Field Device to Measure Viscosity, Density, and Other Slurry Properties in Drilled Shafts

GRIP 2016

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Problem Statement

- Drilled excavation requires slurry that falls within a set of parameters regarding density, viscosity, pH and sand content; typically, each slurry property is tested using a unique, separate test method.
- Slurry properties are measured every 2 hours for the first 8 hours and 4 hours thereafter.
- A downhole device to measure all properties real time may improve data quality and expedite construction.
- Establish method to automate each test

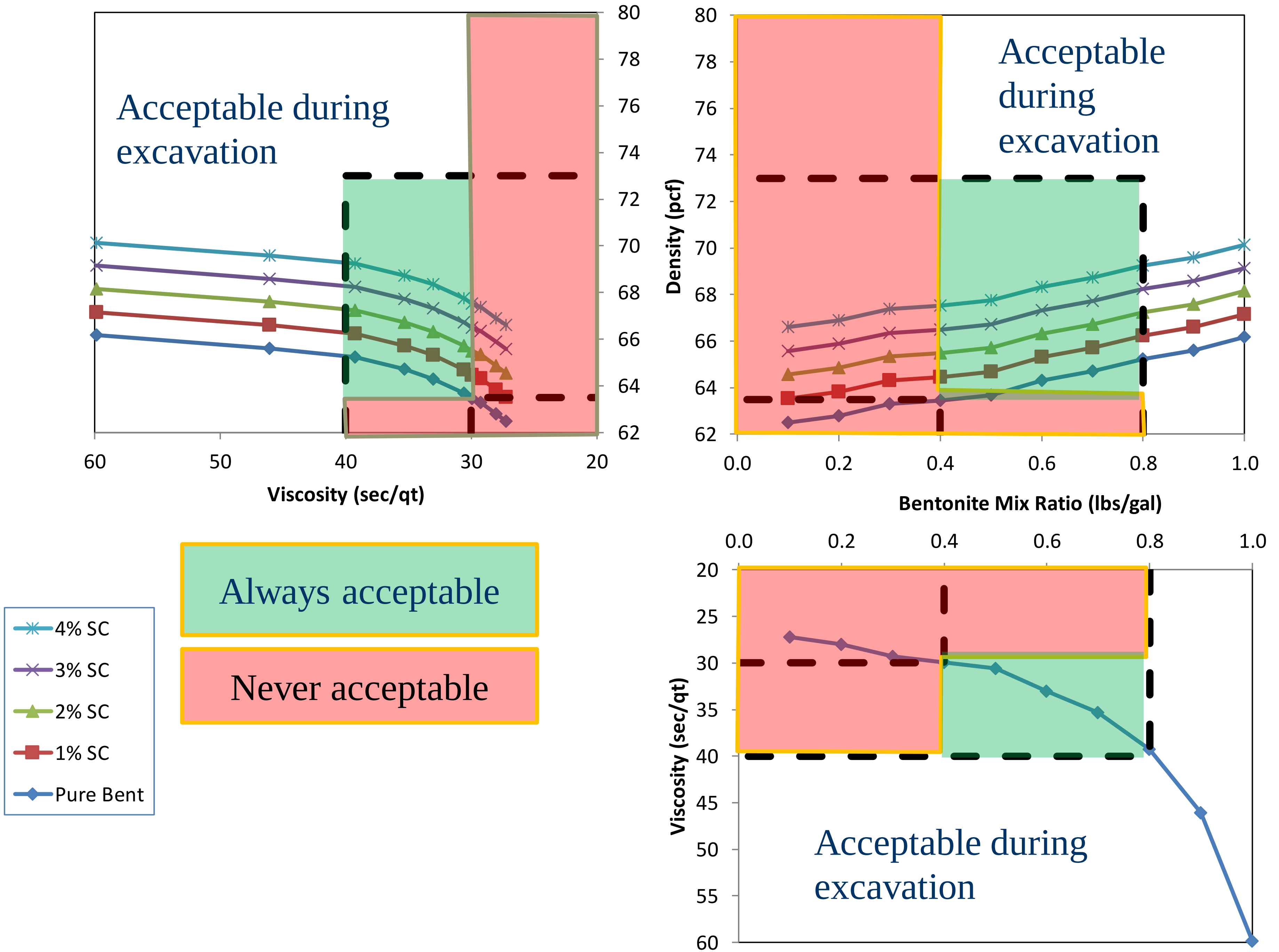
FDOT Standard Specifications for Road and Bridge Construction Section 455-15.8

Mineral slurries

Item to be measured	Range of Results at 68°F	Test Method
Density	64 to 73 lb/ft^3 (in fresh water environment) 66 to 75 lb/ft^3 (in salt water environment)	Mud density balance: FM 8-RP13B-1
Viscosity	30 to 50 seconds	Marsh Cone Method: FM 8-RP13B-2
pH	8 to 11	Electric pH meter or pH indicator paper strips: FM 8-RP13B-4
Sand Content	4% or less	FM 8-RP13B-3

Polymer slurries

Mixed Polymer Slurry Properties		
Item to be measured	Range of Results at 68°F	Test Method
Density	62 to 64 lb/ft^3 (fresh water) 64 to 66 lb/ft^3 (salt water)	Mud density balance: FM 8-RP13B-1
Viscosity	Range Published By The Manufacturer for Materials Excavated	Marsh Cone Method: FM 8-RP13B-2
pH	Range Published By The Manufacturer for Materials Excavated	Electric pH meter or pH indicator paper strips: FM 8-RP13B-4
Sand Content	0.5% or less	FM 8-RP13B-3


Acceptable during excavation
Viscosity (sec/qt)
60
50
40
30
20
80
78
76
74
72
70
68
66
64
62
Density (pcf)
Acceptable during excavation
Bentonite Mix Ratio (lbs/gal)
0.0
0.2
0.4
0.6
0.8
1.0
Always acceptable
Never acceptable
4% SC
3% SC
2% SC
1% SC
Pure Bent
Viscosity (sec/qt)
20
25
30
35
40
45
50
55
60
Acceptable during excavation

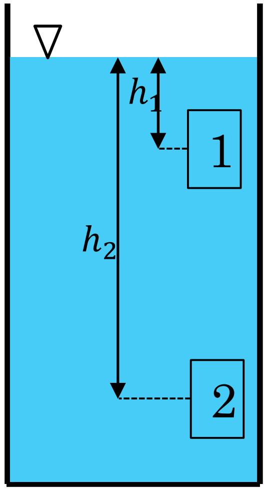
Existing Method to Measure Density

Standard mud balance


How to Automate Density Measurements

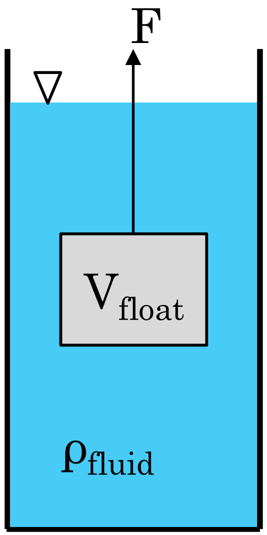
- Hydrostatic Pressure Differential
  - By comparing pressure data from two points with a known elevation difference, density can be calculated using:

$$\rho = \frac{\Delta P}{g(h_2 - h_1)}$$



- Archimedes Principle
  - By monitoring the buoyant force created by a “float” of known volume, the density of the surrounding fluid may be calculated using the following equation:

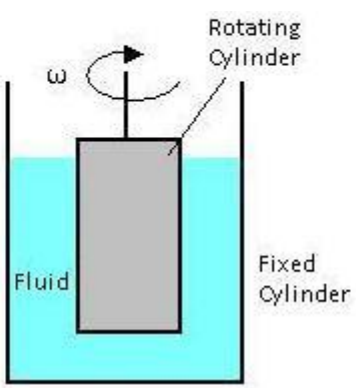
$$F_{buoyancy} = \rho_{fluid} * V_{displaced}$$



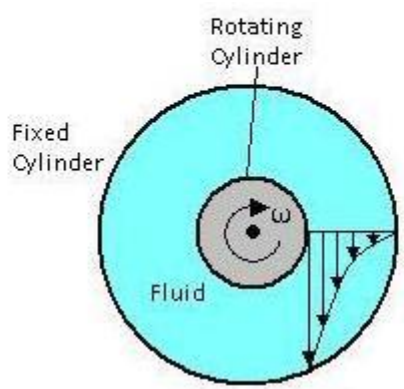
Viscosity
Viscometer Measurements

Newtonian fluids
- -Viscosity

Shear-thinning fluids
- -Apparent viscosity
- -Gel strength
- -Yield point



Side view



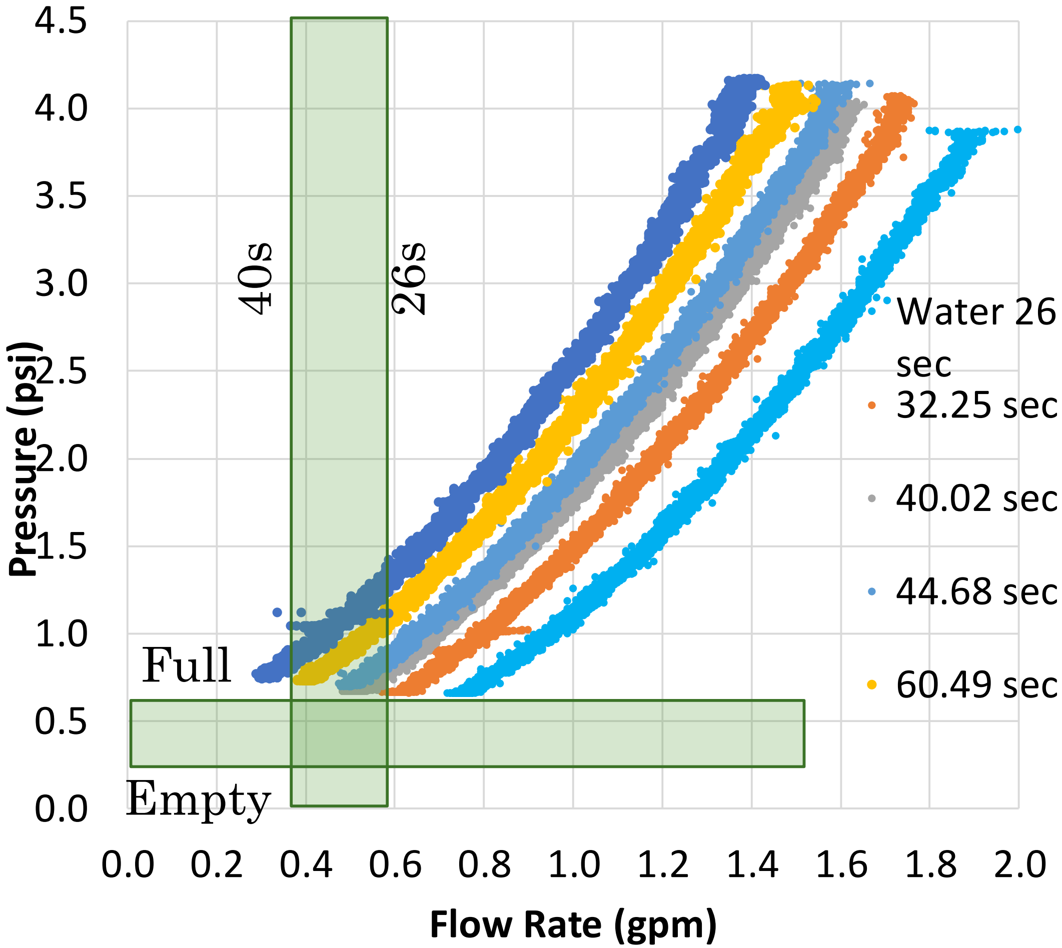
View from above

Viscosity
Marsh Funnel Measurements

- Time (sec) required for 1qt of fluid to flow from standardized 3/16in orifice of a funnel.
- Pressure ranges from 0.8 - 0.5psi
- Flow ranges from 0.6 - 0.2gpm (26 to 75 sec)

How to Automate Viscosity Measurements

- Different viscosity slurries have unique flow vs pressure curves
- For the same flow rate, a more viscous material causes higher pressure to be developed.

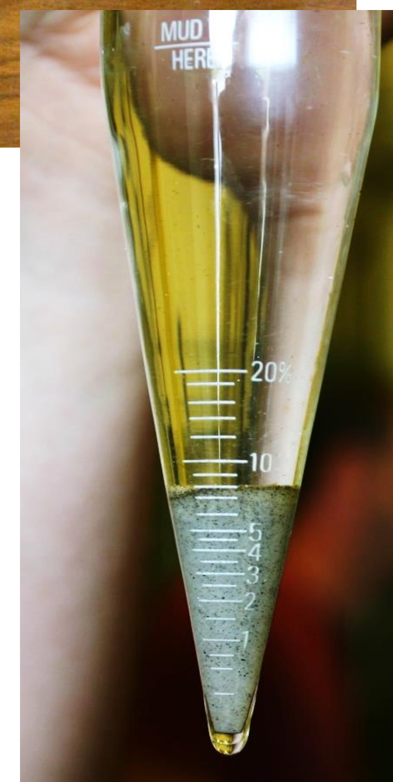


Sand Content

Fixed volume of slurry is sieved wet washed through 200 sieve.

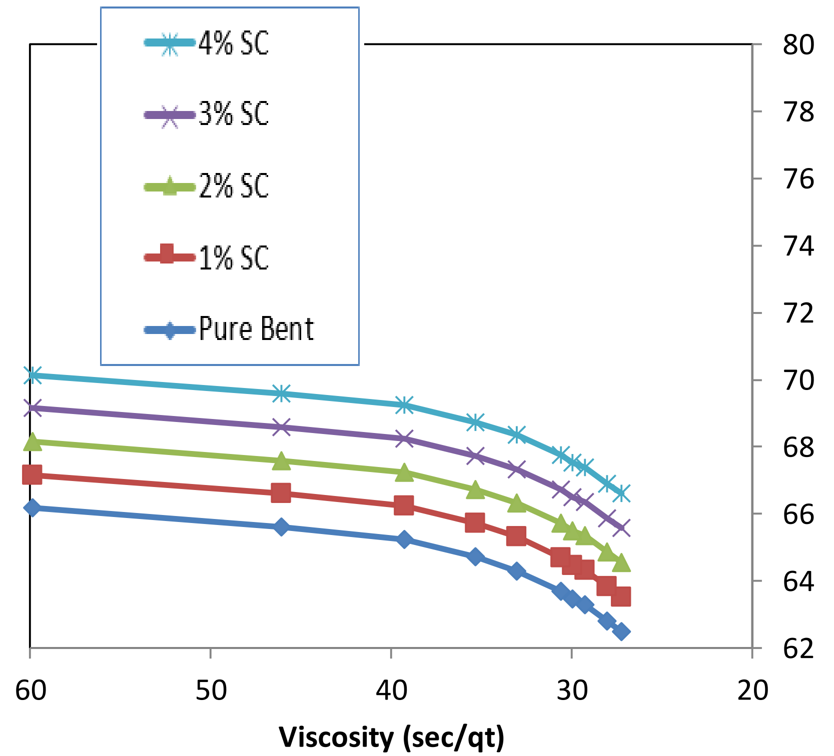
NOTE: Volumetric Sand Content

Indirect measure of suspended solids

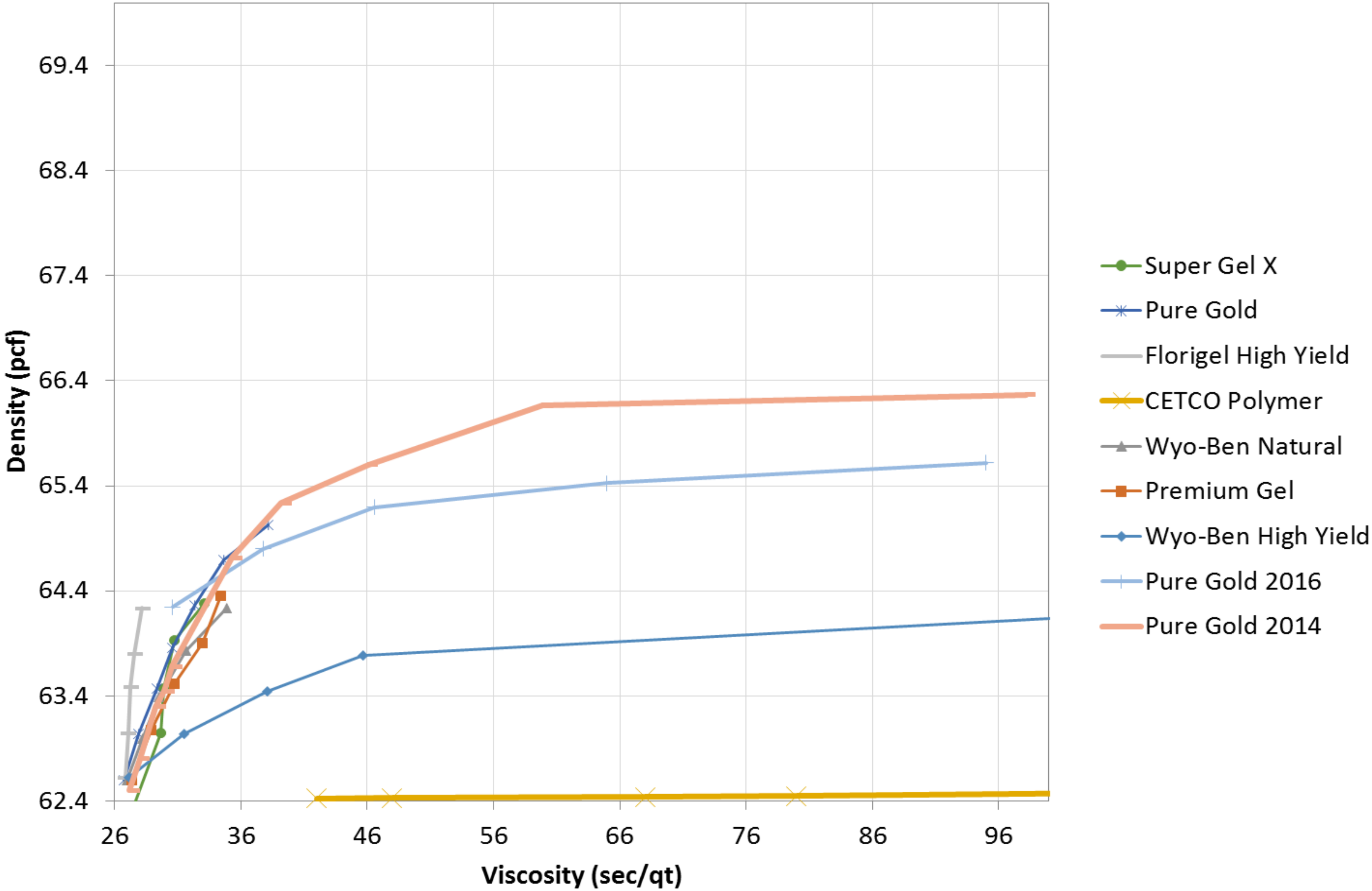


How to Automate Sand Content Measurements

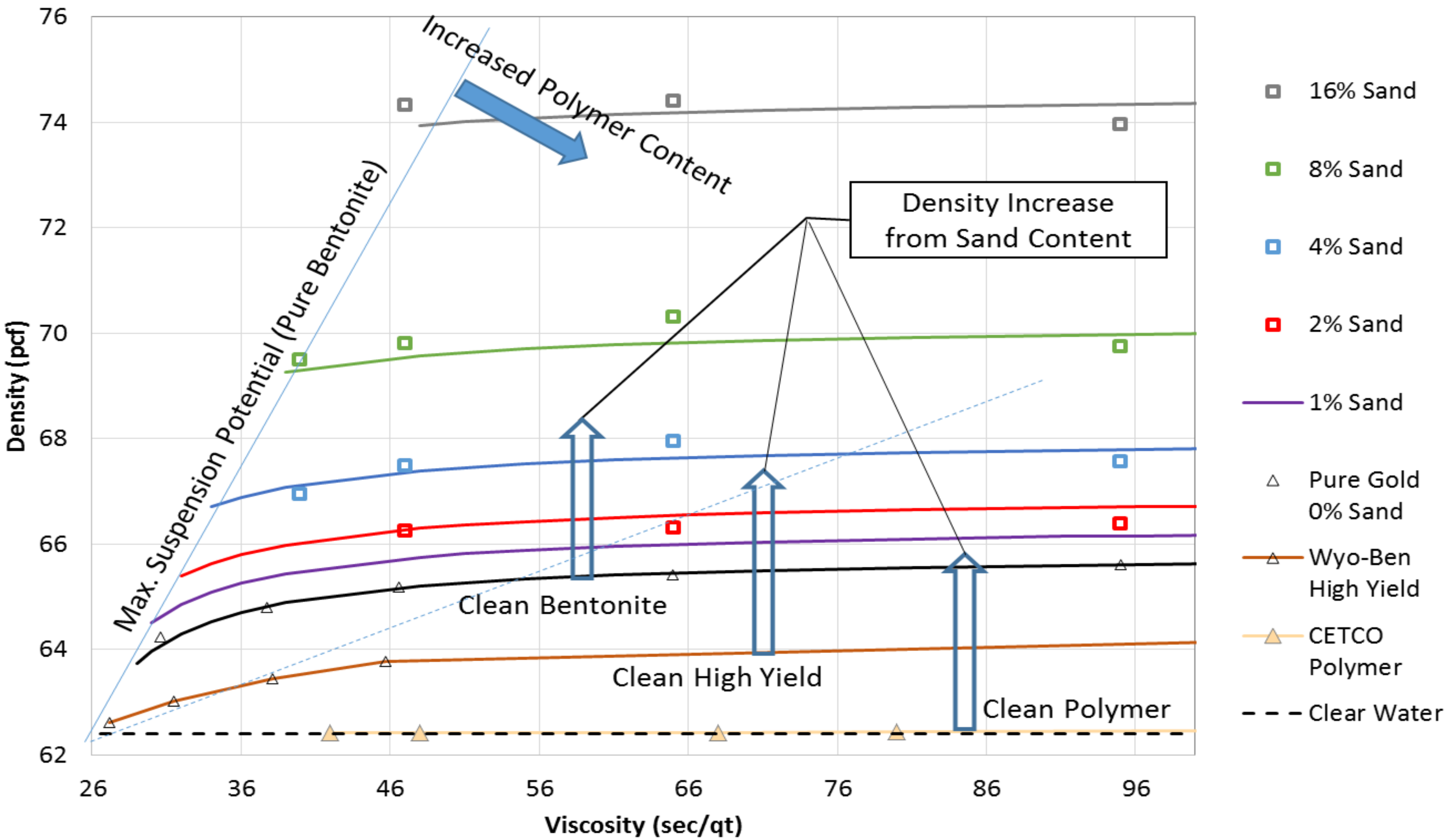
- If the viscosity of a pure bentonite slurry is known, a corresponding density can be expected.
- Any density increase above pure bentonite can be attributed to the suspended solids.
- Sand content is a portion of suspended solids.



Clean Slurry Density



Sand content from density and viscosity



Approach

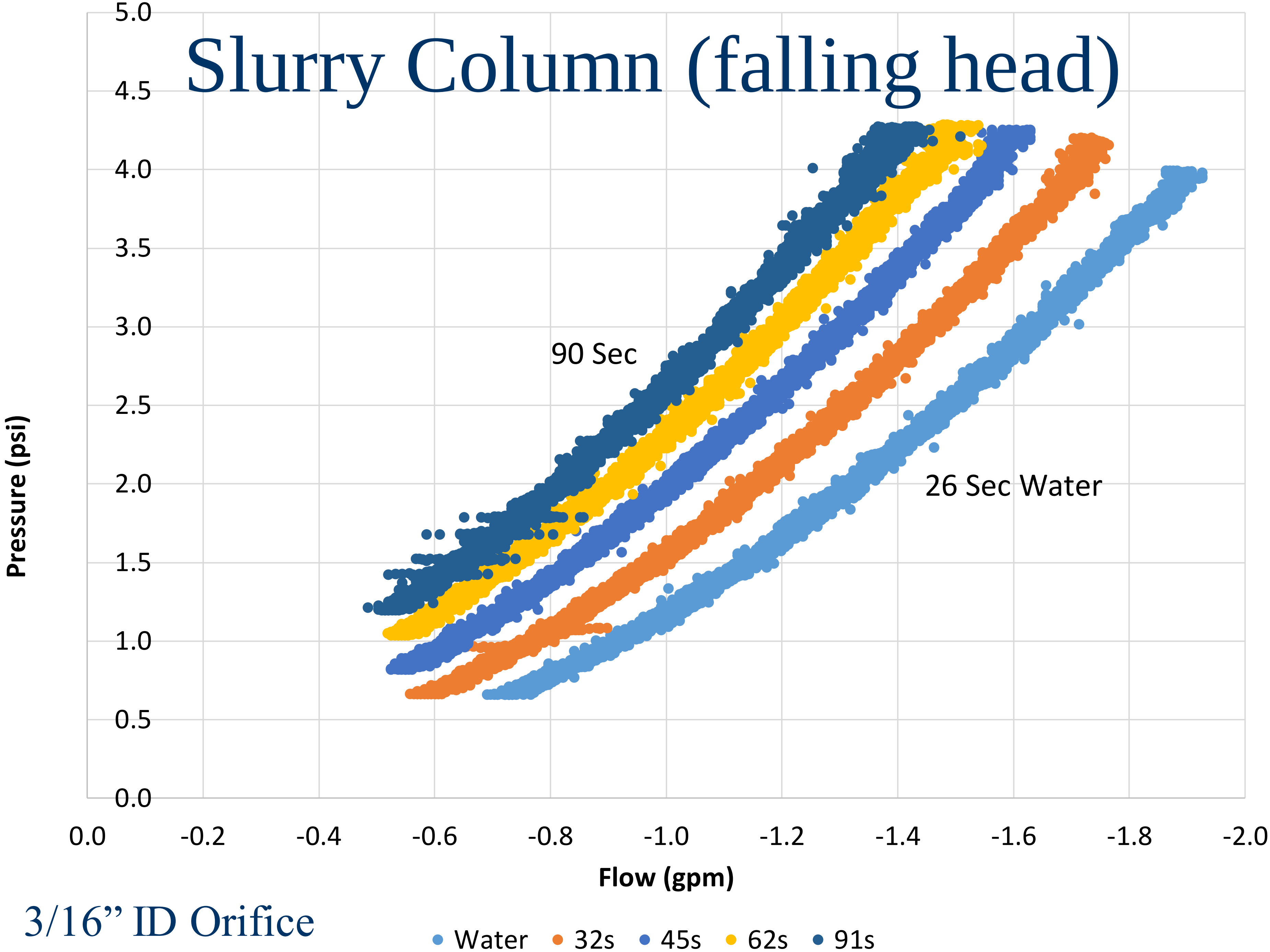
- Proof of concept
- Component Development
- System Fabrication
- Lab and Field Testing

Slurry Column Tests (Falling Head)

Slurry Column Tests

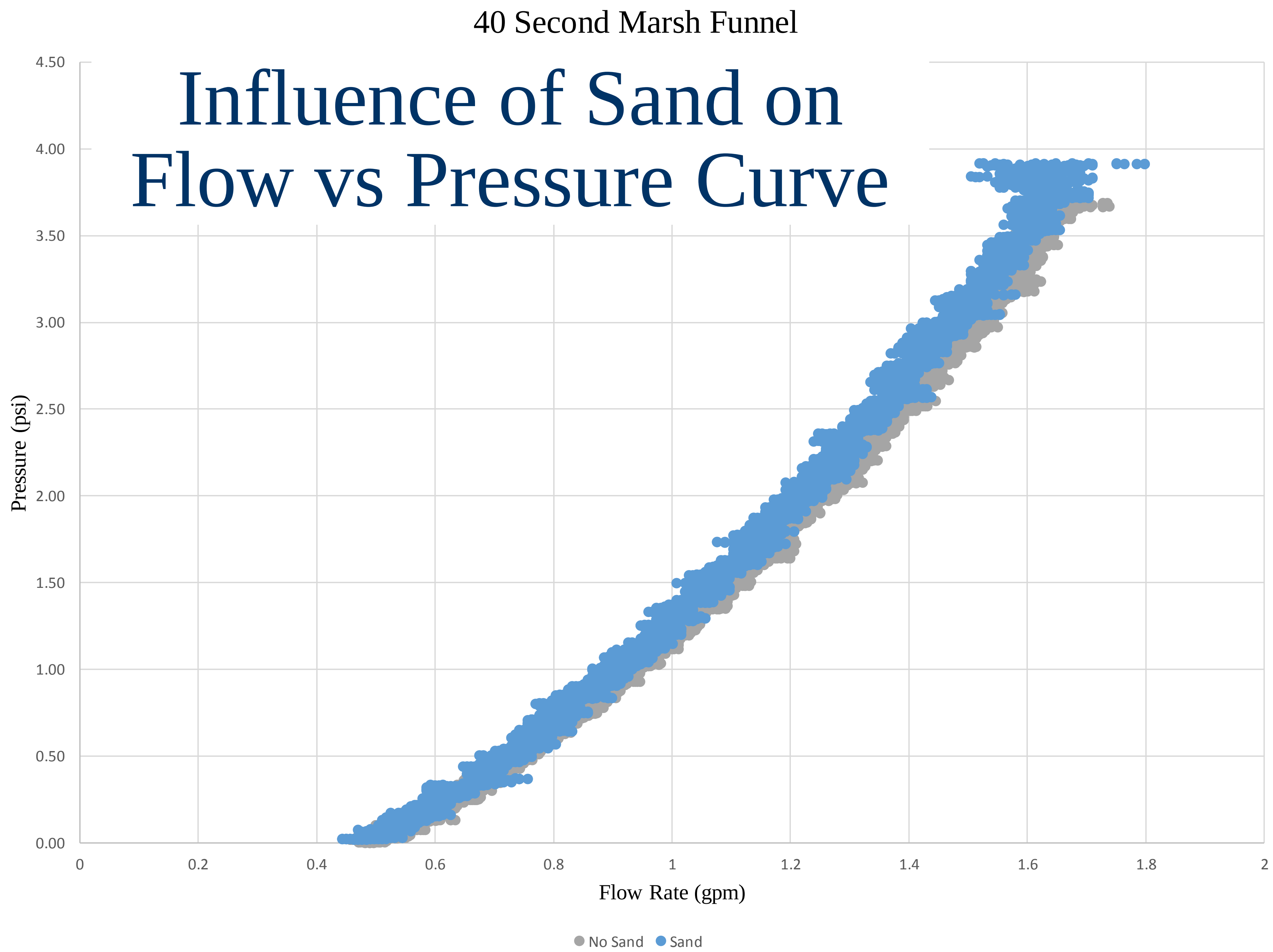
- Bentonite slurry viscosity
  - ranged from 26 (water) to 90 sec/qt
- Flow rates (12ft falling head)
  - 0 to 2gpm
- Density
  - 64 to 71 pcf
- Sand contents
  - 0.25 to 10% by volume

Slurry Column (falling head)



3/16” ID Orifice

Influence of Sand on Flow vs Pressure Curve

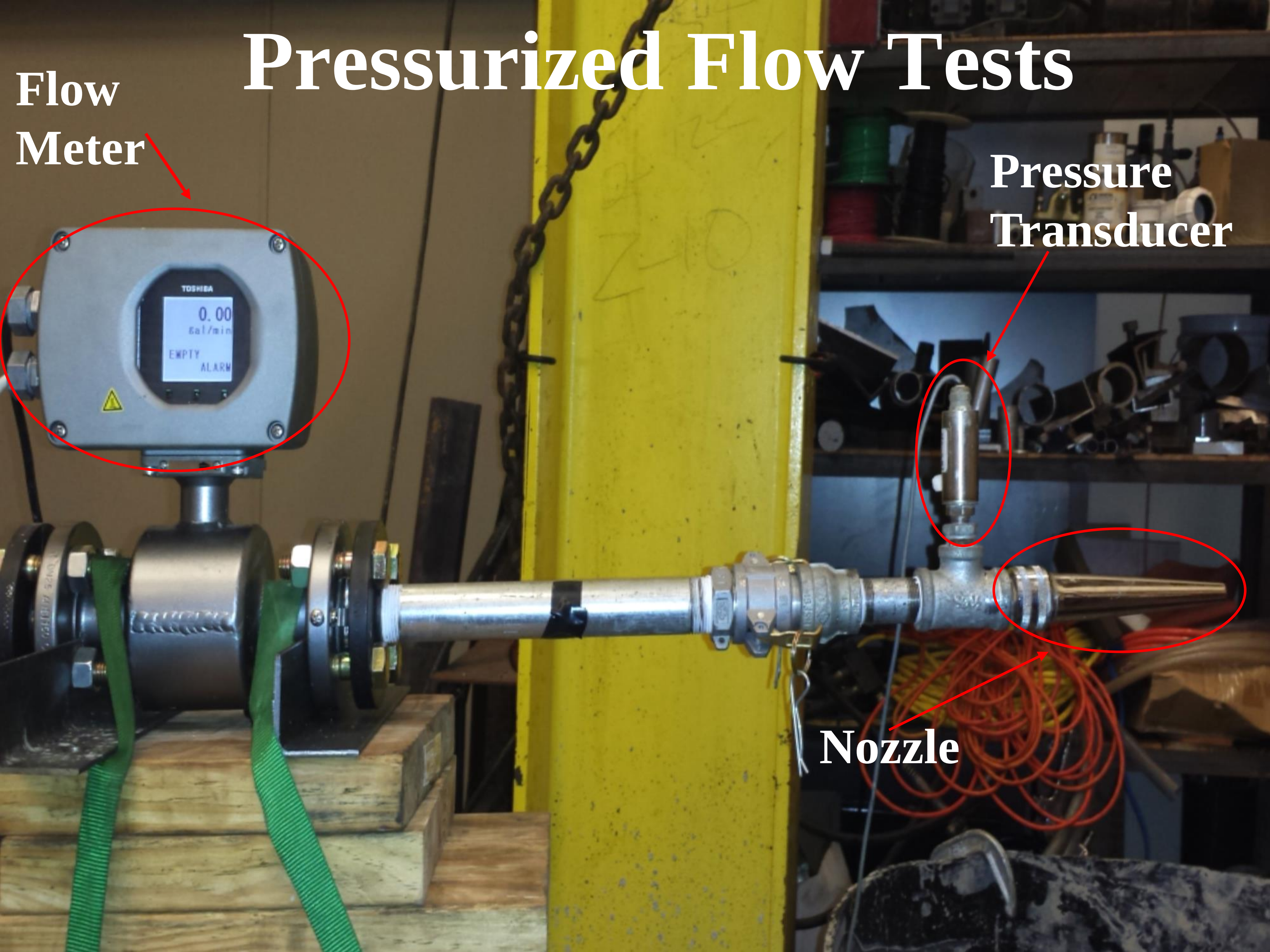


Test Batch Summary

Batch	Average Marsh Funnel Test (sec)	Average Sand Content (%)	Density (lb/ft^3)
No Sand	40.03	.25	64.81
Sand	39.3	6.58	68.24

Use density measurements to determine gravimetric sand content

Pressurized Flow Tests

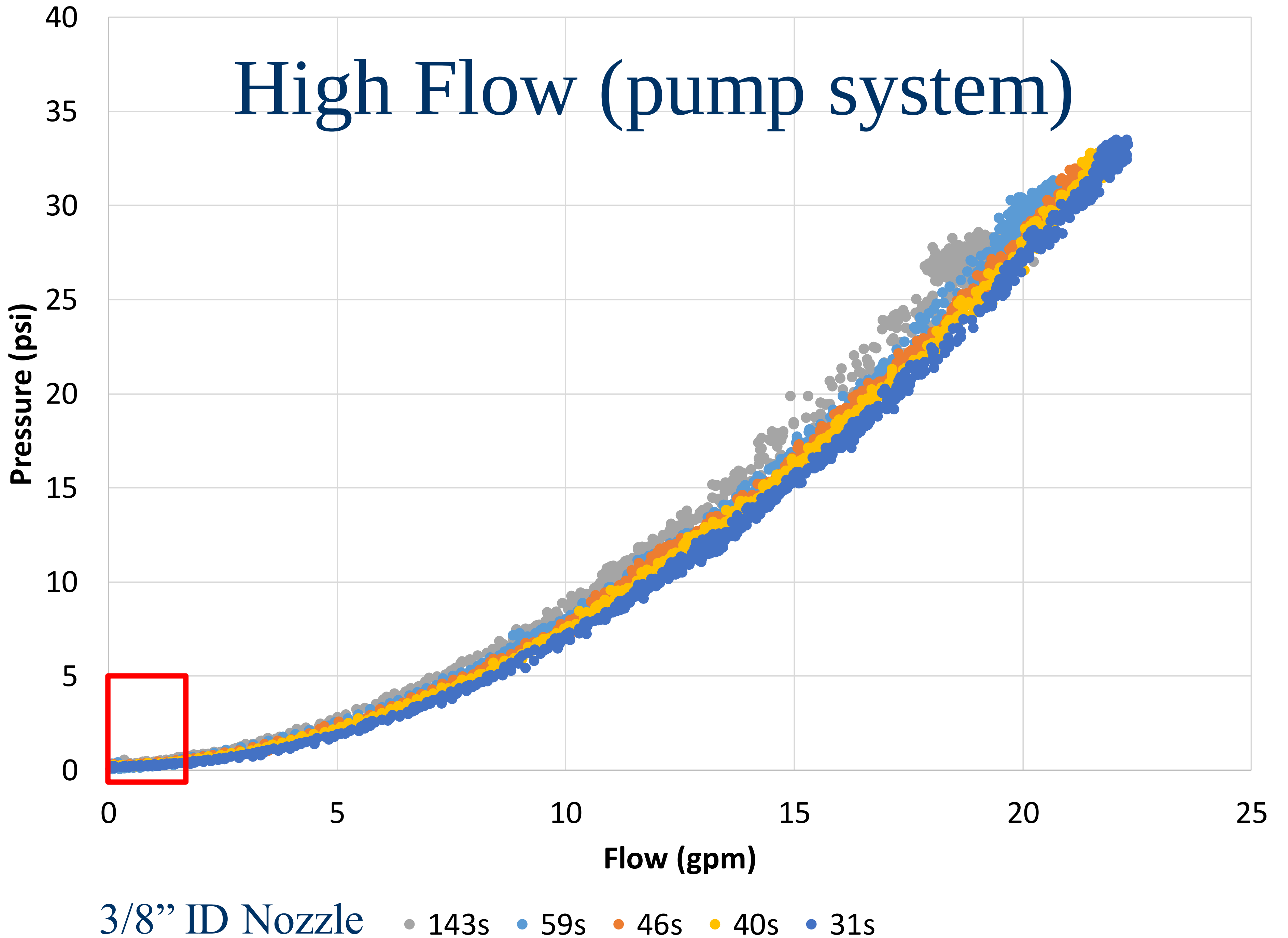


High Flow Nozzles

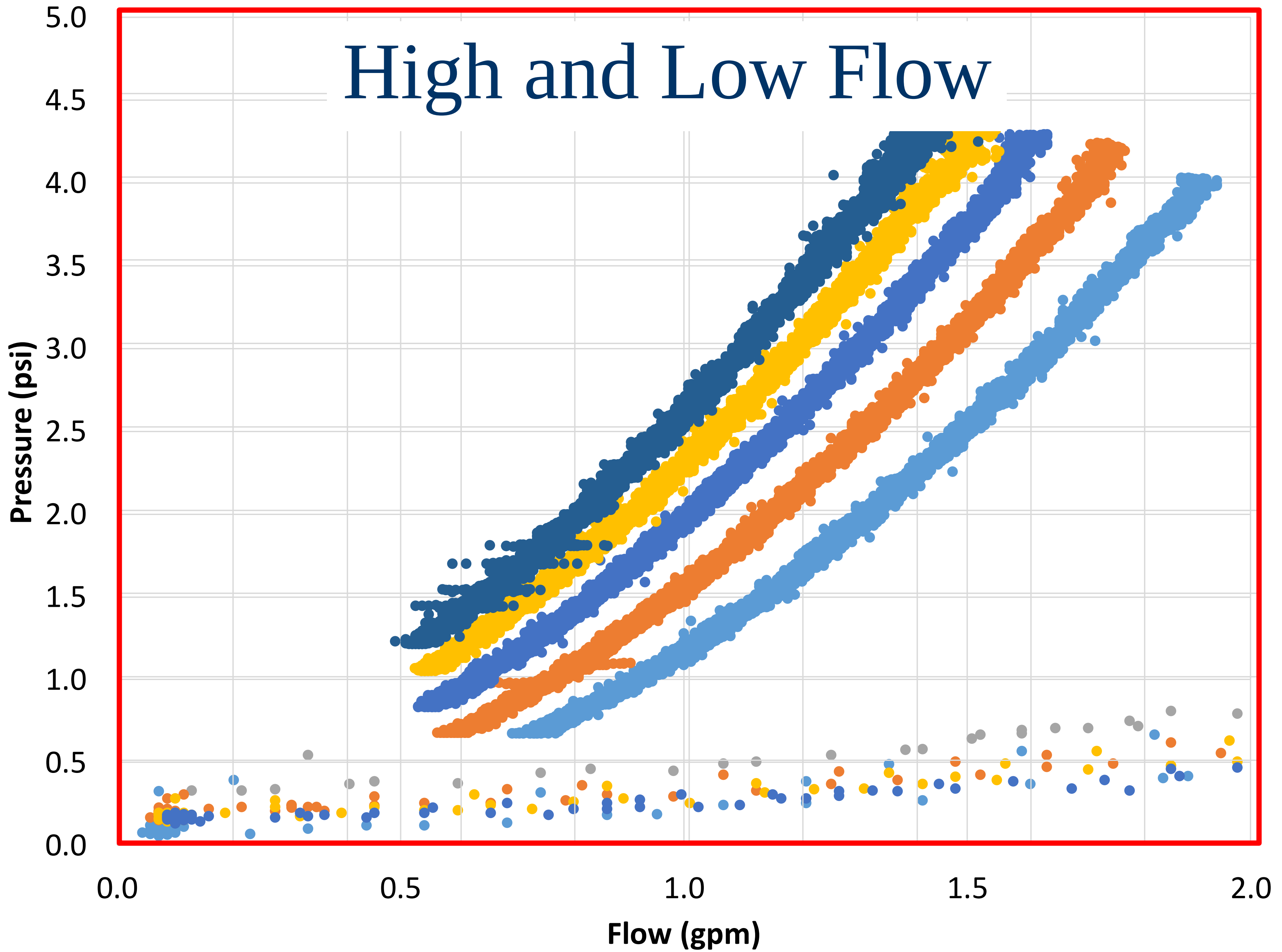
High Flow / Pressurized

- Bentonite slurry viscosity
  - ranged from 30 to 140 sec/qt
- Flow rates (pumped)
  - 0 to 23gpm
- Density
  - 64 to 66 pcf
- Sand contents
  - 0.25% pure bentonite only

High Flow (pump system)



3/8" ID Nozzle

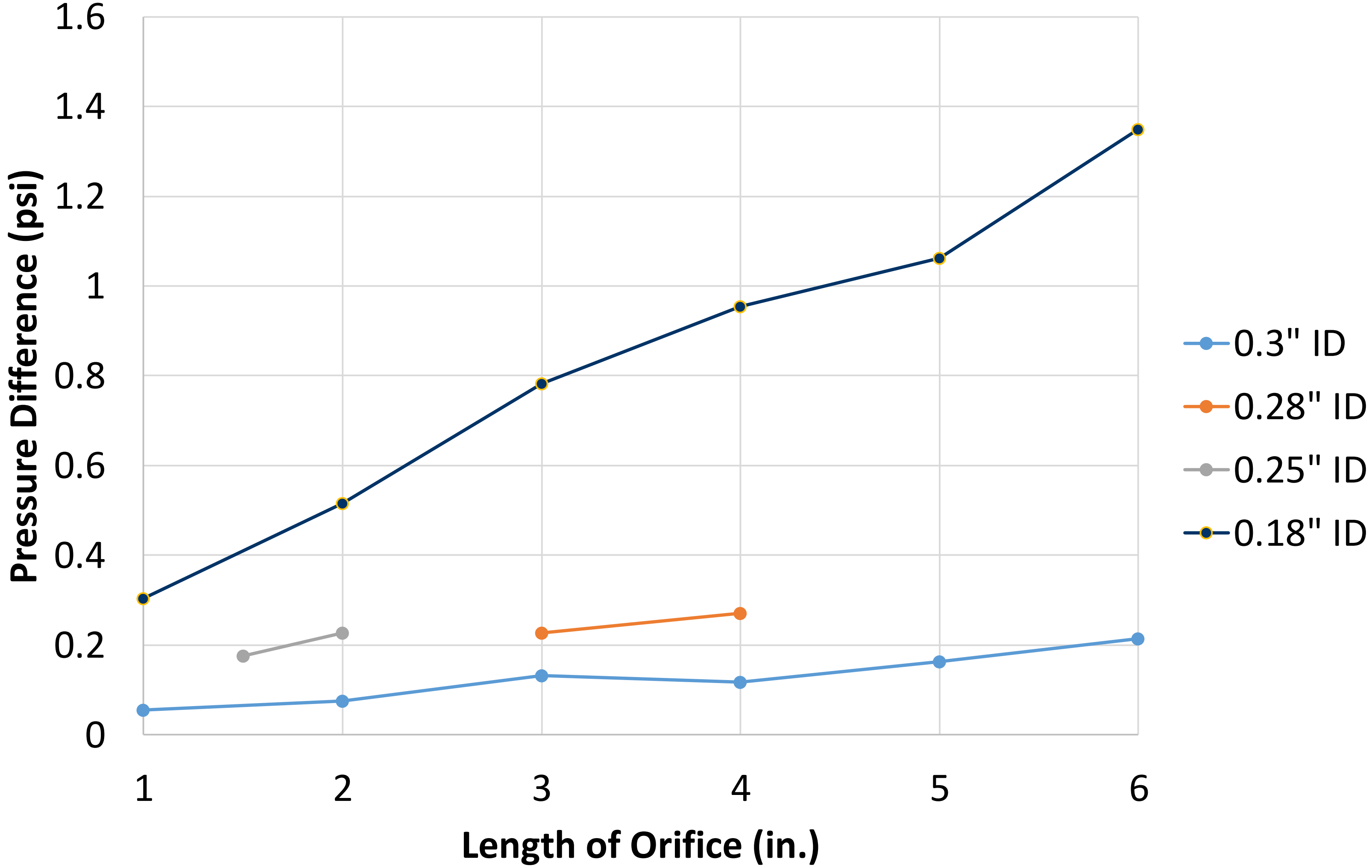

High and Low Flow
Pressure (psi)
Flow (gpm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
0.5
1.0
1.5
2.0

Select System Orifice

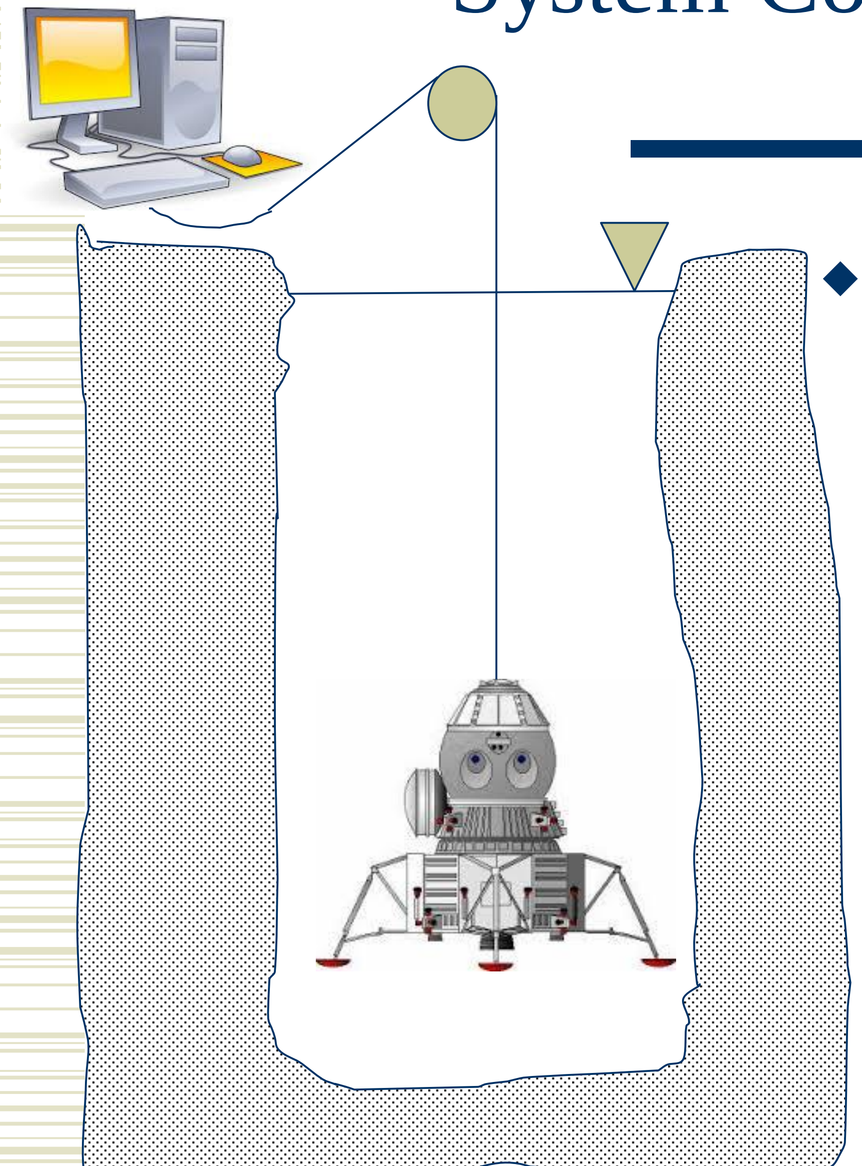
- Small orifice is affected most by changes in viscosity
- Large orifice less affected by debris
- Selection of system orifice based on balancing positive benefits
- Need largest possible pressure difference relative to transducer sensitivity

Low Flow Nozzles

Optimum Nozzle Selection

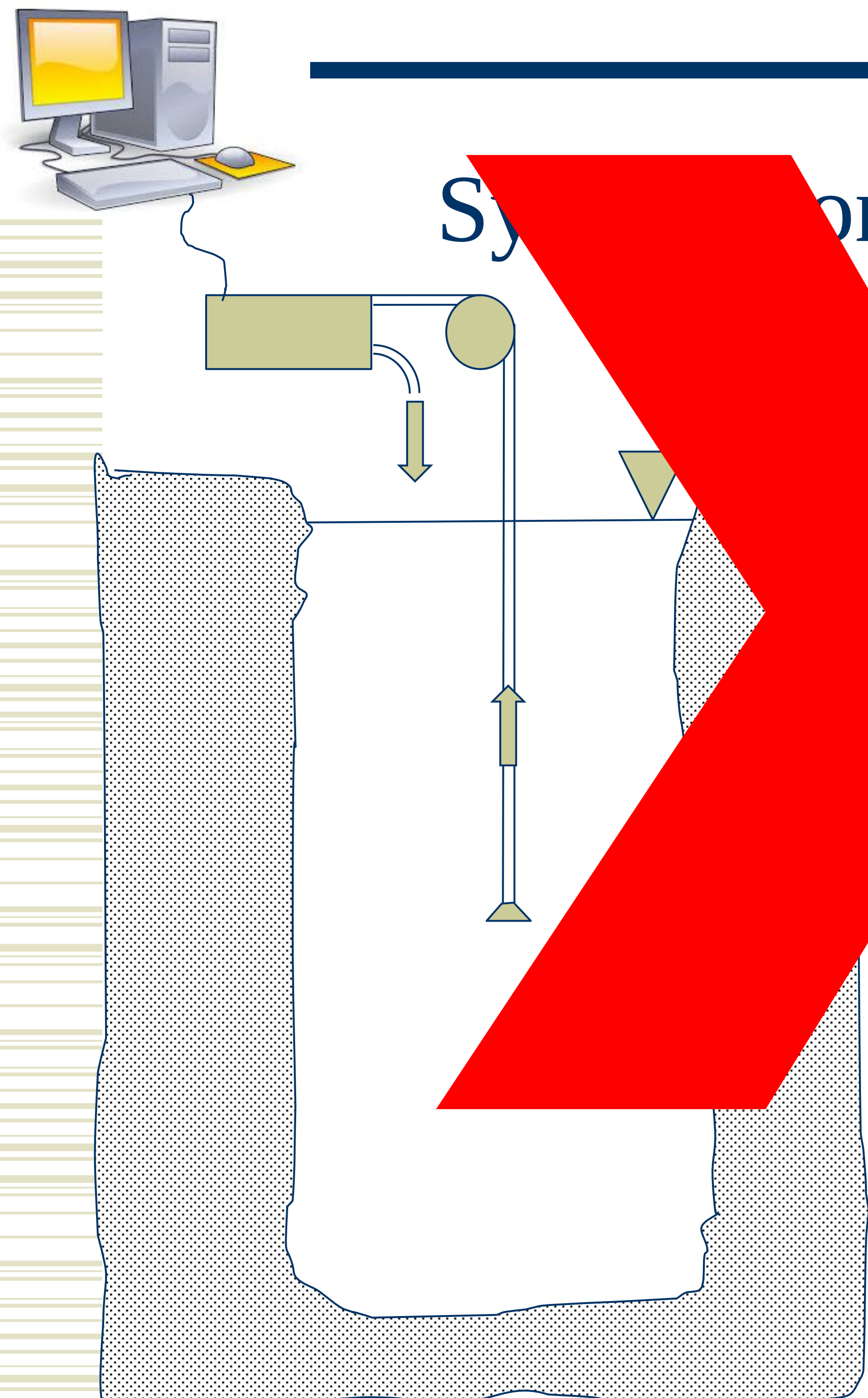


System Concepts GRIP 2015



- Downhole self contained "dive bell"
  - Pressure
  - Flow
  - Density
  - Depth measured topside

Sy oncepts 2015)



- e measurements
  - hose
  - hose depth
  - from a given depth t ide systems.
- Co le to measurements base sition and time in hose / flow

Downhole Component Selection Considerations

- Pressure transducer(s)
  - Differential vs absolute
- Flow meter
  - Magnetic flux, Doppler, paddle wheel, ultra sonic
- Pump type and size
  - Centrifugal, diaphragm, peristaltic, Archimedes screw, piston pump
- Component power requirements
  - AC, DC, hydraulic, pneumatic
- Power source (top side power vs on-board batteries)

Downhole Component Selection Considerations

- Pressure transducer(s)
  - **Differential**
- Flow meter
  - **Magnetic flux**
- Pump type and size
  - **Centrifugal** with variable flow
- Component power requirements
  - **DC** (24-32, 10-15, 12 or 24VDC)
- Power source (**2 On-board batteries; 12 or 24)**

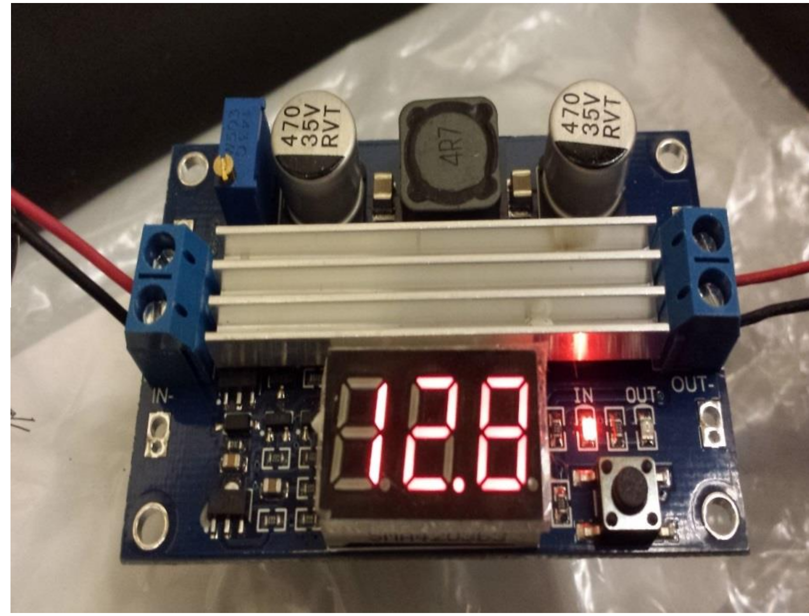
Power Requirements

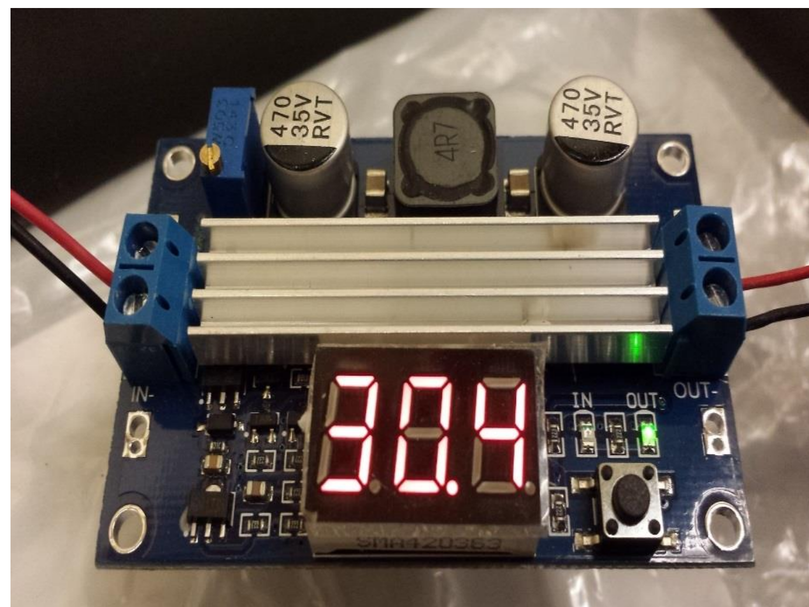
- Onboard batteries 12 VDC
- 5 amps require large, heavy wire to combat voltage drop over a 100ft distance of cable.
- Component input requirements do not fall within the same range.
  - 12 VDC for pump
  - 10-15 VDC for flow meter
  - 24-32 VDC for both pressure transducers

Description	Power Requirement	Reqd. No. Cable / Tether Conductors	Output Type
Pump	12 or 24VDC	None for operation	N/A
Pump relay	12VDC triggered by computer system	2	N/A
Flow meter	10-15VDC	2 or 4 (for both output)	4-20mA current or digital counts
Nozzle pressure	24-32VDC	2	0-5VDC
Density pressure	24-32VDC	2	0-5VDC
Battery Charge	12 or 24VDC top to bottom feed	2	N/A
Battery Monitor	N/A	2	N/A
Pump Speed Control	N/A	3	N/A

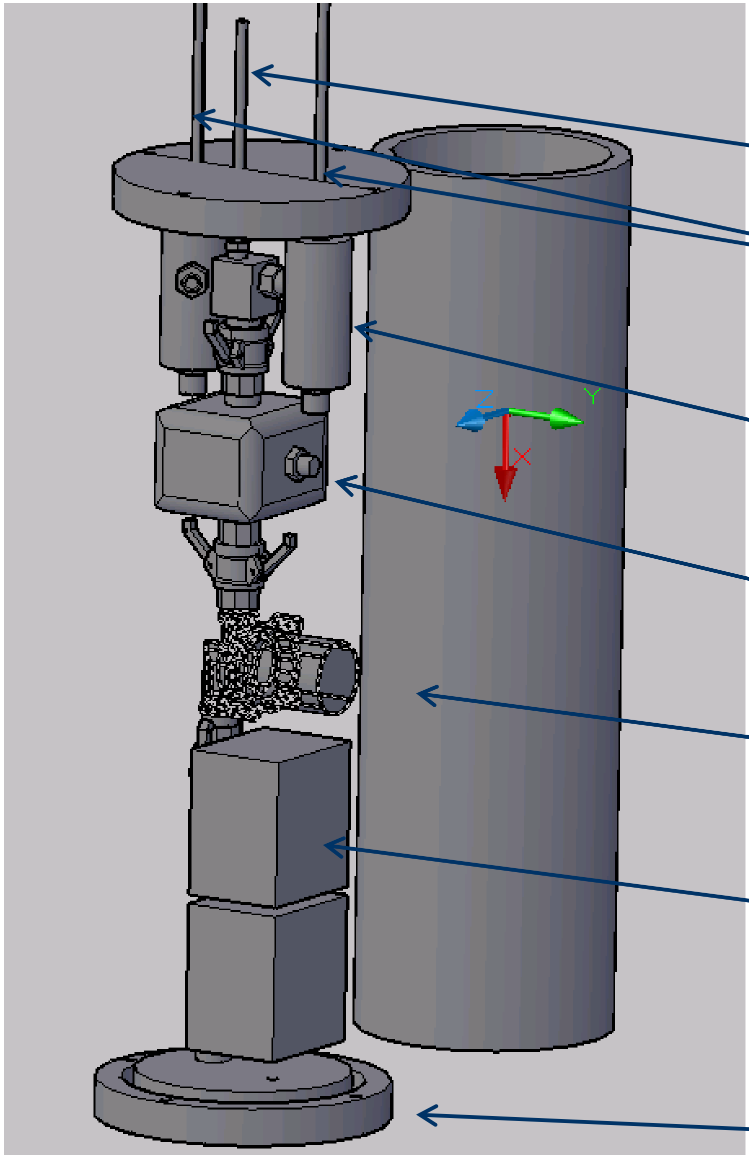
Power Requirements (continued)

- Boost Converter
- Input Voltage (3 to 35VDC)
    - 12.8 V (battery)
- Output Voltage (3.5 to 35VDC)
    - 30.4 V (chosen)





Concept Device



Discharge nozzle

Differential
Pressure
Reference Ports

Two differential
transducers

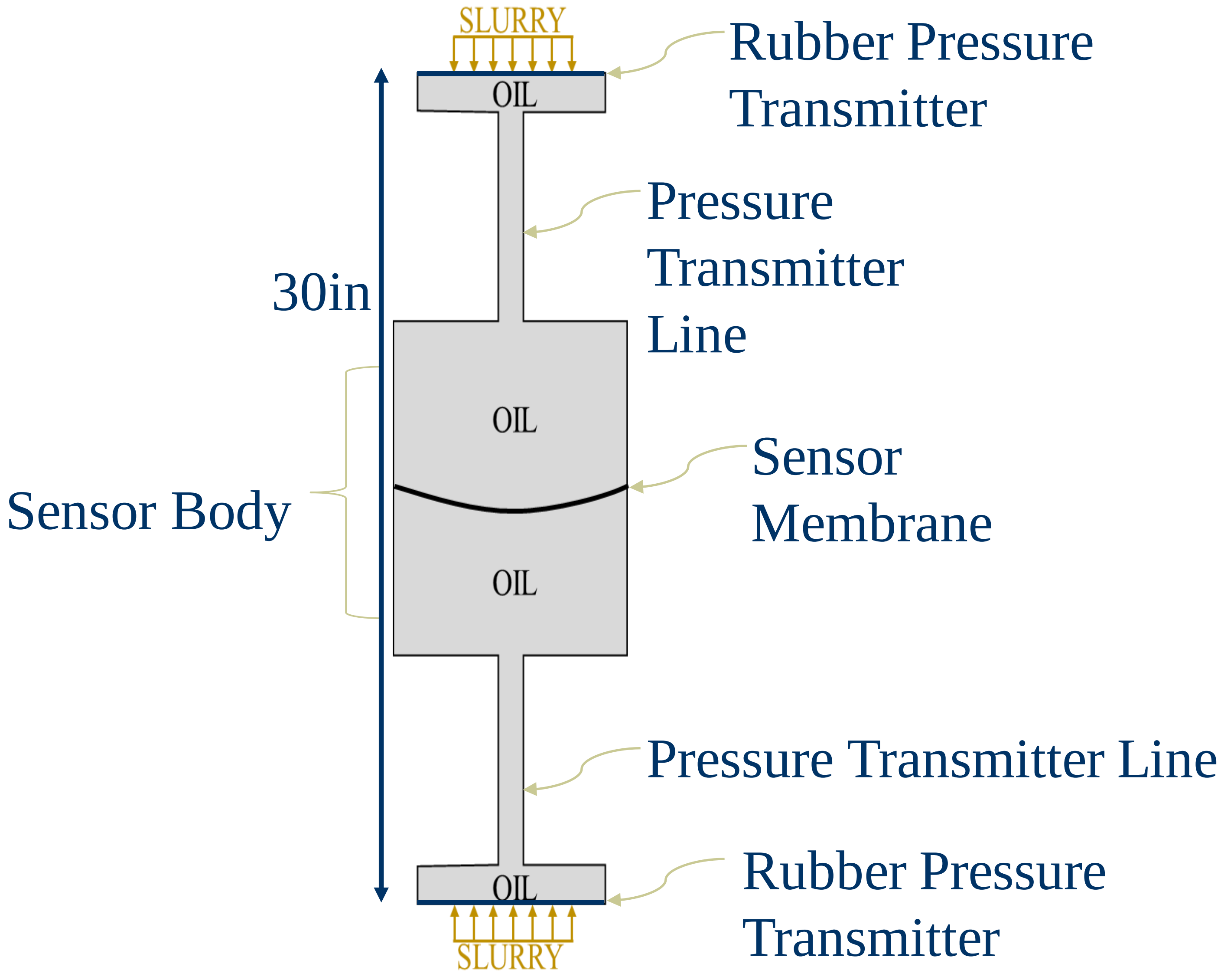
Mag flux flow meter

Variable flow pump

Two 12V 5.5amp-hr batteries
(optional 12 or 24V
configuration)

Pump pickup screen

Differential Pressure Transducer (density)



Computerized DAQ System (CDS)

Connections

Case charger

USB DAQ / CPU

DHU connector

Depth encoder

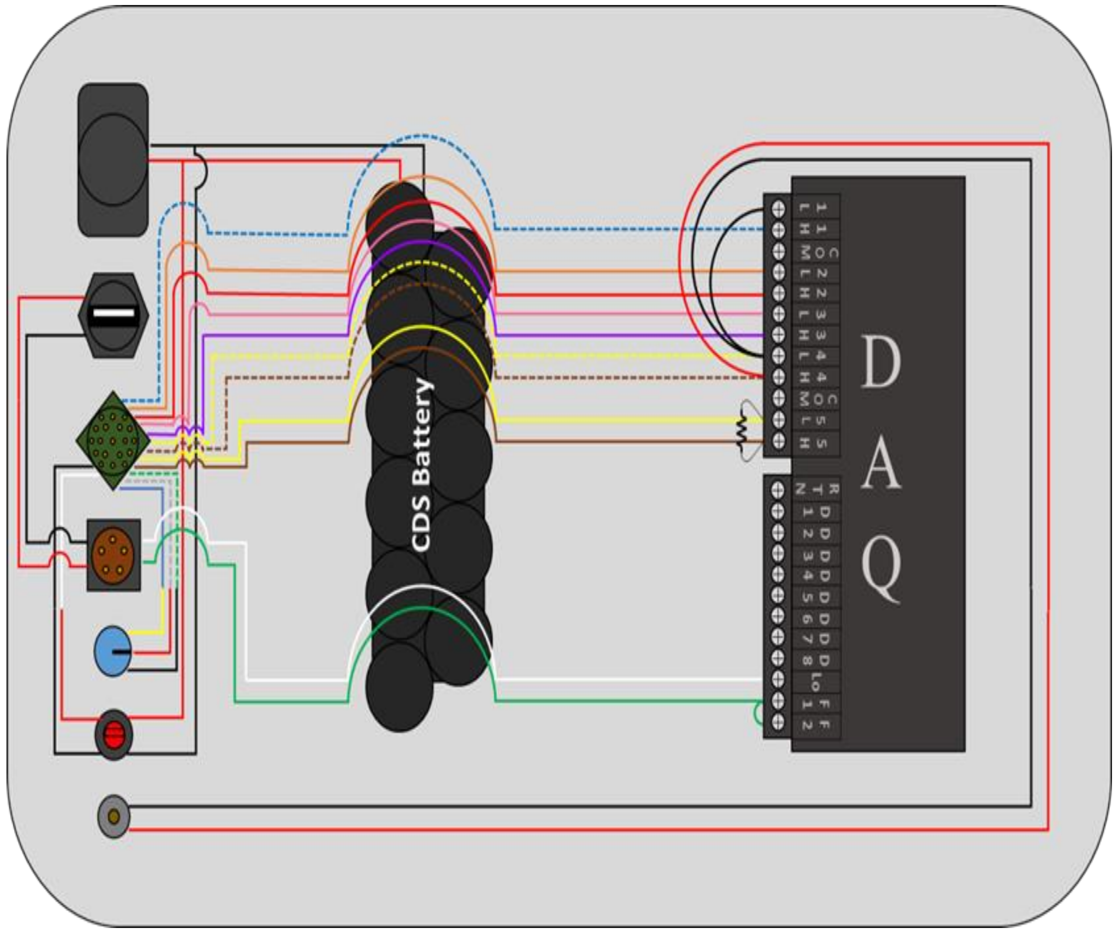
Pump control

DHU relay/power

DHU charger

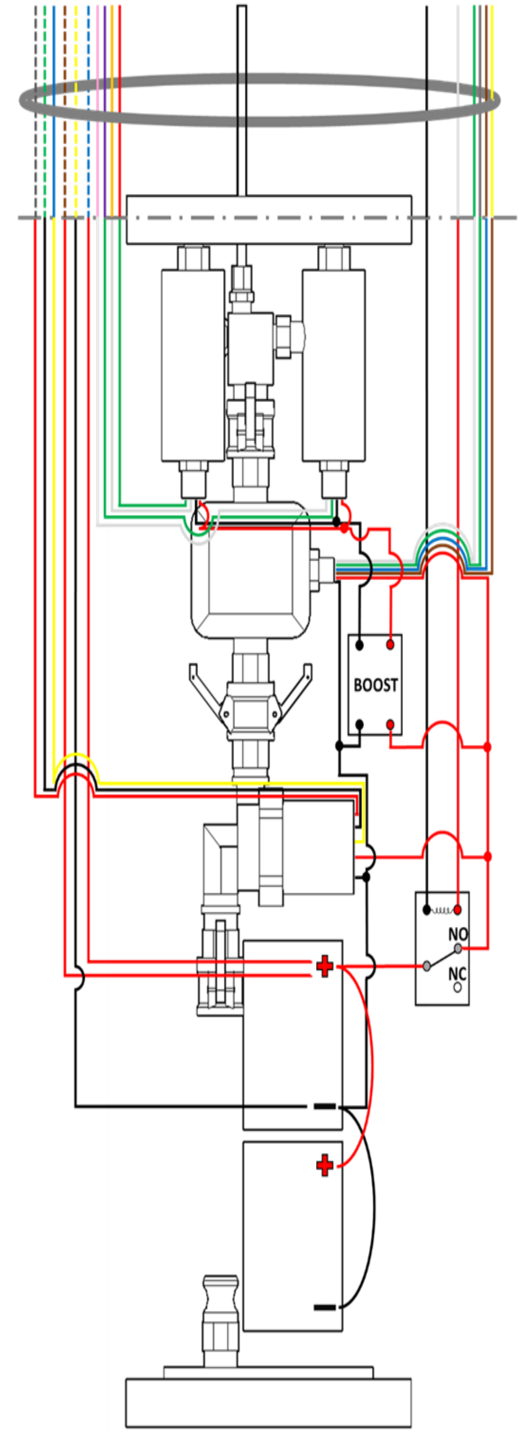
Computerized DAQ System (CDS)

Component	Sensor	Harness	DAQ
Density PT	White	Orange	2L
	Green	Red	2H
Flow PT	White	Pink	3L
	Green	Purple	3H
Flow Meter	White	Green	N/A
	Green	Gray	N/A
	Brown	Yellow	5L
	Blue	Brown	5H
Pump Controller	Yellow	Blue	N/A
	Red	Bl-Gray	N/A
	Black	Bl-Green	N/A
Hot Line	Red	Bl-Brown	4H
	Black	Bl-Yellow	4L
Monitor	Red	Bl-Blue	1H
Relay	Red	White	N/A
	Black	Black	N/A

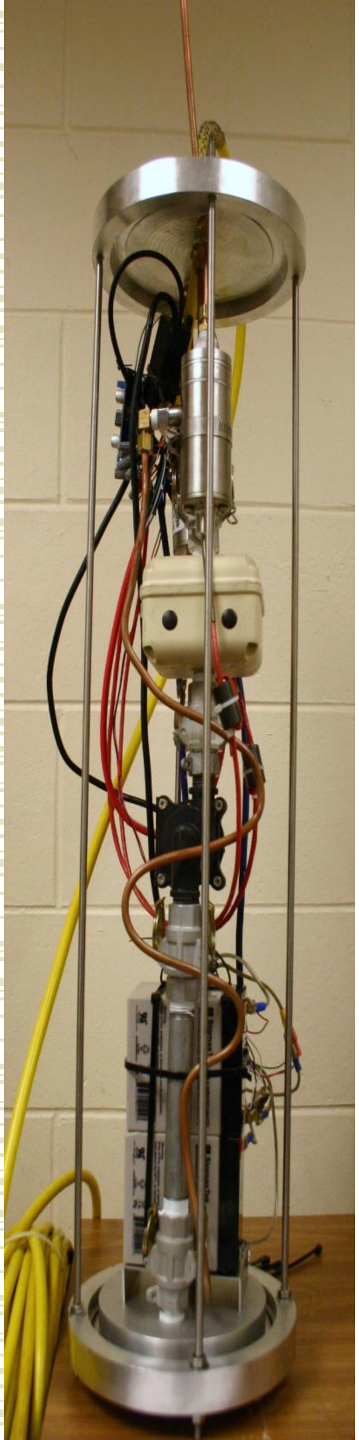


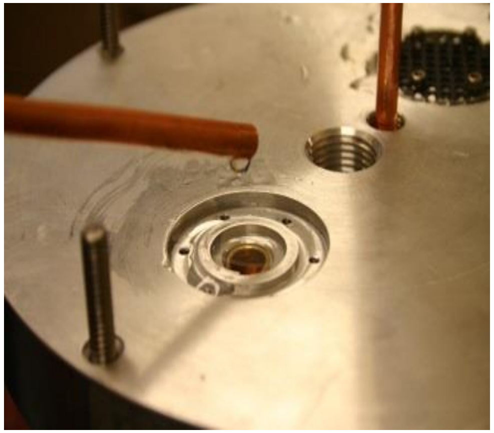
Down Hole Unit (DHU)

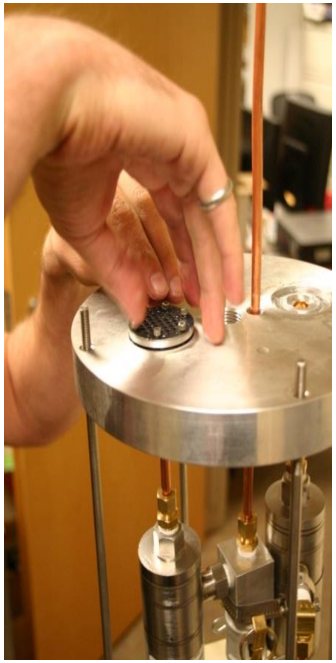
Component	Sensor	Harness	DAQ
Density PT	White	Orange	2L
	Green	Red	2H
Flow PT	White	Pink	3L
	Green	Purple	3H
Flow Meter	White	Green	N/A
	Green	Gray	N/A
	Brown	Yellow	5L
	Blue	Brown	5H
Pump Controller	Yellow	Blue	N/A
	Red	Bl-Gray	N/A
	Black	Bl-Green	N/A
Hot Line	Red	Bl-Brown	4H
	Black	Bl-Yellow	4L
Monitor	Red	Bl-Blue	1H
Relay	Red	White	N/A
	Black	Black	N/A

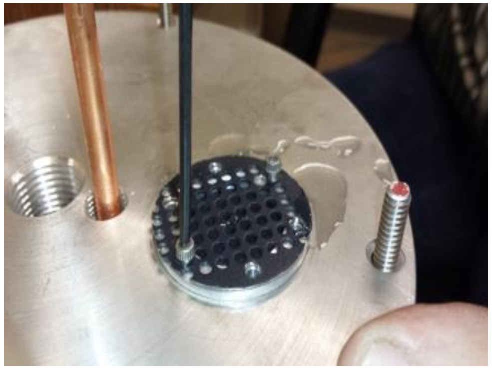


Transmitter / diaphragm purging





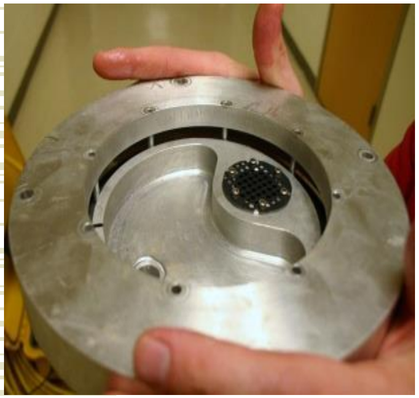


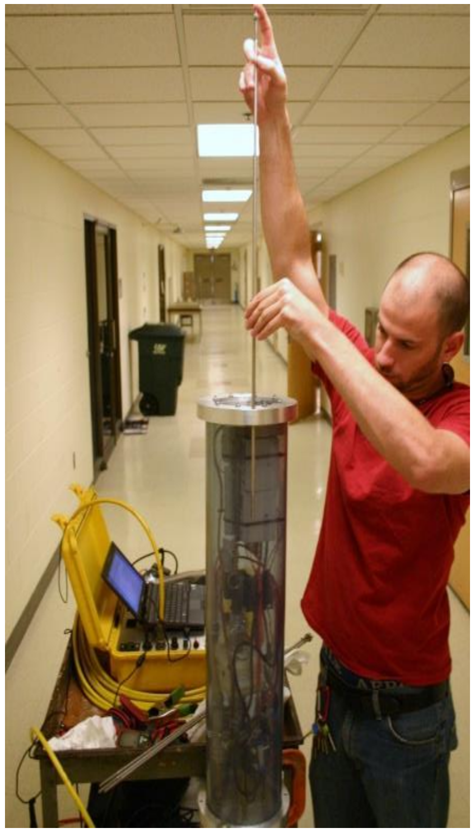


Assembly



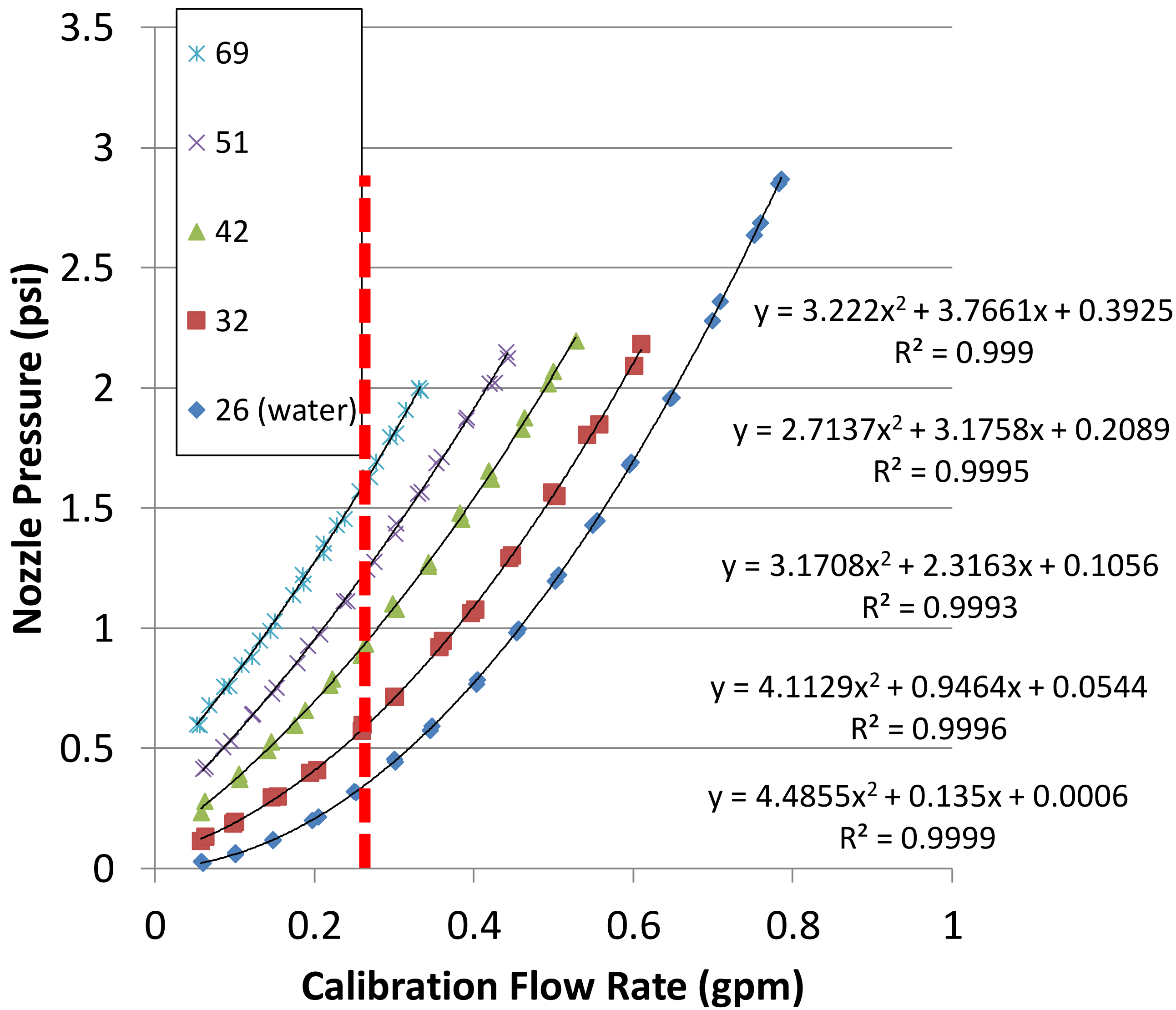

Assembly



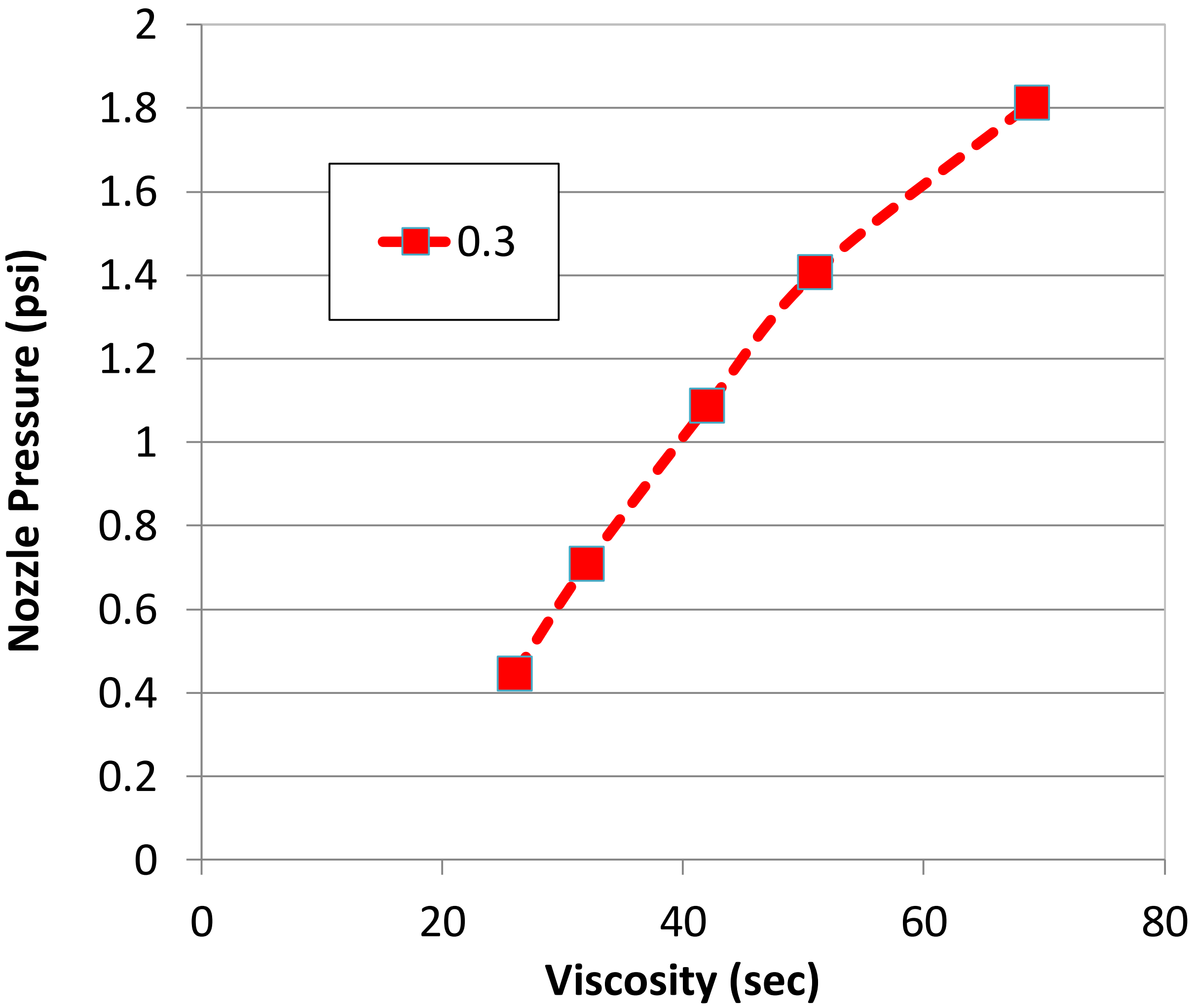



Calibrating Viscosity Measurements

- Very repeatable
- Actually two overlapping test curves at each viscosity
- 2nd order polynomial fit
- Slice this graph vertically at tenth points

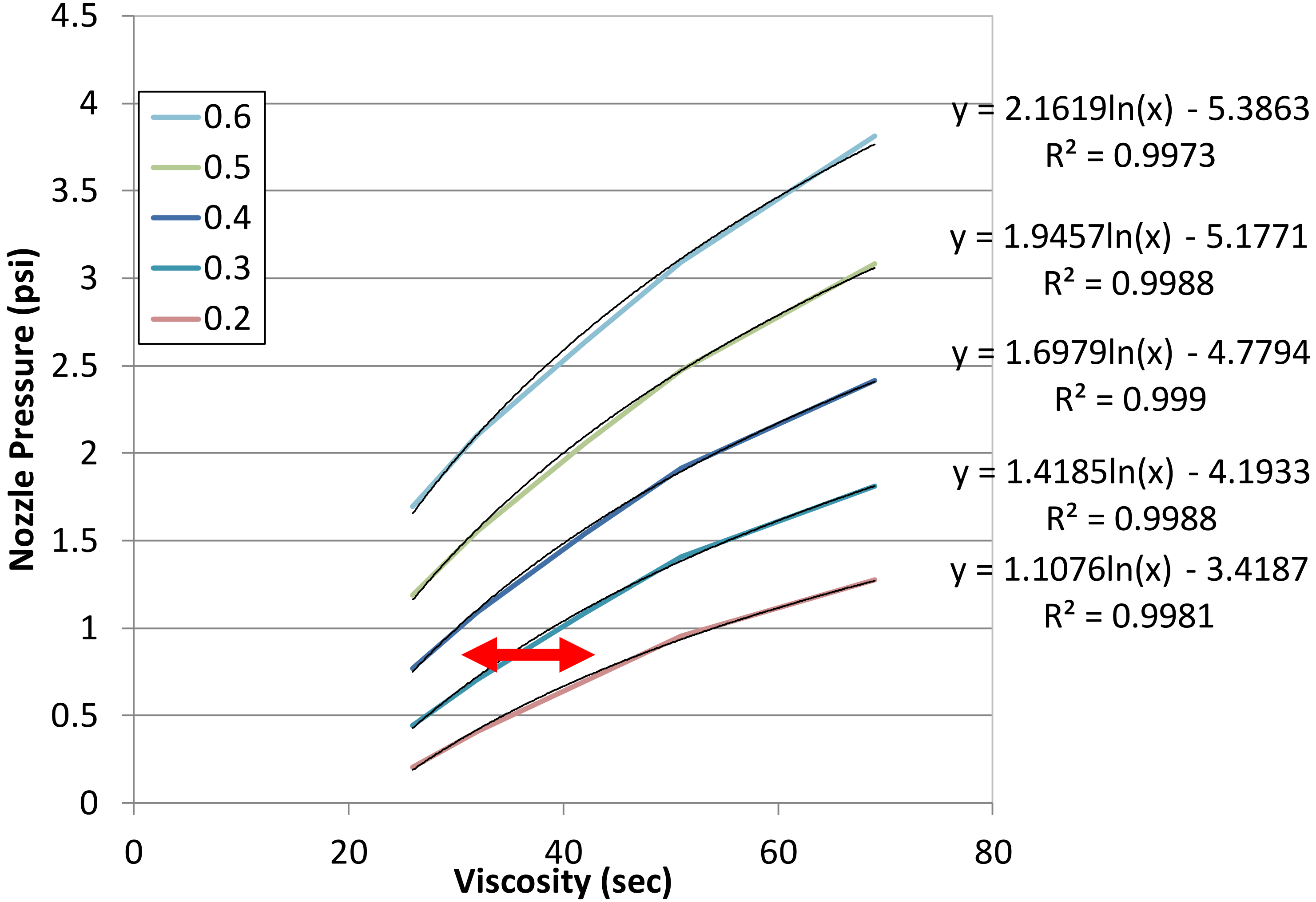


Calibrating Viscosity Measurements



- Constant flow rate curves

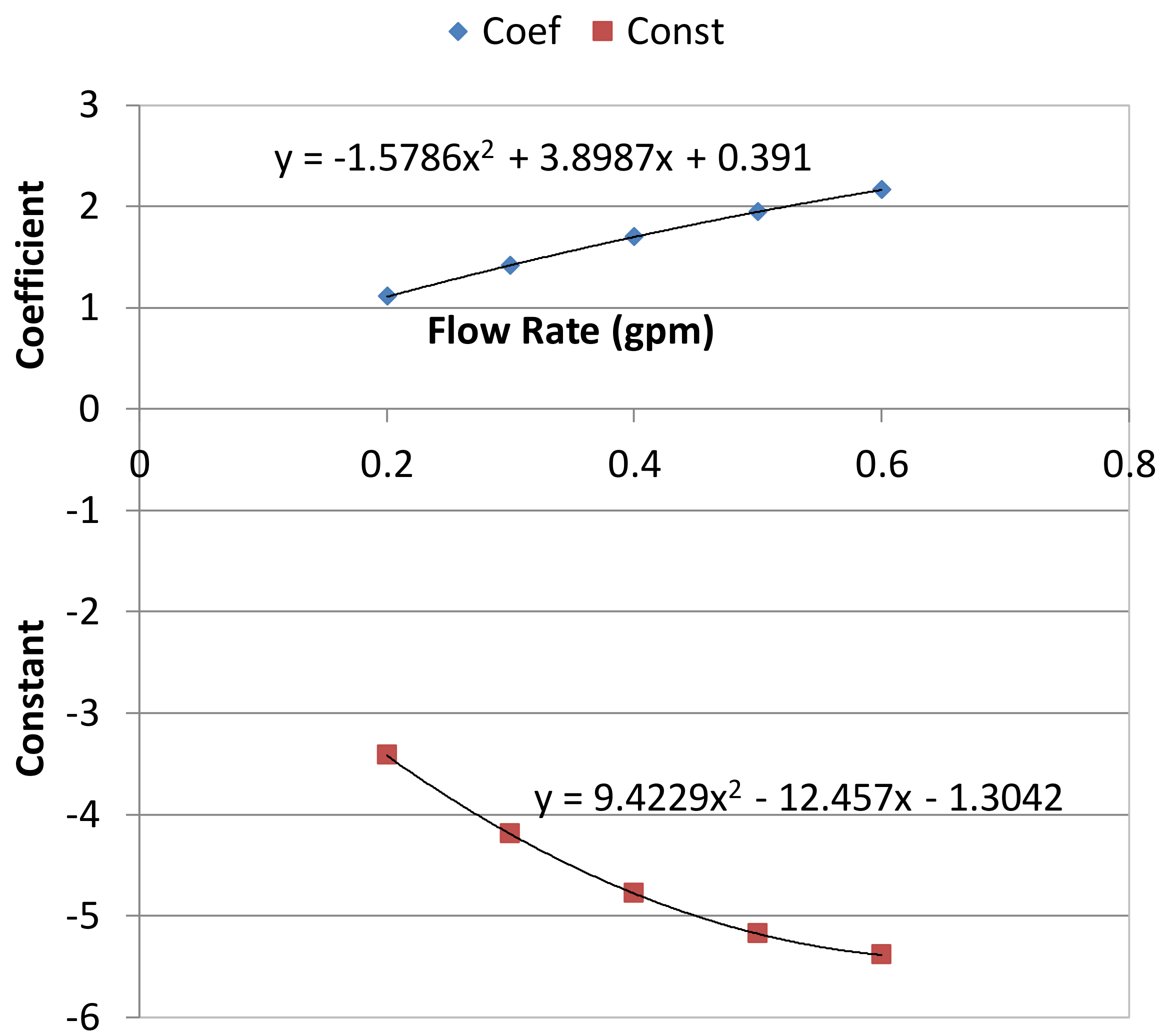
Calibrating Viscosity Measurements



- Constant flow rate curves
- Natural logarithm fit

Calibrating Viscosity Measurements

- Plot of coefficients and constants of trend lines



$y = 2.1619\ln(x) - 5.3863$
$R^2 = 0.9973$

$y = 1.9457\ln(x) - 5.1771$
$R^2 = 0.9988$

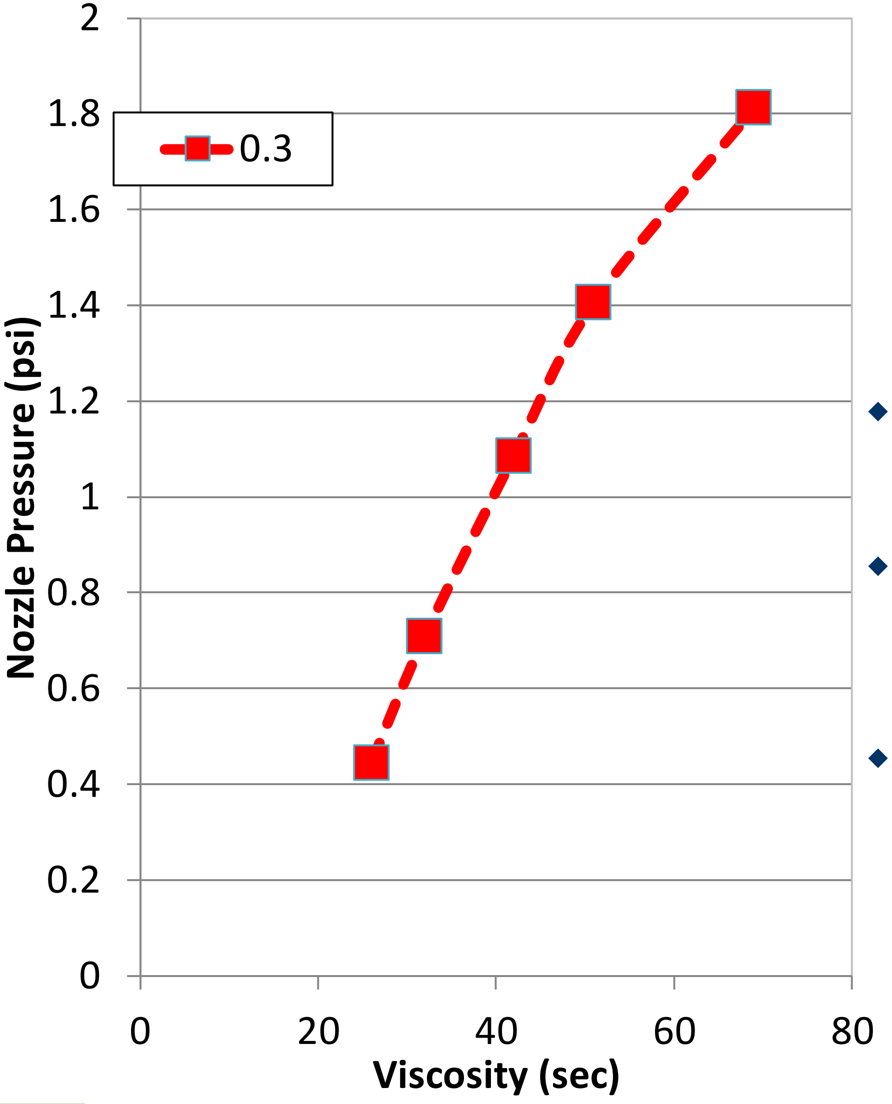
$y = 1.6979\ln(x) - 4.7794$
$R^2 = 0.999$

$y = 1.4185\ln(x) - 4.1933$
$R^2 = 0.9988$

$y = 1.1076\ln(x) - 3.4187$
$R^2 = 0.9981$

- Equations from previous slide

Calibrating Viscosity Measurements



P = 1.4185 ln(V) - 4.1933

- $P = coefficient * \ln(viscosity) + constant$
- $\ln(viscosity) = \frac{pressure - constant}{coefficient}$
- $viscosity = e^{\left(\frac{pressure - constant}{coefficient}\right)}$

Calibrating Viscosity Measurements

- Example for 0.32 gpm:

Coefficient:
$= -1.5786x^2 + 3.8987x + 0.391$
$= 1.477$

Constant:
$= 9.4229x^2 - 12.457x - 1.3042$
$= -4.326$

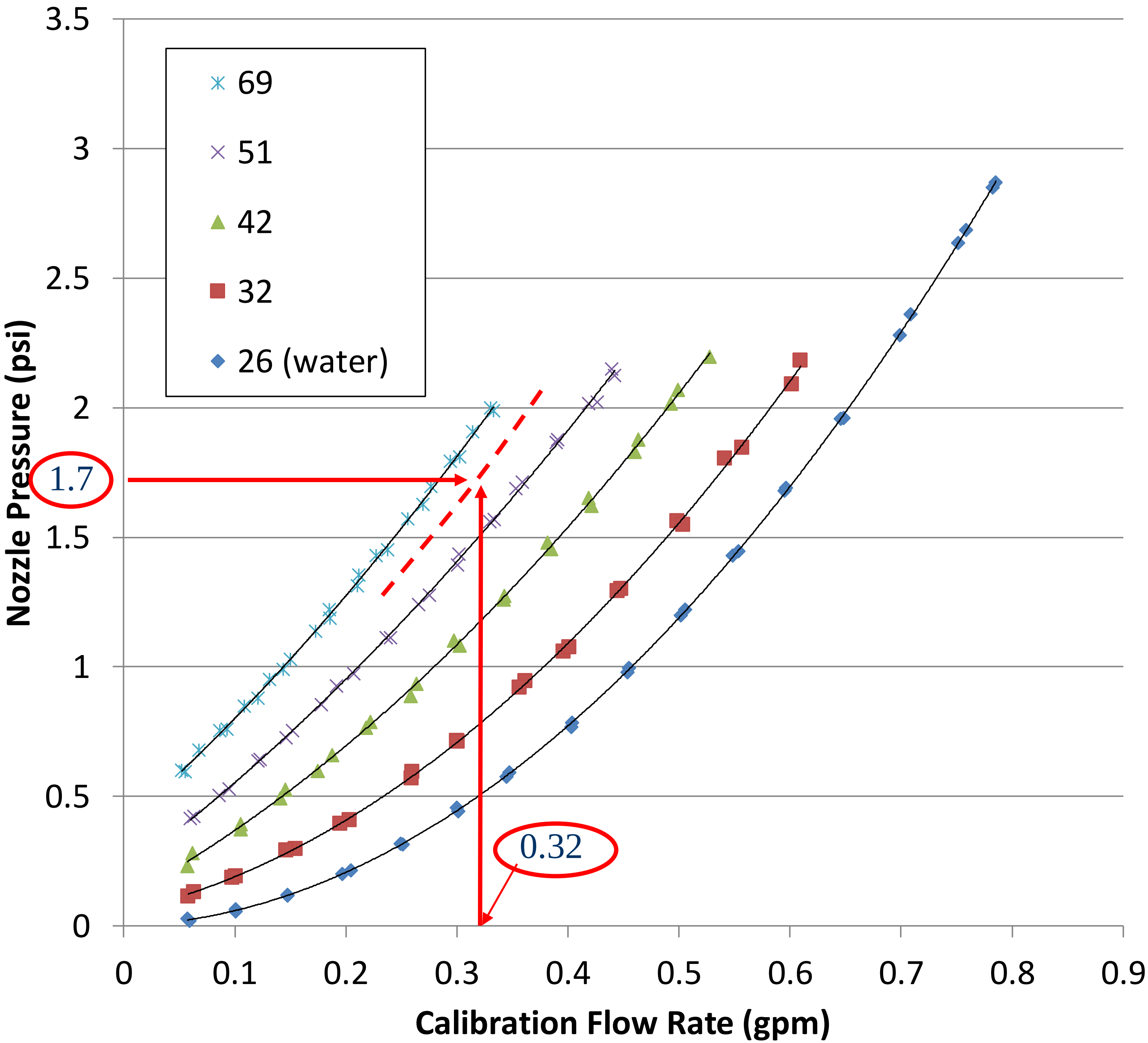
$$P = 1.477 \ln V - 4.326$$

0.3gpm
P = 1.4185 ln(V) - 4.1933

$$viscosity = e^{\left(\frac{P-(-4.326)}{1.477}\right)}$$

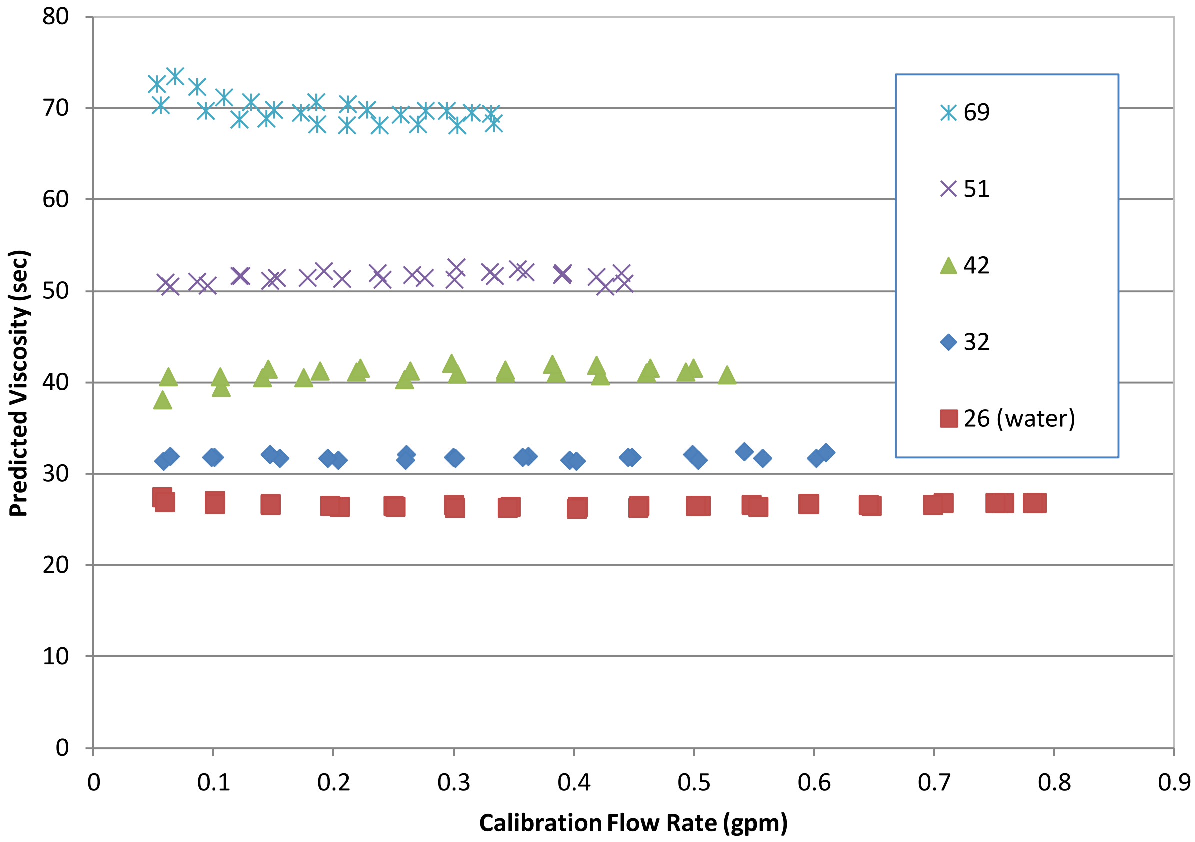
- Given a measured pressure of 1.7 psi:

$$viscosity = \mathbf{59.1}\ s$$



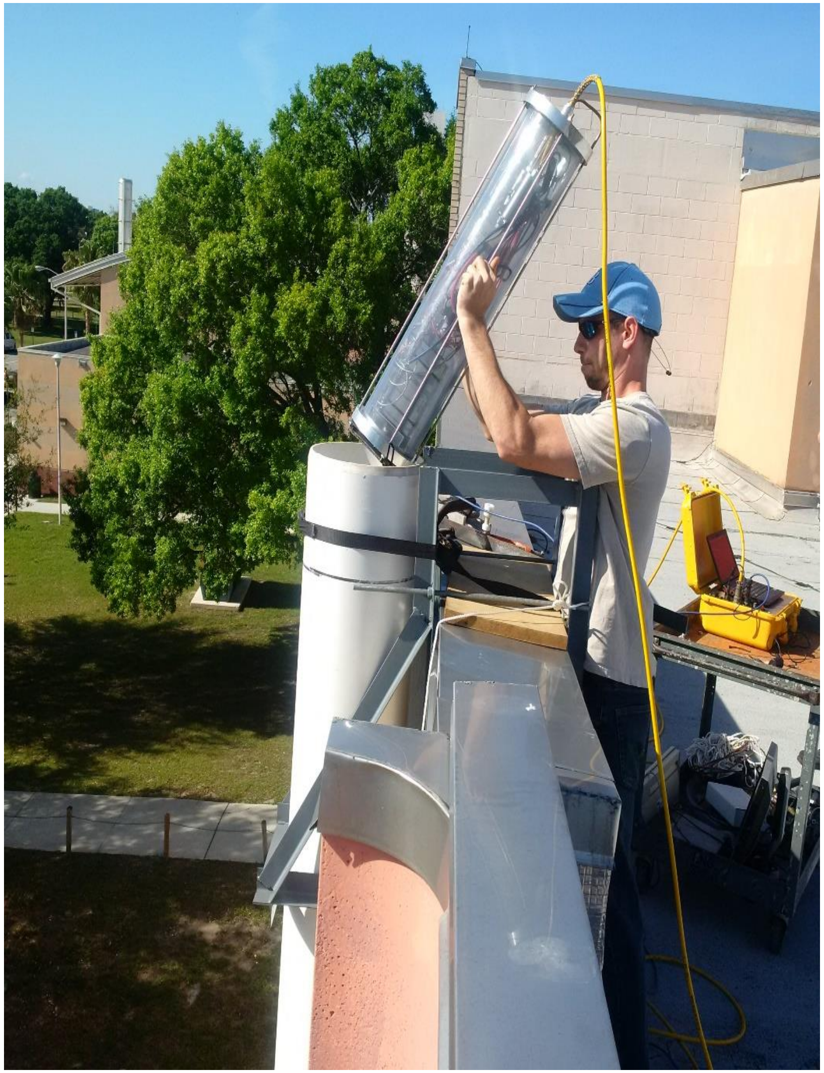
69
51
42
32
26 (water)
1.7
0.32
Nozzle Pressure (psi)
Calibration Flow Rate (gpm)
0
0.5
1
1.5
2
2.5
3
3.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Calibrating Viscosity Measurements

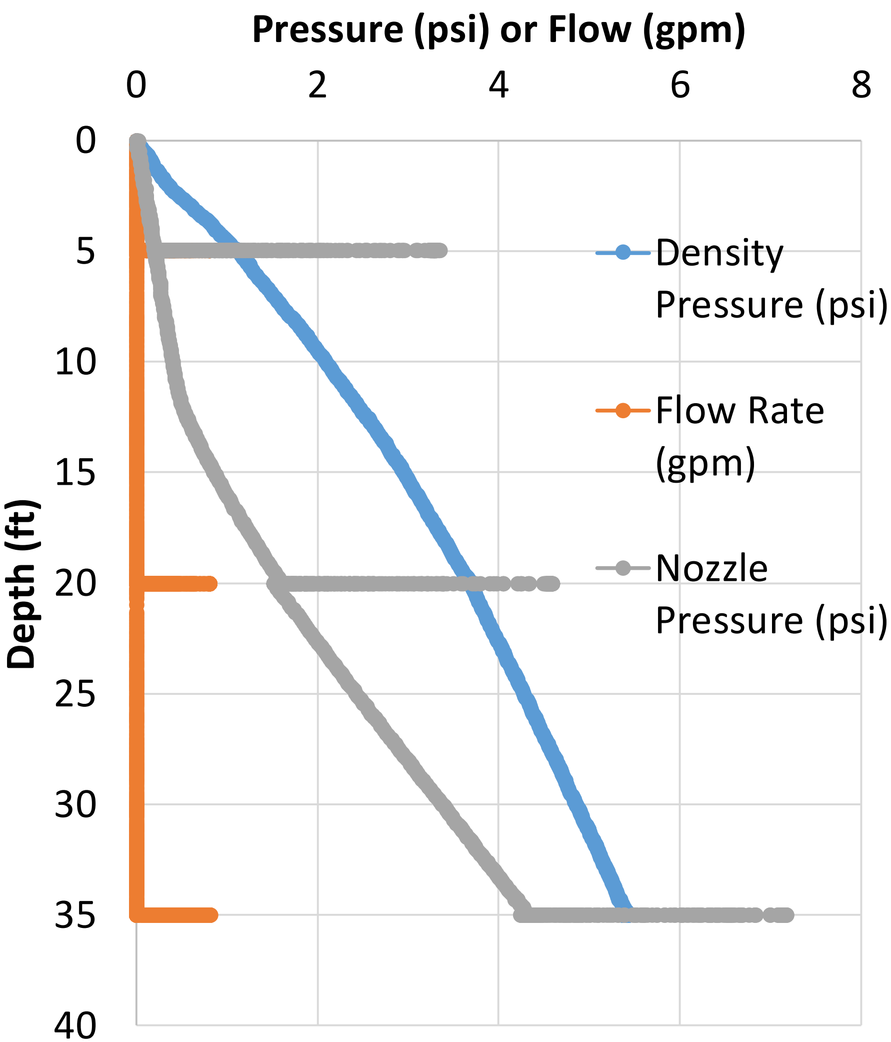


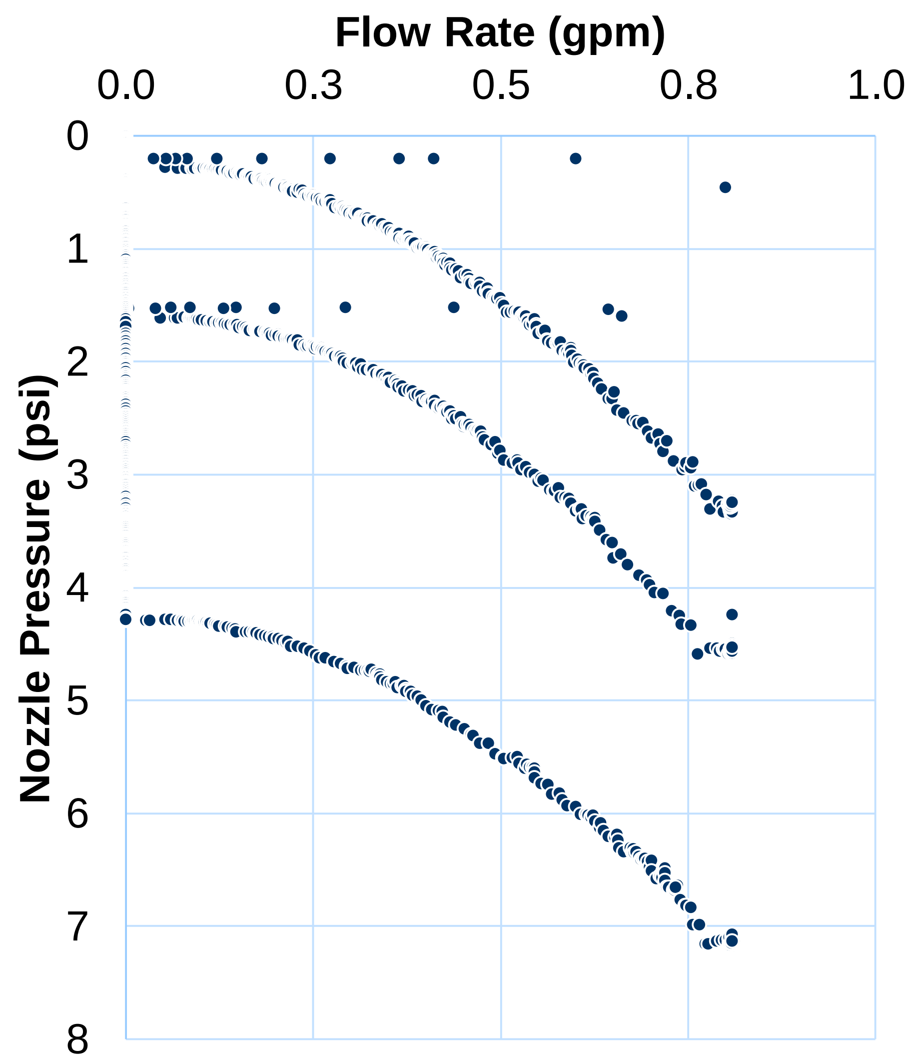
Calibration test shows predicted viscosity curve throughout flow range

Field Testing – Shaft Simulator



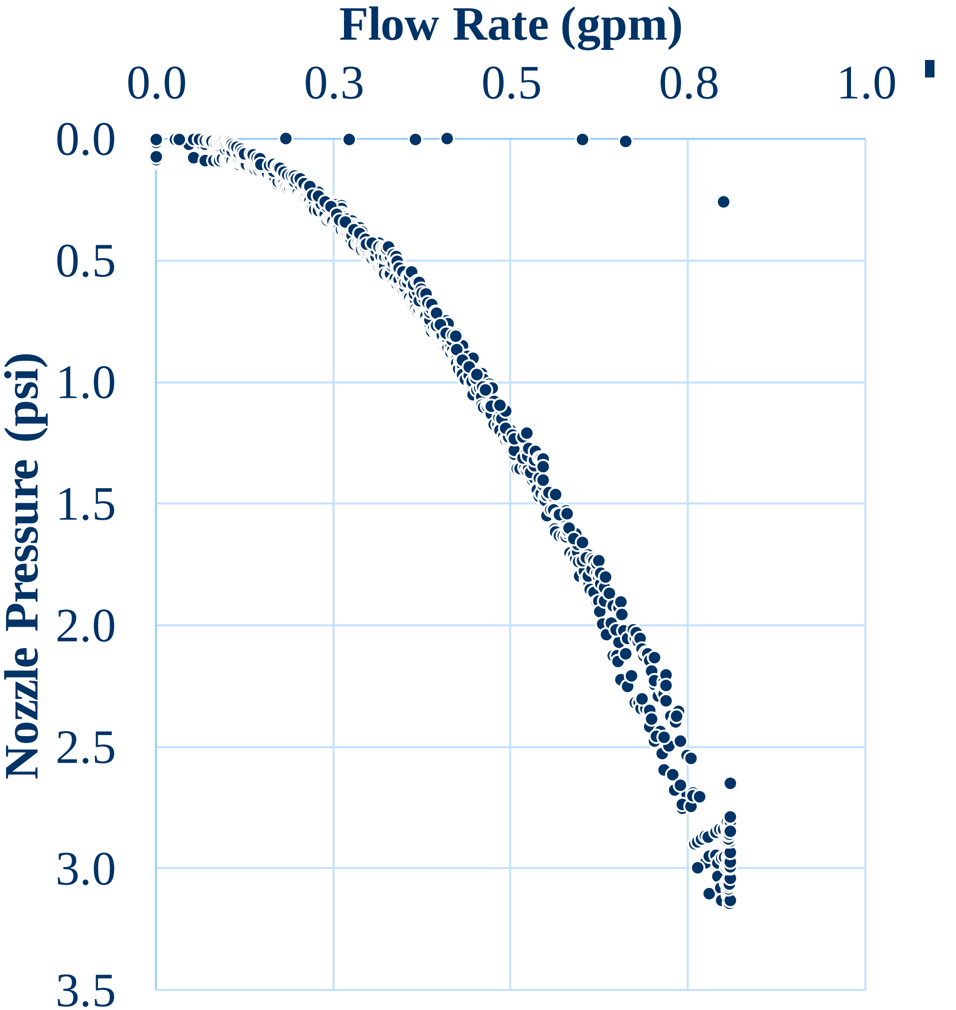
System Check (water)





Test Procedure

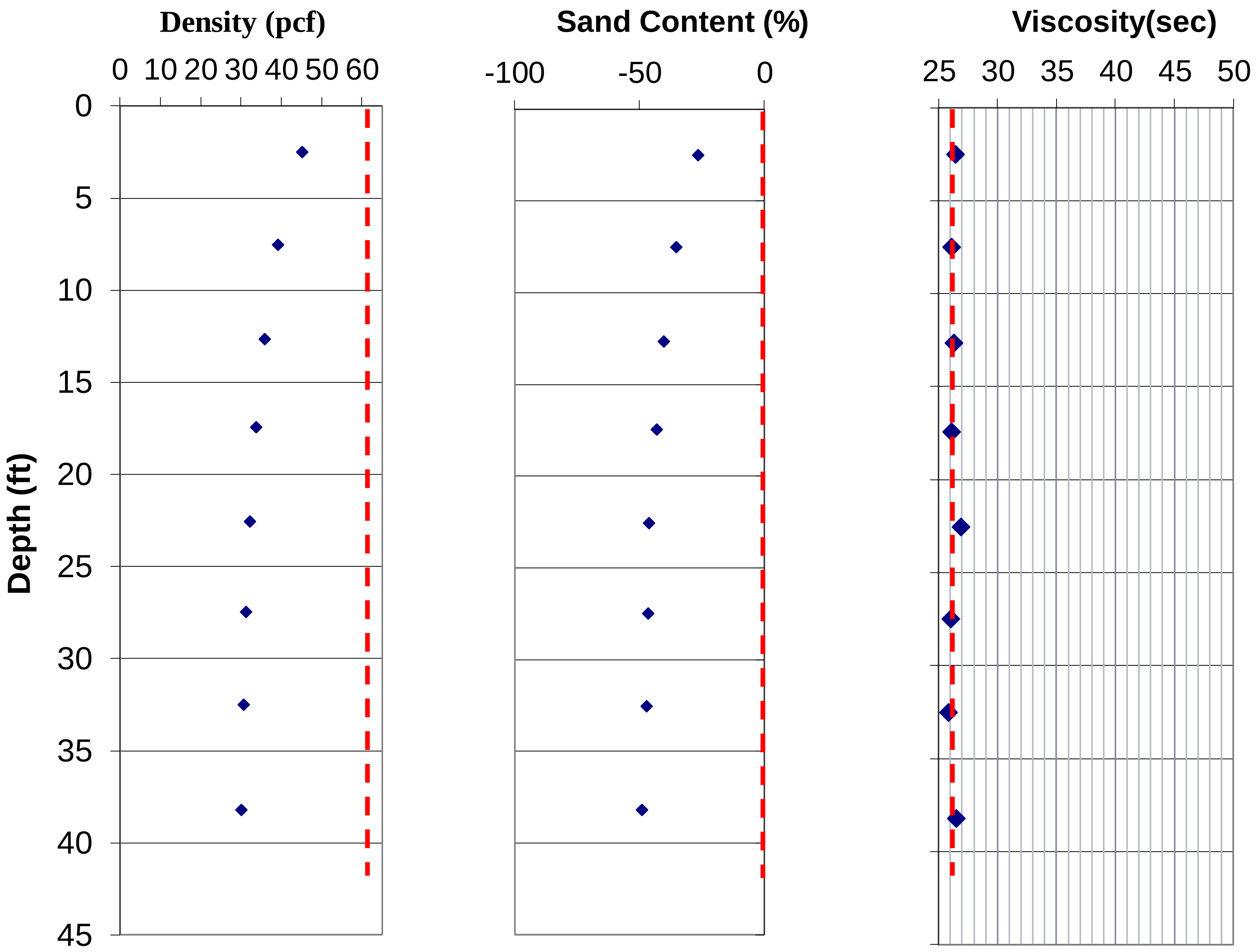
- Nozzle pressure required depth corrected offset



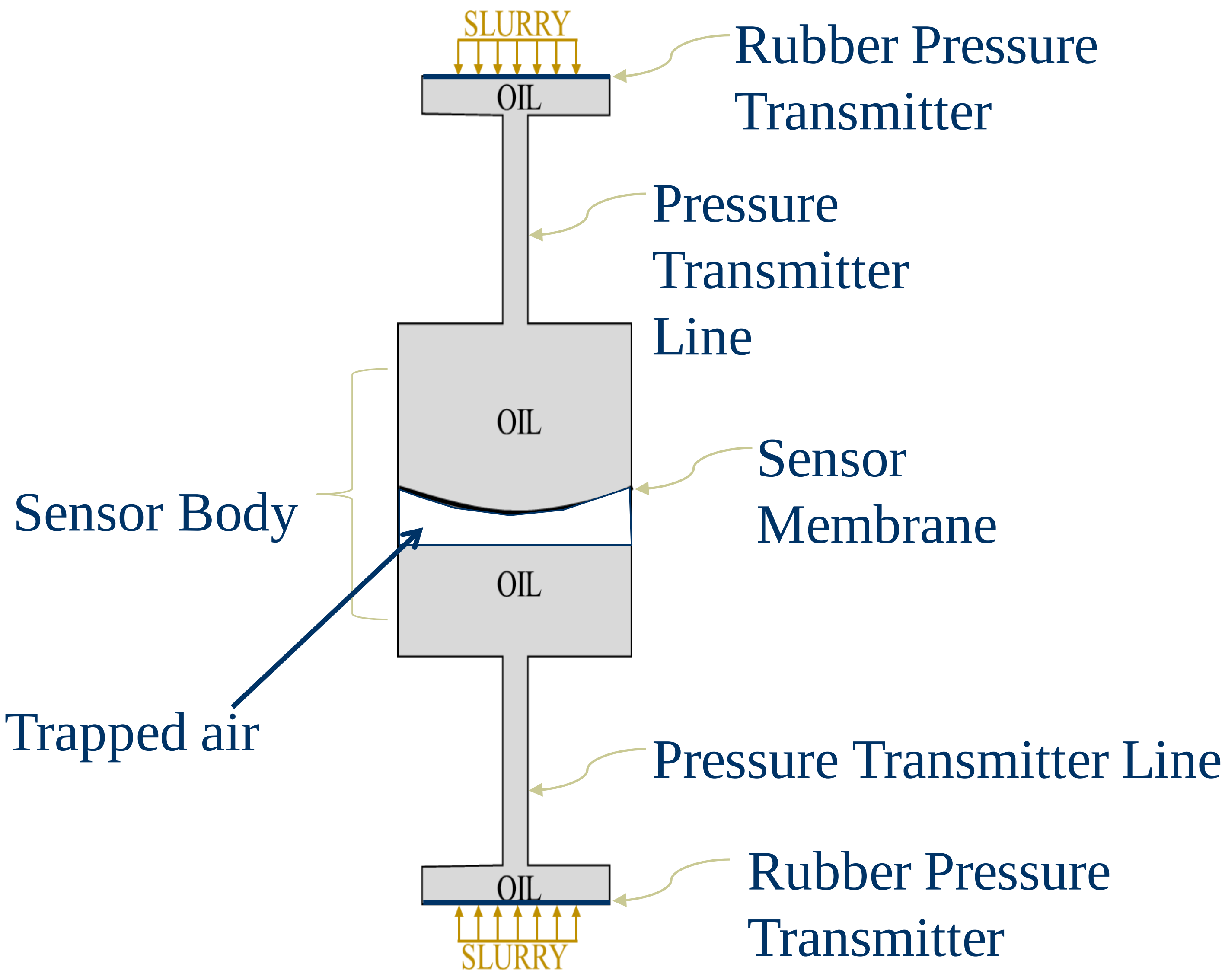
Field Testing – Procedure

1. Take baseline density pressure before introduction
2. Introduce device into hole, lower to first depth
3. Take baseline viscosity pressure at zero flow rate
4. Increase flow rate to desired test range, wait for stabilization (e.g. 0.25-0.35gpm)
5. Take pressure and flow rate data until average is stable (10 sec)
6. Reduce flow rate to zero and move on to next depth
7. Repeat steps 3-6 at subsequent depths

Field Testing – Shaft Simulator



Differential Pressure Transducer (density)



Field Testing – Sarasota

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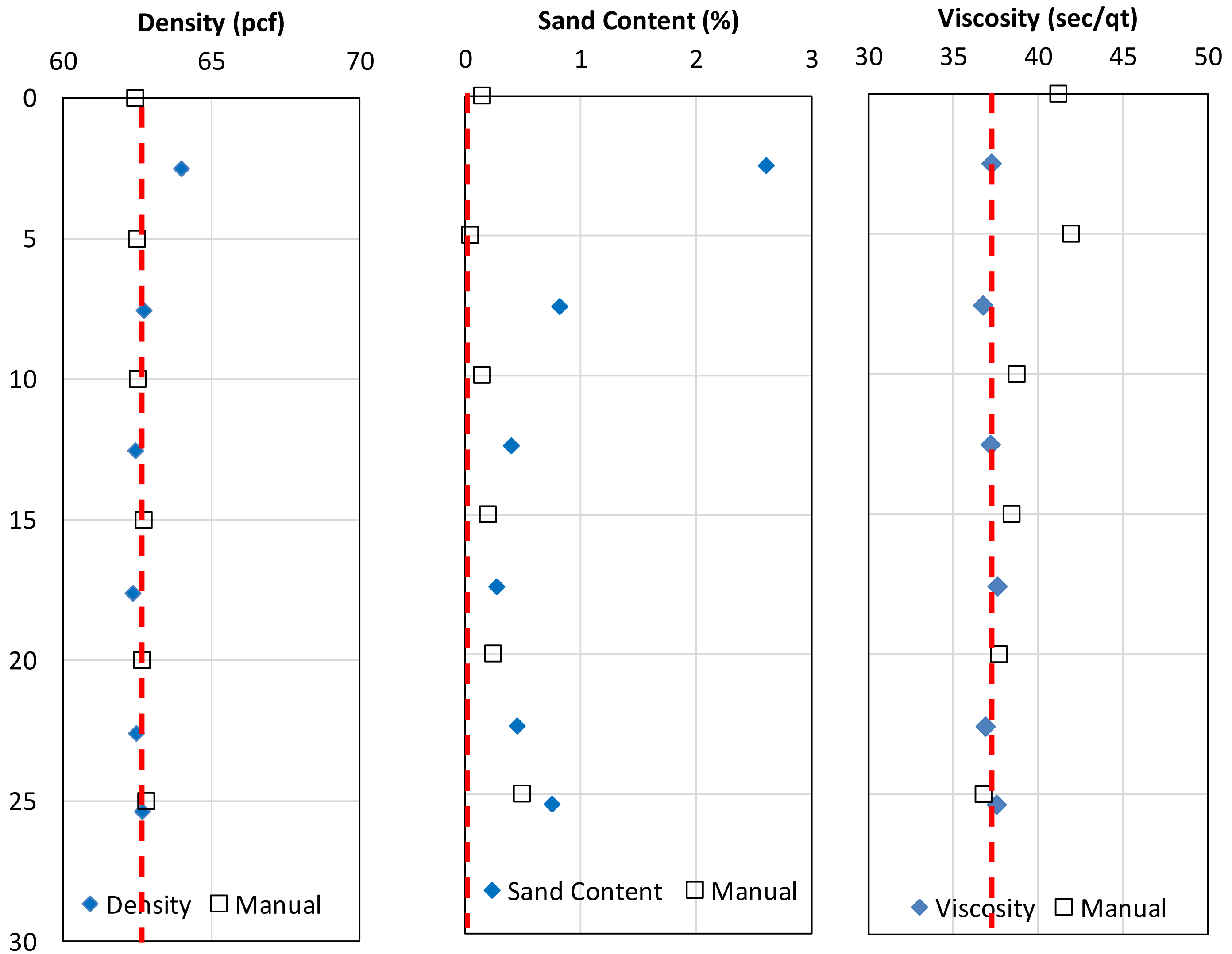

Field Testing – Ft. Myers

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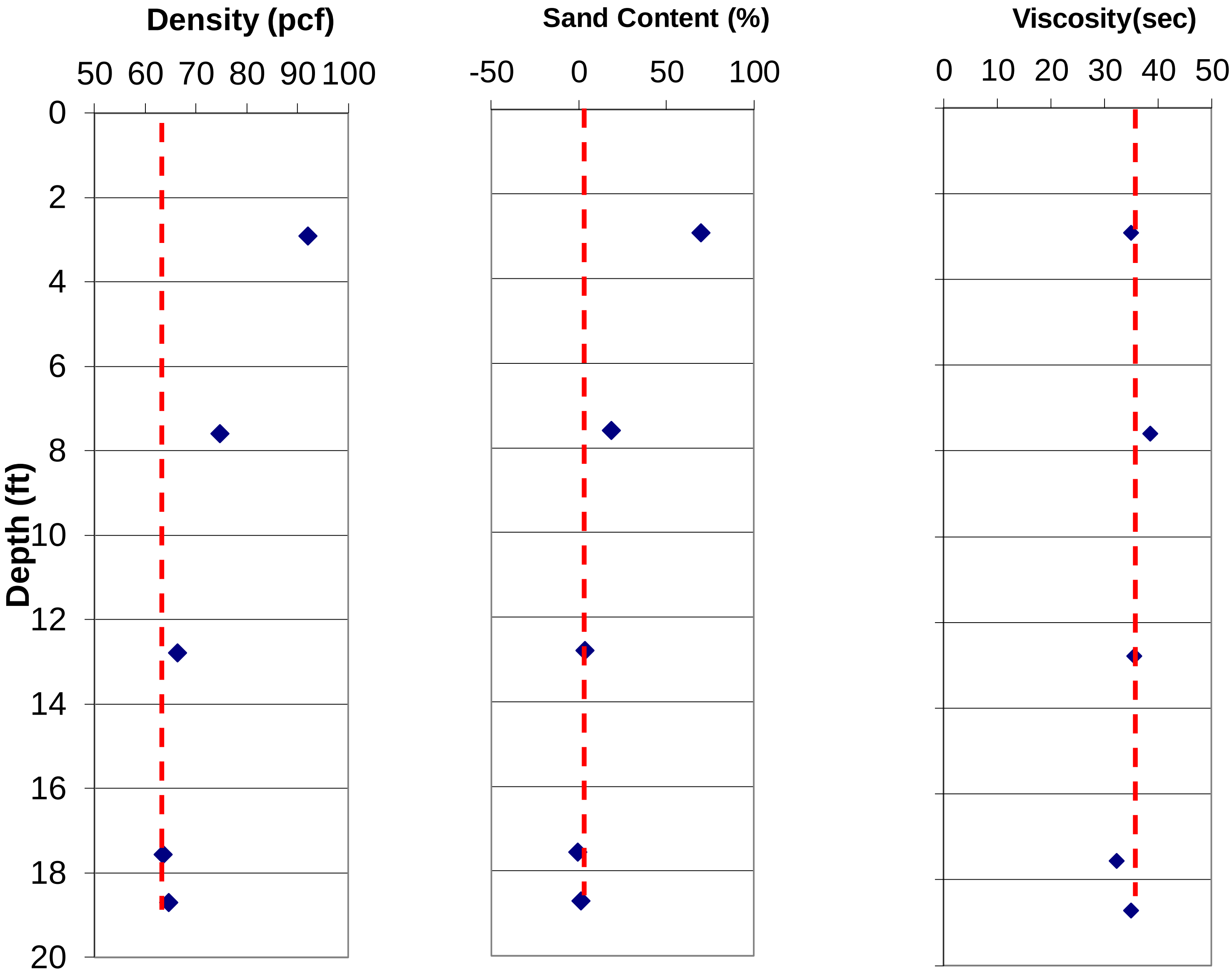
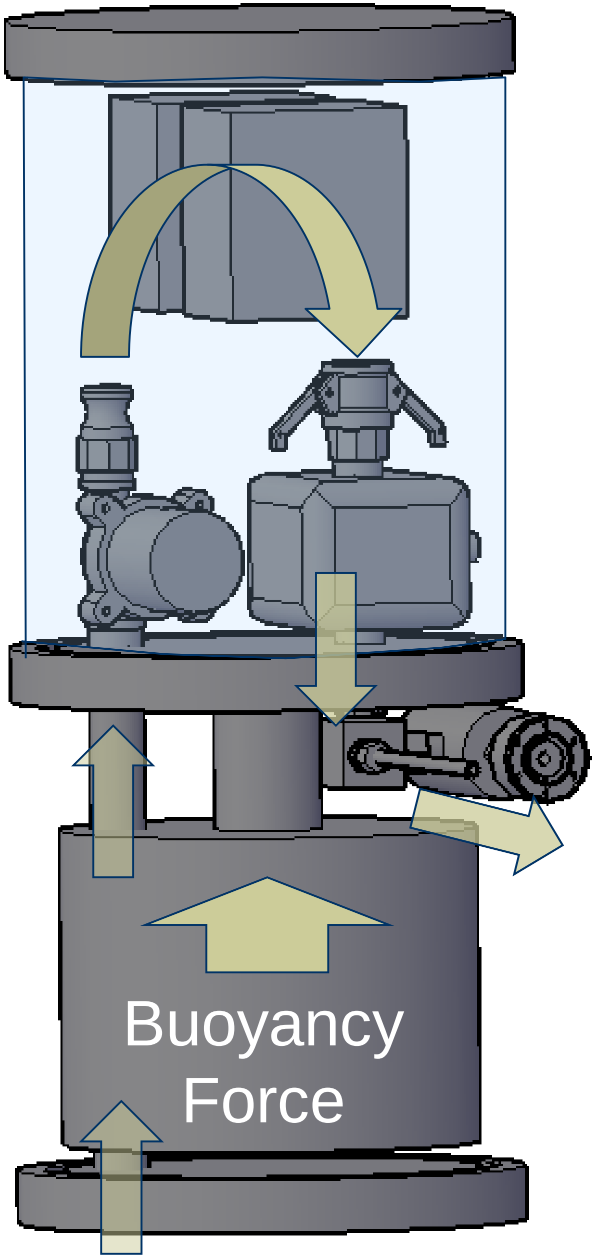


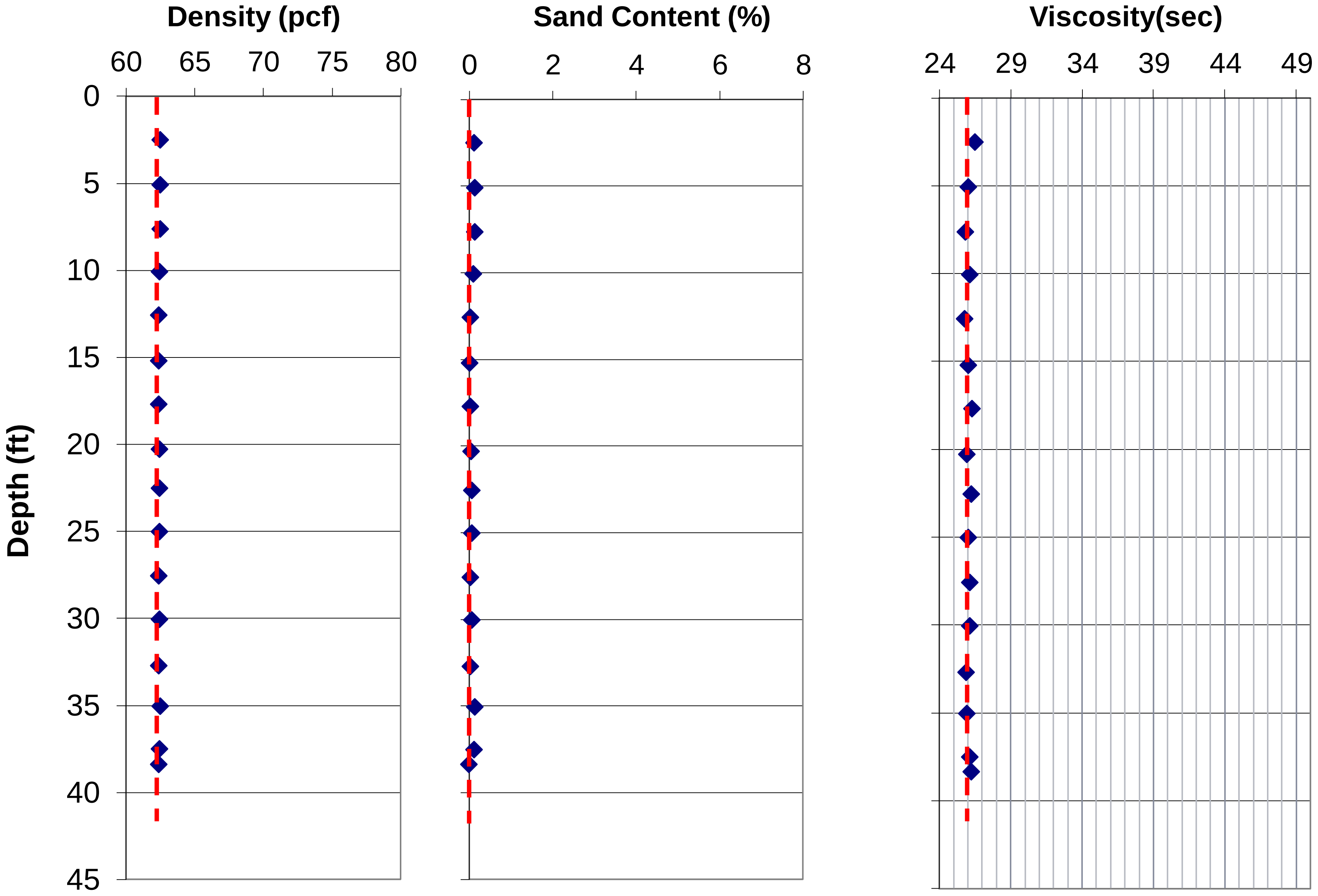
Second Generation

- Smaller unit
- Displaced volume / load cell
- Same pump, flow and nozzle pressure



Slurry in

Redesigned DHU (in water)



Conclusions / Lessons Learned

- Viscosity measurement system very stable.
- Density from differential hydrostatic pressure not a trivial pursuit.
  - Any bubbles will delay and skew pressure readings
  - Different length capillary tubes will cause temperature related drift in readings.
  - Transmitter to sensor elevations must be same on both sides of sensor.
- Displaced volume system shows promise
- Gravimetric suspended solids may be better measure of “sand content”
  - Poorly graded vs well graded suspended can have significant difference on actual “sand content”
  - Silt content, presently unmeasured, is detected with new system.
- Experimental prototypes were fast and easy to use.

Questions?