The Permian Basin Prototype Super Basin
Permeability Measurement & Modeling
for Source Rock Mudstones

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Introduction

• Conventional permeability measurements on whole core samples have evolved to include accurate measurements on lower permeability, nanodarcy samples. In conventional quality reservoirs, measurement techniques transitioned from steady-state to unsteady state. However, in unconventional reservoirs the majority of permeability measurements are conducted on disaggregated samples using unsteady-state techniques, closely following SPE 26633 Luffel et. al., 1993. These methods have now evolved to include measurements on full plug samples at an appropriate reservoir net confining stress, something that was previously not possible.

• Evaluation of mudstone reservoirs requires a new set of analytical methods and core to log models. Early permeability modeling in source rock mudstones used GRI (crushed rock) data to model Km(efl) by combining core porosity/permeability relationships and the porosity log model. These early models were appropriate for a single formation or producing interval. Later models handled multiple zones by using Vclay cutoffs. These models became increasingly granular and were able to model both effective and absolute permeability. However, they were most effective in the mudstones, but less resilient in carbonates. Current models employ 3D surfaces to model both mudstones and non-mudstones with equal precision.

• Current petrophysical modeling efforts are focused on (1) regional petrophysical models where core data is absent, (2) pressure modeling in complex, compartmentalized reservoirs found in the Delaware Basin, and (3) predicting mobile water.
Permeability – Summary

• A primary objective of Core Analysis is to characterize the end point, or ‘absolute’, permeability.

• Additional measurements are required to study how permeability may vary at reservoir conditions.

• A primary objective of core-log integration is to develop a model to predict permeability from log responses.
Factors Affecting Permeability

- Inertial or Rate Effects
- Klinkenberg Slippage
- Net Confining Stress (NCS)
- Flowing Phase
- Qv & Salinity
- Secondary Phase Saturation & Direction of Saturation Change
Example Core Sample Sizes

<table>
<thead>
<tr>
<th>Core Sample</th>
<th>Diameter, in</th>
<th>Displayed Length, in</th>
<th>Common Lengths, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Diameter*</td>
<td>4</td>
<td>6</td>
<td>4 to 12</td>
</tr>
<tr>
<td>1.5&quot; od Plug</td>
<td>1.5</td>
<td>2.75</td>
<td>1.5 to 3</td>
</tr>
<tr>
<td>1&quot; od Plug</td>
<td>1</td>
<td>1.5</td>
<td>1 to 2.5</td>
</tr>
</tbody>
</table>

* diameter dependent on coring hardware
CMS-300™: An Automated Klinkenberg Permeameter - Porosimeter
Pressure Transient (Falloff) Data for Permeability Parameters (range 30,000 md to 0.001 md)

\[ \Delta P = \sqrt{P_1 - P_2} \]

Instantaneous Flow rate determined from slope at \( \Delta P \)
## Comparison of Kair to $K_\infty$ Typical Values
(Core Lab. training manual up to 2013)

<table>
<thead>
<tr>
<th>Air Permeability, md</th>
<th>Klinkenberg Permeability, md</th>
<th>Ratio of $k_\infty/ka$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18</td>
<td>0.12</td>
<td>0.66</td>
</tr>
<tr>
<td>1</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>10</td>
<td>7.8</td>
<td>0.78</td>
</tr>
<tr>
<td>100</td>
<td>88</td>
<td>0.88</td>
</tr>
<tr>
<td>1,000</td>
<td>950</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Pulse Decay Permeability Data

METHOD ADVANTAGES

- Rapid, accurate
- Practical kg range: 0.1 to 0.00001 md
- Slip minimized at 1000+ psi $P_{\text{mean}}$
- Very low $\Delta P$:
  - Minimized inertial effects
  - No alteration of $Sw$
- Very low net stress gradient
- Ideal for effective kg@$Sw$

![Graph showing pulse decay permeability data with method advantages listed.](image)
Crushed Sample

- 20-35 U.S. Mesh
  - Coarse sand size
  - 0.0335" to 0.0197"
  - 0.85 to 0.5 mm
- 50 grams
  - Matrix permeability (km)
- 100 grams
  - Total porosity
  - Grain density
  - Saturations
Measured Rock Properties
Reservoir Core Analysis: Hybrid Reservoirs

- Petrographic analysis
- XRD - Bulk and Clay Analysis
- AIM-SEM
- TOC
- Absolute Permeability
- Effective Hydrocarbon Porosity
GRI Process Details
Matrix Permeability, km (SPE 26663)

- Equipment
  - Boyle’s Law Matrix Cup device

- Experiment
  - 30 cm$^3$ helium at 200 psig expanded to sample chamber
  - Pressure-time data recorded for up to 2000 seconds

- History match yields effective permeability
  - Input
    - Weight & bulk density
    - Gas-filled porosity
    - Pressure-time data

SPE 26633, Luffel et al, 1993
Matrix Permeability, km
Pressure vs Time

![Graph showing normalized pressure over time for different permeabilities.

- 1.03 x 10^-8 md
- 5.96 x 10^-7 md
- 5.12 x 10^-6 md

Normalized Pressure

Time, seconds

0 500 1000 1500 2000 2500

Normalized Pressure vs Time for different permeabilities.

Permeability values are
- 1.03 x 10^-8 md
- 5.96 x 10^-7 md
- 5.12 x 10^-6 md

The graph illustrates how the normalized pressure changes with time for each permeability value.
## Comparison of Kair to $K_\infty$ Typical Values (2016)

<table>
<thead>
<tr>
<th>Air Permeability, md</th>
<th>Klinkenberg Permeability, md</th>
<th>Ratio of $k_\infty/ka$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.000007</td>
<td>0.07</td>
</tr>
<tr>
<td>0.001</td>
<td>0.00013</td>
<td>0.13</td>
</tr>
<tr>
<td>0.01</td>
<td>0.0024</td>
<td>0.24</td>
</tr>
<tr>
<td>0.1</td>
<td>0.05</td>
<td>0.50</td>
</tr>
<tr>
<td>1</td>
<td>0.68</td>
<td>0.68</td>
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<td>88</td>
<td>0.88</td>
</tr>
<tr>
<td>1,000</td>
<td>950</td>
<td>0.95</td>
</tr>
</tbody>
</table>
(Upper Eagle Ford Example)

Sample:  4HB
km:  2.8 e^-06
Phit:  11.23
Sw:  36.2
Calcite:  40% vol
Clay:  32% vol
kerogen:  8.7% vol

0.000000001
0.00000001
0.0000001
0.000001
0.0001
0.01
0.1

0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
NCS, psi

GRI kg at 0 NCS
SS kg measured; plug A
SS kg slip-corrected
3 Methods Agree
USS kg Pulse Decay; plug B

Sample:  4HB
km:  2.8 e-06
Phit:  11.23
Sw:  36.2
Calcite:  40% vol
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Effect of Stress on Permeability
Steady-State Nano-Permeameter

- Upstream Pressure \( (P_1) \) \( \sim \) 32 psig
- Downstream Pressure \( (P_2) \) \( \sim \) 0 psig
- Gas Used: Nitrogen
- Net Confining Stress (NCS) to 10,000 psi
- Typically 3 measurements per NCS
- Effective or Absolute Permeability
- Kinf from multi-point \( kg vs 1/Pm \)

\[
K_g = \frac{2000 \ P_a \ \mu \ Q \ L}{(P_1^2 - P_2^2) \ A}
\]

- \( K_g \) = Permeability, millidarcies
- \( Q_a \) = Flow rate, cm3/sec, at Pa
- \( \mu \) = Viscosity of air, cp
- \( L \) = Length of sample, cm
- \( A \) = Cross sectional area of sample, cm²
- \( P_1 \) = Upstream pressure, atm
- \( P_2 \) = Downstream pressure, atm
- \( P_a \) = Atmospheric pressure, atm
Permeability Comparisons

Conventional Reservoir Core Analysis Terminology

Tight Gas & Gas Shale Reservoir Terminology

UNITS:
- attodarcy ($10^{-18}$)
- femtodarcy ($10^{-15}$)
- picodarcy ($10^{-12}$)
- nanodarcy ($10^{-9}$)
- microdarcy ($10^{-6}$)
- millidarcy
- Darcy

Steady State (specialized instruments required @ both extremes of the measurement range)

Methods:
- GRI (pressure decay)
- PDP (pulse decay)
- CMS (pressure falloff)
- Probe (pressure falloff)
Core-Log Petrophysical Modeling

• Goal is to calibrate downhole logs with measured core data.
• Develop a model(s) for key reservoir properties (e.g. porosity, water saturation) that can be applied to uncored intervals or non-cored wells.
• Source rock mudstone reservoirs pose a challenge to the industry since they cannot be adequately modeled with traditional techniques developed for conventional reservoirs.
• Conventional models are developed for milidarcy to darcy rock and cannot adequately model nanodarcy permeabilities.
• Hence empirical, mudstone-specific models have been developed.
Measured Rock Properties

BASIC ROCK PROPERTIES
(Effective & Absolute Perm vs Total Porosity)

Matrix permeability (Km) suppressed by oil saturation

$y = 2E-07x^{3.836}$

$y = 1E-09x^{4.0887}$

Permeability, md

Total (Interconnected) Porosity, percent

Plug: Absolute, Reservoir Stress
GRI: Crushed (20/35 mesh)

All JIP Wells, Km, GRI
All JIP Wells, Km(abs), GRI
All JIP Wells, Ka(abs), Plug
Early Models – Single Producing Interval

Core Porosity Modeled to RHOB Curve

Km Modeled from Core Porosity Model
Later Models – Multiple Intervals

Perm. Models from Multiple Intervals

Models Typically Separated by Vclay

Avalon Shale
Later Models – $K_{m_{abs}}$ & $K_{m_{eff}}$

MULTIPLE MODELS
Separated by $V_{clay}$ – 2D

$K_{m_{abs}}$ & $K_{m_{eff}}$
New 3D Models Handle Both Mudstone & Non-Mudstones
Regional Petrophysical Modeling.

Use an aggregate of core-calibrated log models to model a specific formation (e.g. Wolfcamp or Bone Spring).

Useful where rock data is sparse or absent – almost all wells are logged, few are cored.

Only needs logs, so a comprehensive petrophysical interpretation can be made prior to completion to define:

- Best porosity/TOC intervals
- Lowest Sw
- Potential frac. barriers
What Does the Future Hold?

- Pressure modeling in structurally compartmentalized basins – Delaware Basin.
• Mobile water prediction to avoid zones with higher water cut.