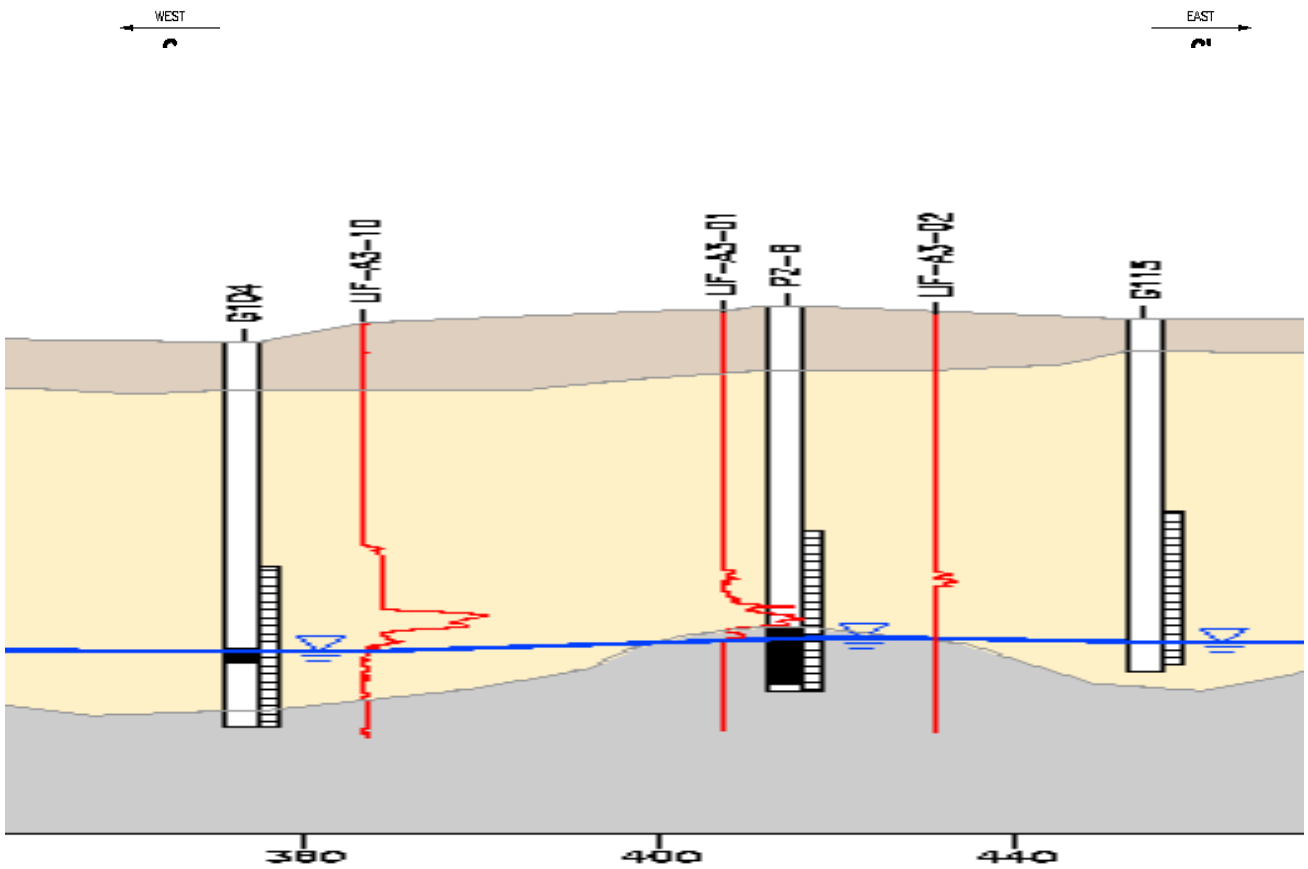
  - LNAPL water above confining contact and equilibrium potentiometric surface

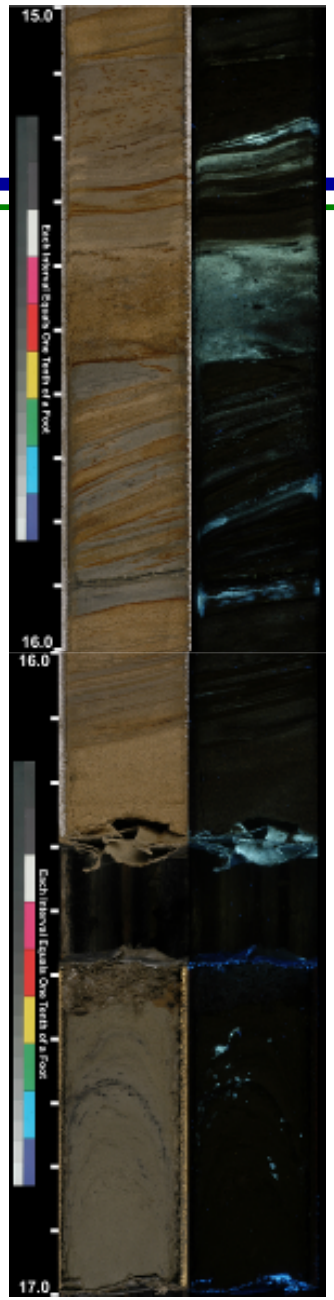
$$s_{n\_confined} = b_{nf}\frac{1 - \rho_r}{\rho_r}$$

- Perched

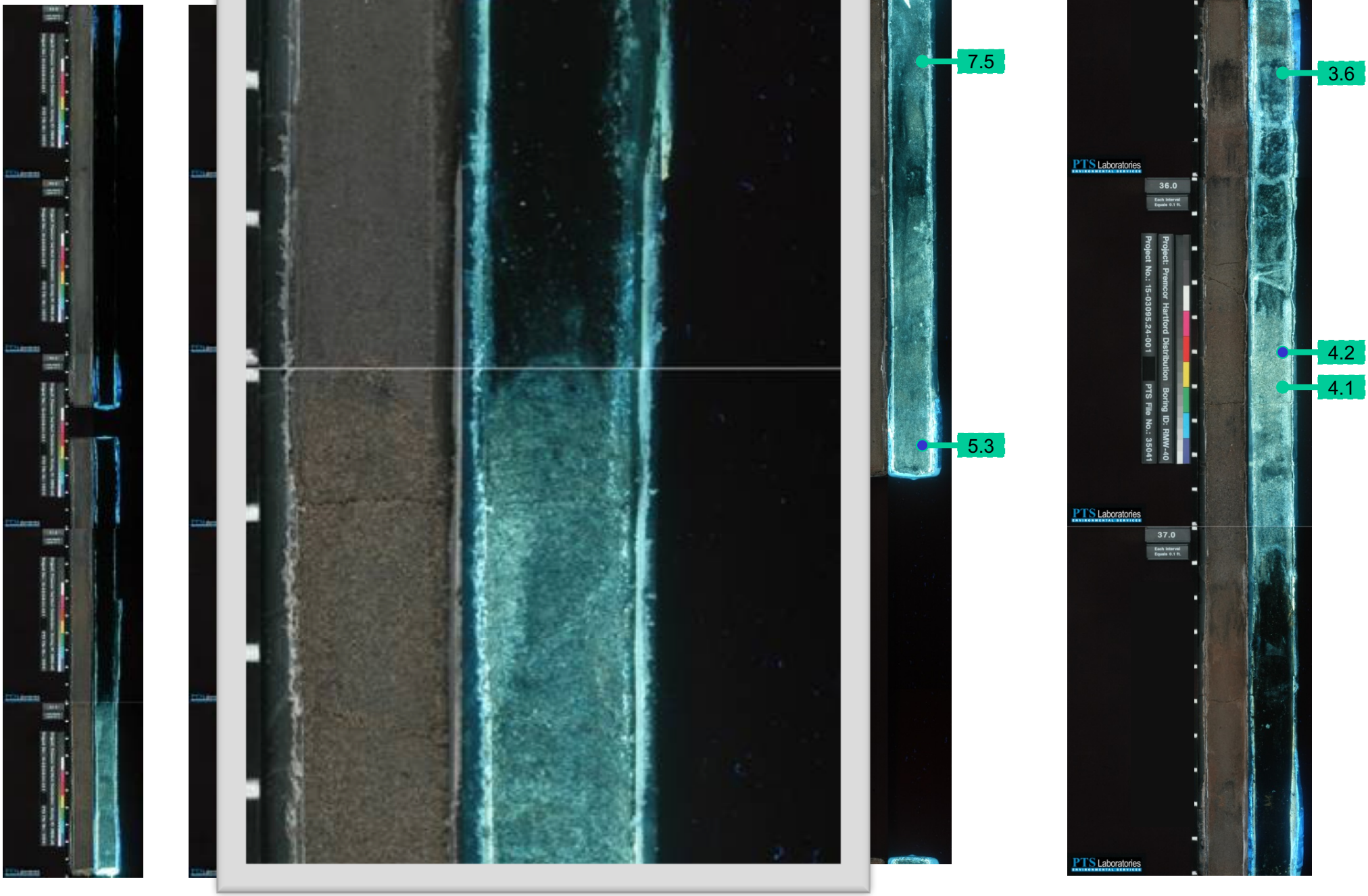
$$s_{n\_perched} = b_{nf}$$

Rail Car Shops Facility Perched LNAPL





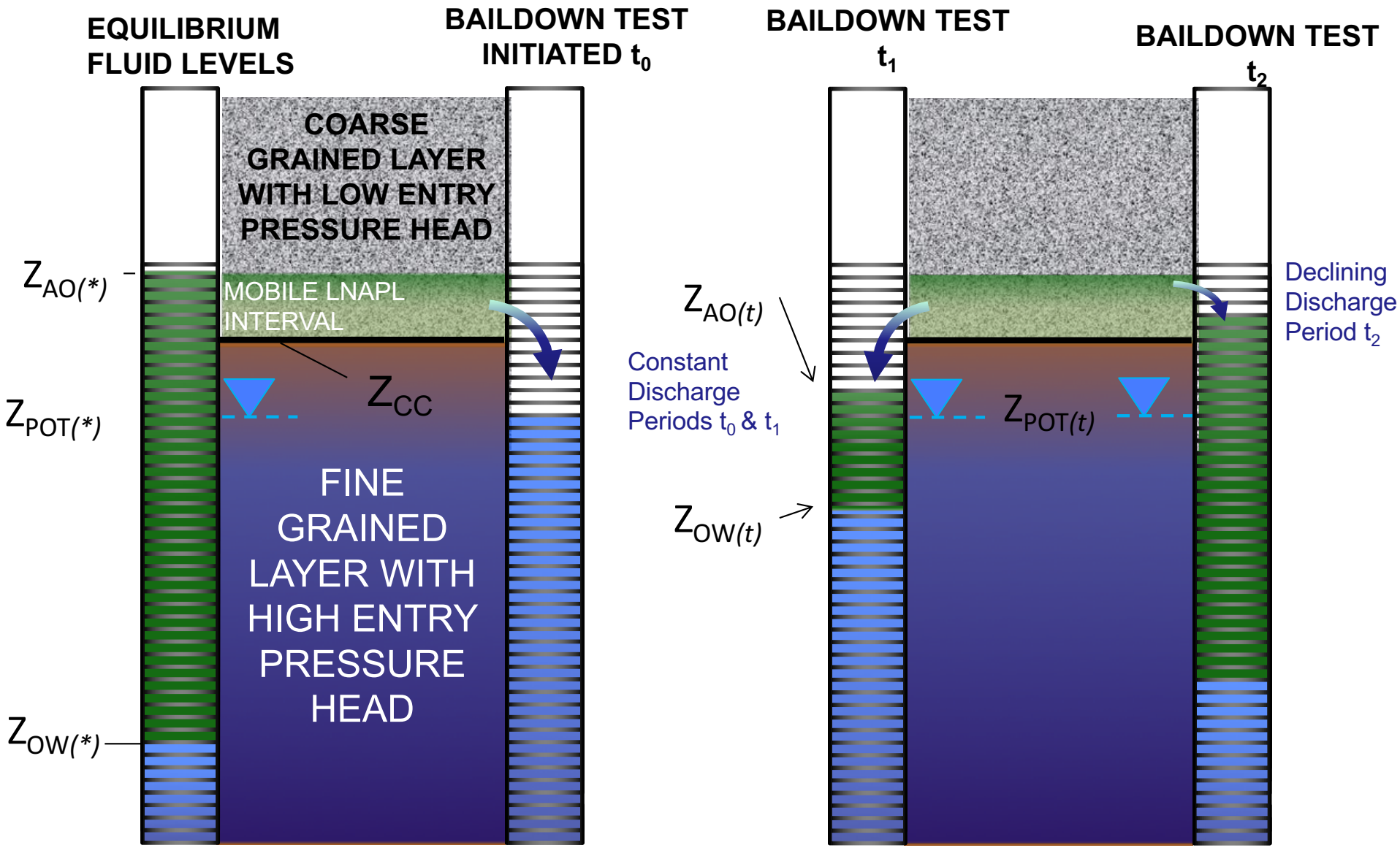
Confined LNAPL



HOW DO WE CALCULATE DRAWDOWN

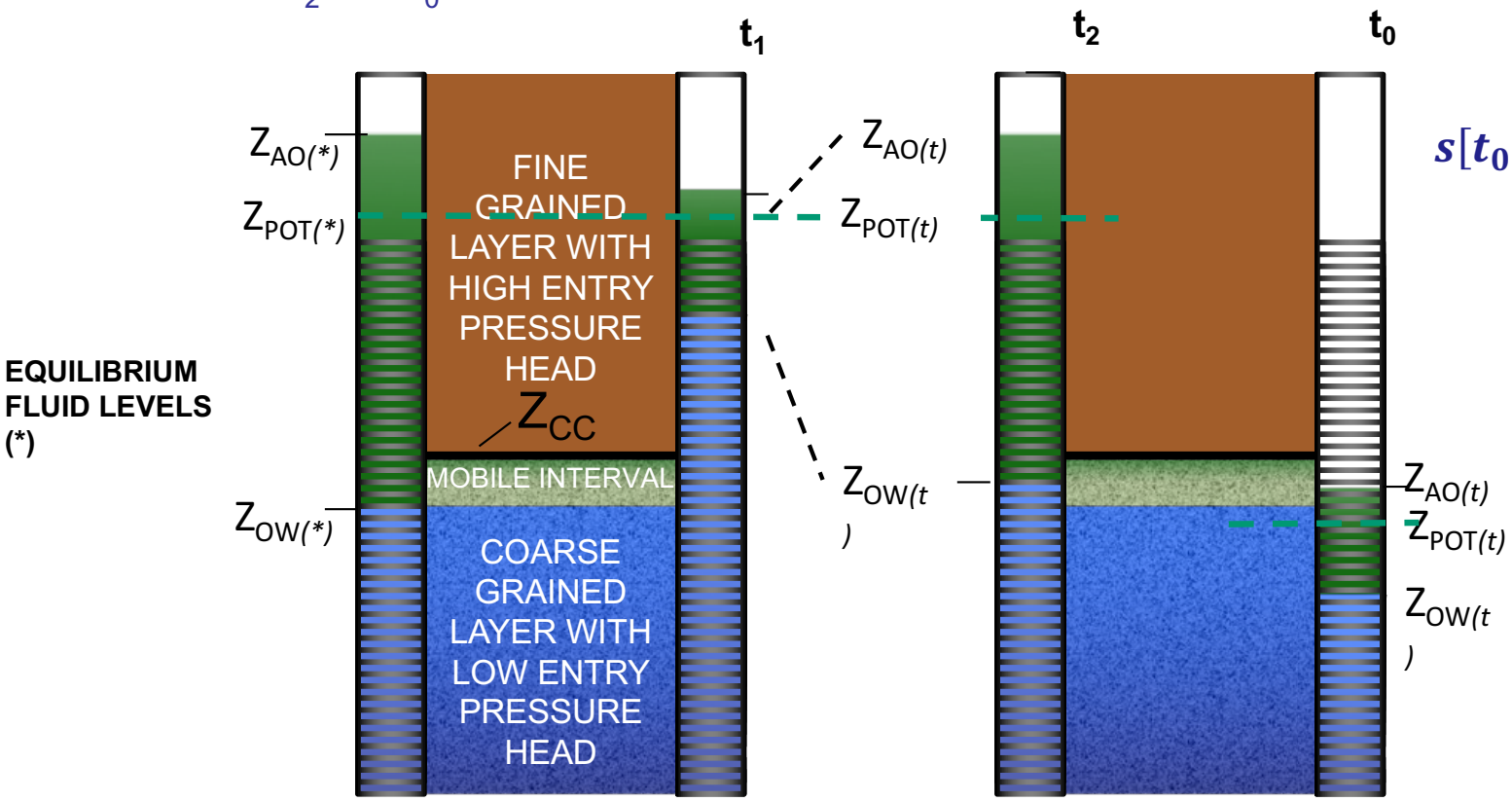
CHANGE IN AIR/LNAPL INTERFACE?

Consider The Pressure Difference in the Mobile Interval



Confined LNAPL Baildown Test Scenario's

- 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

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

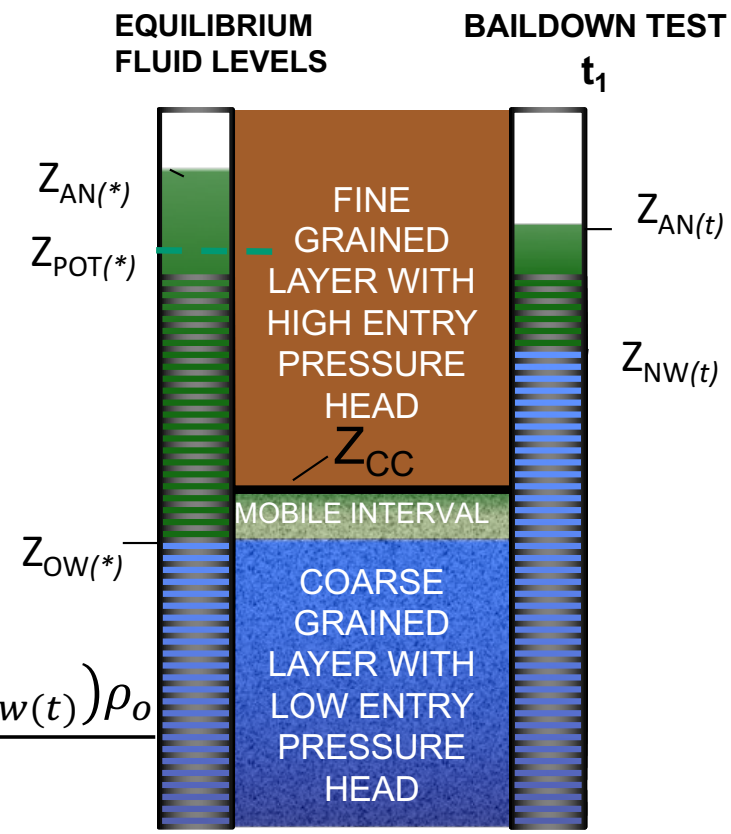
Non-Equilibrium Pressure

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

$$s[t_{1,0}] = Z_{an(t)} - Z_{an*}$$

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?