STRATUM
RESERVOIR

RELATIVE PERMEABILITY
BEST PRACTICE FOR STEADY STATE METHOD

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SOCIETY OF PETROPHYSICISTS AND WELL LOG ANALYSTS
Qatar Chapter

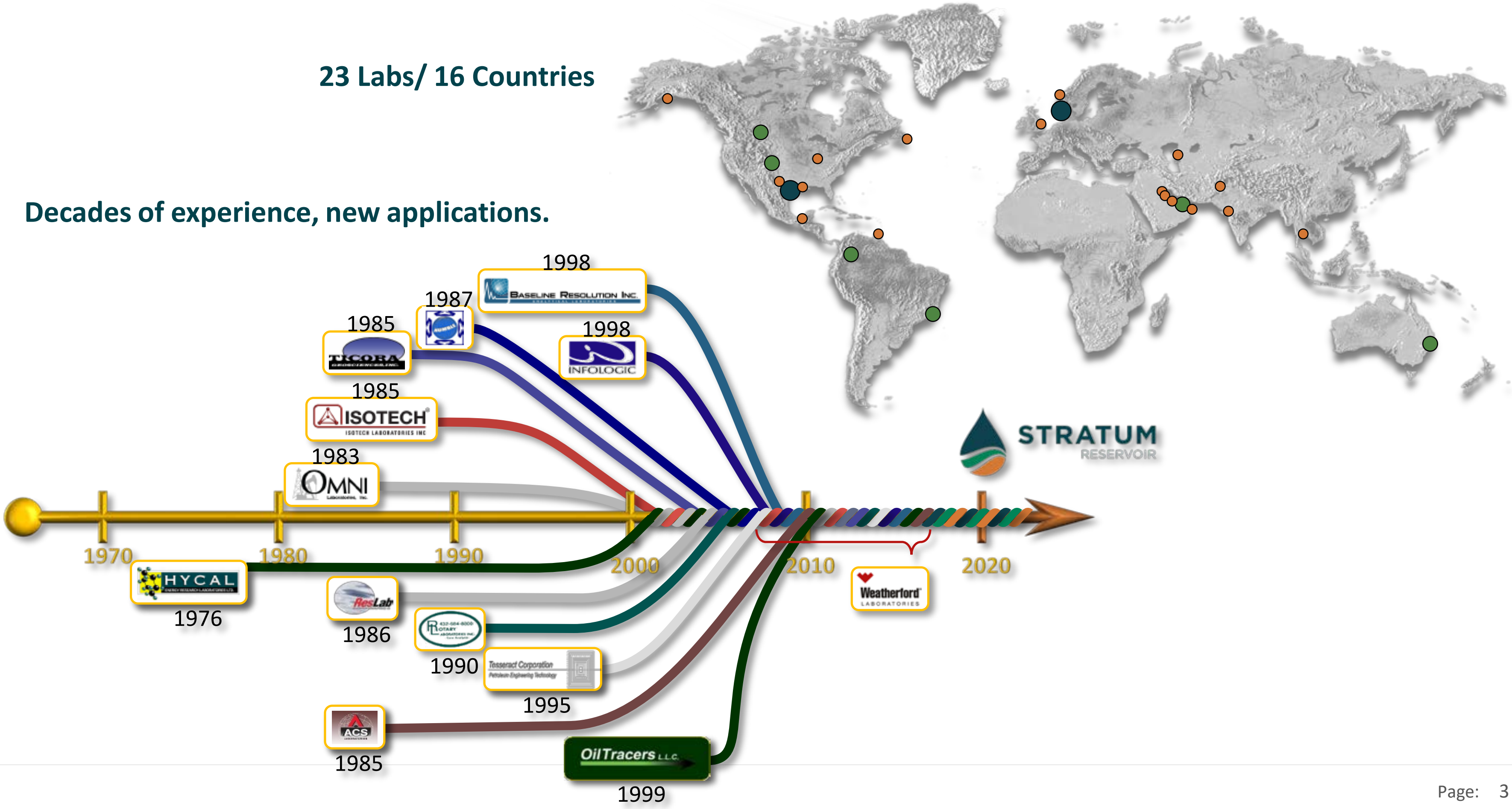
OUTLINE

1. Stratum Reservoir introduction
2. Short introduction to Relative Permeability
3. Relative Permeability by Steady State method

STRATUM RESERVOIR - History and Expertise

23 Labs/ 16 Countries

Decades of experience, new applications.



Key Aspects

Global Experience and Best Practices

Stratum Reservoir has gained extensive experience in both Conventional and Unconventional reservoirs worldwide.

Subject Matter Experts (SME’s)

SME’s are made freely available, covering each discipline. Our specialists are able to assist with each stage of the program –from inception and design to integration and interpretation of all datasets.

Program Design and Objectives

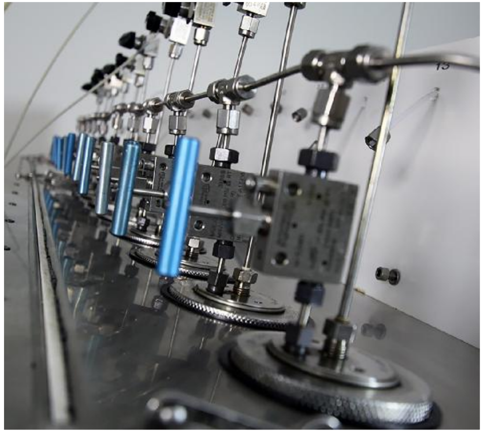
Stratum Reservoir maintains a dynamic technical and managerial approach to ensure any program remains optimized against project objectives and deliverables.

Detailed Laboratory Services Overview

SERVICES & CAPABILITIES

- Global Wellsite Core Preservation & Stabilization
- DECT Scanning (Mineral Modeling)
- Routine Core Analysis
- **Special Core Analysis**
- Rock Mechanics
- Unconventional Core Analysis
- Petrographic Analysis
- Formation Damage Evaluation
- Geochemistry / Production Allocation
- Express Lab cuttings analysis
- PVT / Fluid Phase Behavior
- PVT for Unconventional
- Oilfield Water Analysis
- **IOR/ EOR**
- Pressurized Rotary Sidewall Core Analysis
- H_2S Identification and Mitigation
- Core to Log Integration
- Basin Data Studies
- Core Storage Expertise

SCAL - Petrophysics



- Rock Characterization Studies (XRD, SEM, THS)
- Electrical properties studies at reservoir pressure and temperature (FF, Kw, m-exp.)
- Porosity and Permeability as a function of Reservoir Pressure
- Pc-RI Capillary Pressure and Resistivity Studies Drainage and Imbibition (RI, n-exp., Swi, Sor)
- Capillary Pressure by Mercury Injection Analysis (MICP)
- Semi-Dynamic Electrical Properties Analysis (CI)
- Clay Conductivity Studies (Co/Cw, CEC)
- Nuclear Magnetic Resonance
- Capillary Threshold Pressure Analysis and Seal Capacity Studies (PcTh)
- Water Sensitivity and Critical Velocity Tests (Fines Migration)

SCAL – Dynamics and Advanced Testing

SCAL Semi Reservoir Conditions:

- Capillary pressure by centrifugation
- Relative Permeability by flooding with In Situ Saturation Monitoring (ISSM).
- Relative Permeability by centrifugation (P&T)
- IOR/EOR (Low salinity, ASP,....)
- Trapped Gas Saturation with ISSM
- NMR measurements

SCAL HPHT Reservoir Conditions with ISSM:

- USS and SS Relative Permeability with Live Fluids
- Water Alternating Gas Studies («WAG»)
- Gas Condensate Blockage Studies
- Critical Gas Saturation
- IOR/EOR (HC, CO_2, N_2, ASP, Low sal., ...)
- Miscible floods – Slim tube Experiments
- Miscible floods – Core Sample
- Interfacial tension (IFT)

Short introduction to Relative Permeability

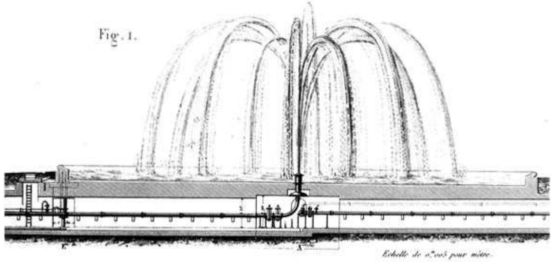
Introduction to Relative Permeability

Relative Permeability:

- Concept used to describe the movement of more than one fluid in a porous medium
- Basic description of how fluids move through the reservoir
- Understanding reservoir economics
  - Hydrocarbon recovery rate
  - Total recoverable reserves
  - Water cut

Permeability Description

General expression for fluid flow developed by Henry Darcy in 1856



$$q = \frac{KA\Delta P}{\mu L}$$

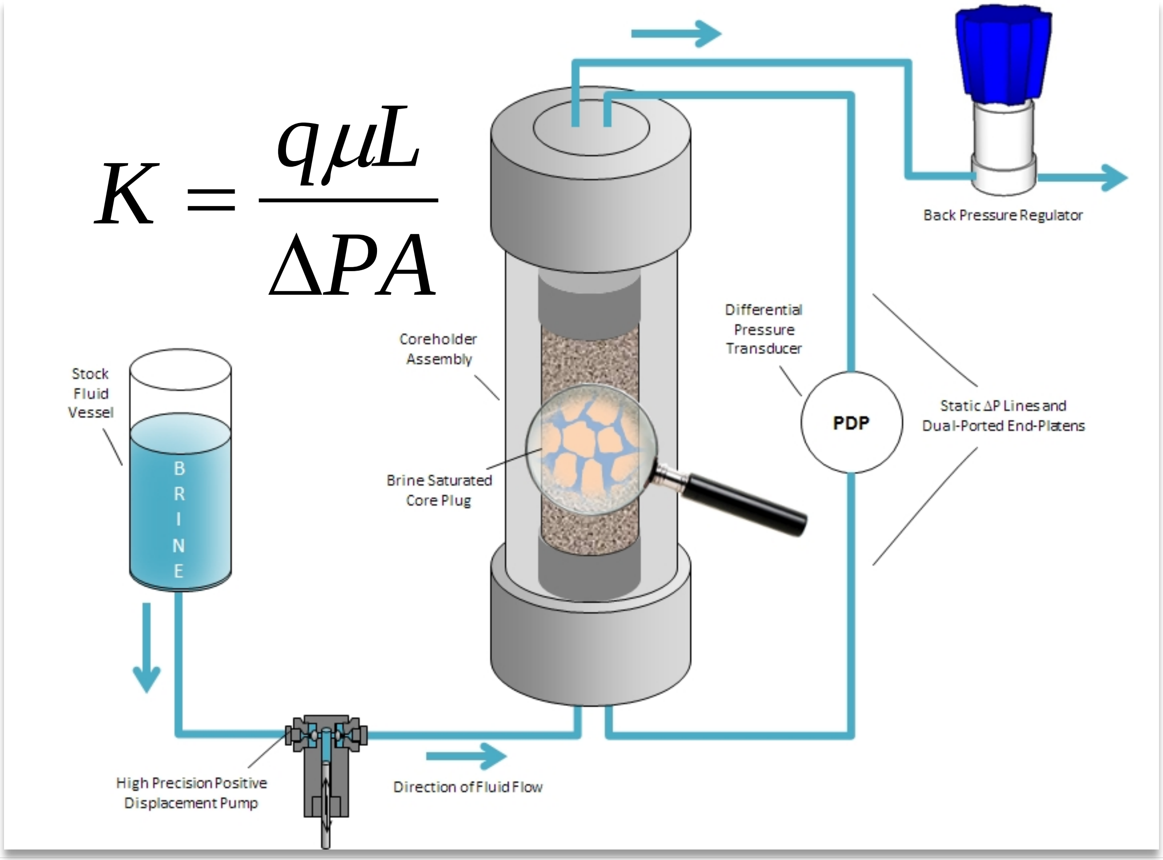
Where:

q = the rate of fluid flow (m^3/s)
A = cross-sectional area (m^2)
μ = viscosity of the flowing fluid (cP)
ΔP = pressure drop across the sample (Pa)
L = core length (m)
K = permeability (m^2)

K is a constant when:

- the flow is laminar and Newtonian
- the fluid does not interact with the rock
- the rock is completely saturated and fluid continuous

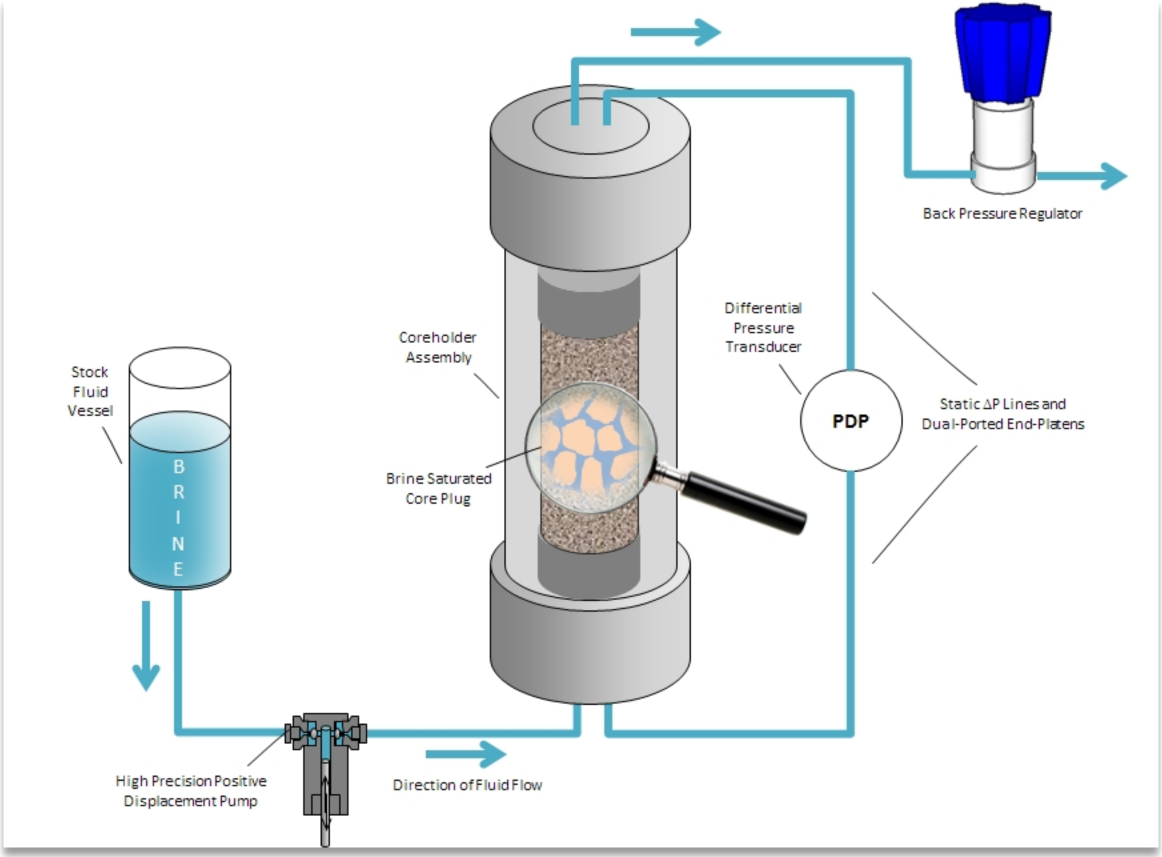
Liquid permeability



$$K = \frac{q\mu L}{\Delta P A}$$

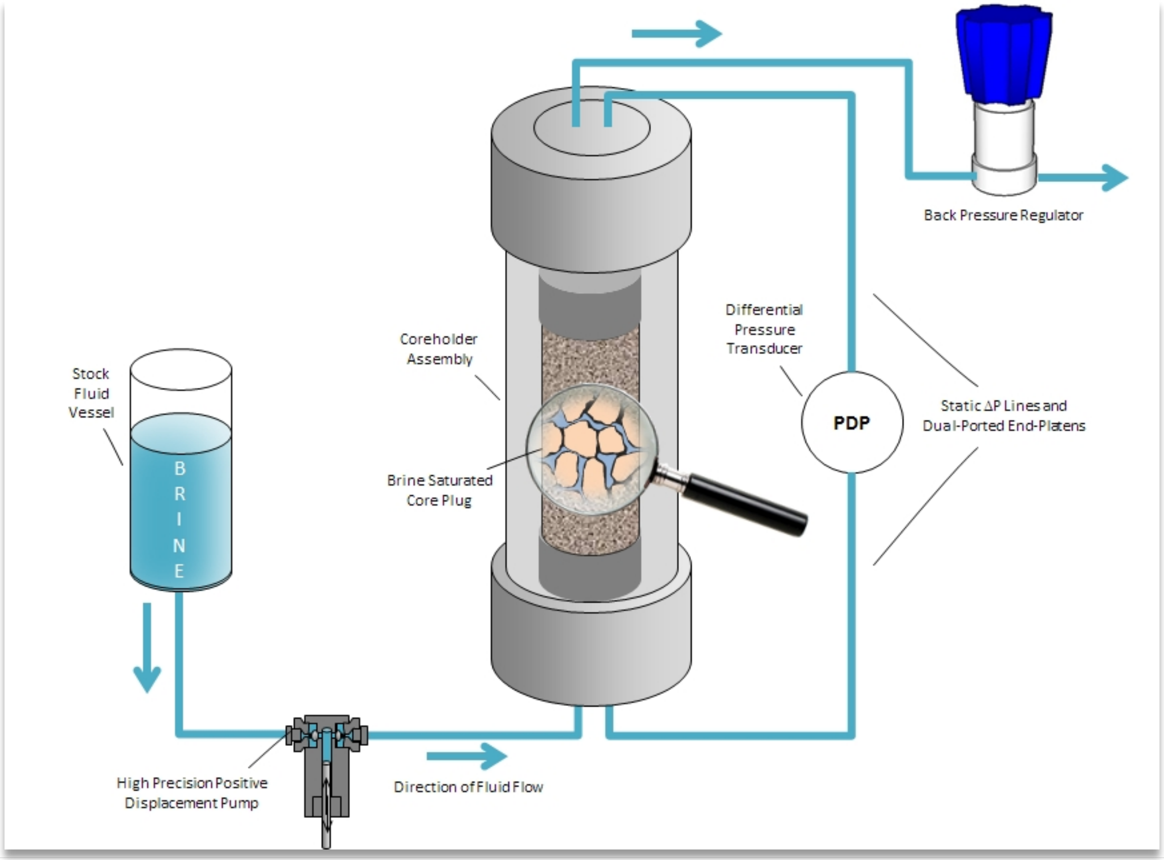
Absolute permeability…

…is the permeability determined with only one fluid present in the pore space



Effective permeability…

…is the permeability to one fluid, when there is more than one fluid present in the pore space

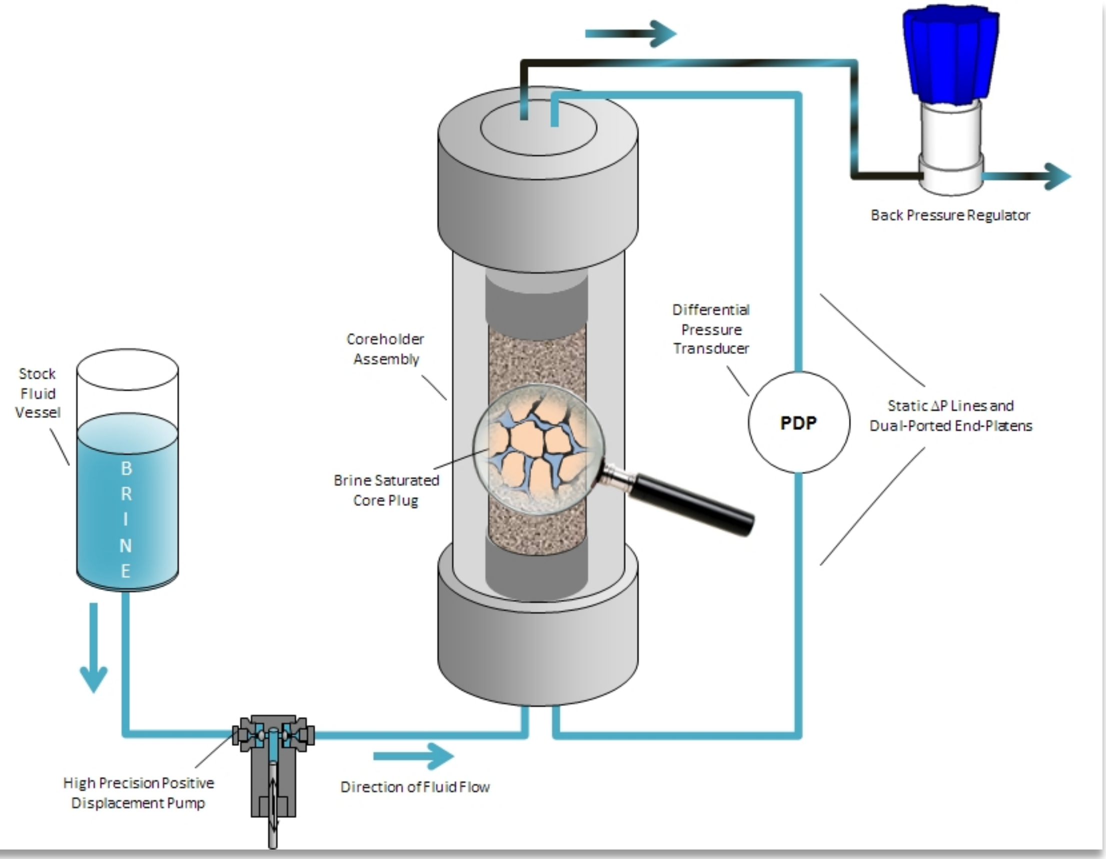


Relative permeability…

…is the effective permeability divided by a specified base permeability

$$k_r = \frac{k_e}{k_{ref}}$$

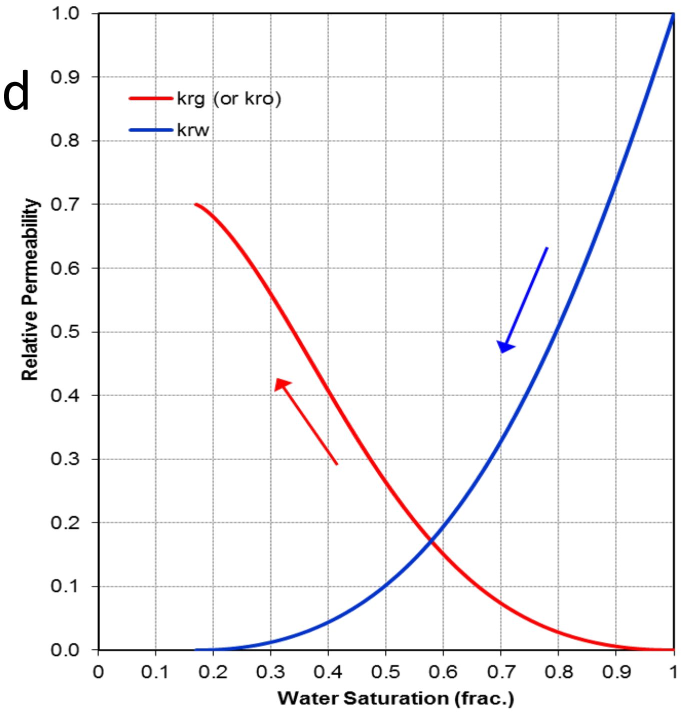
…is a measure of the ability of the porous system to conduct a fluid when more than one fluid is present

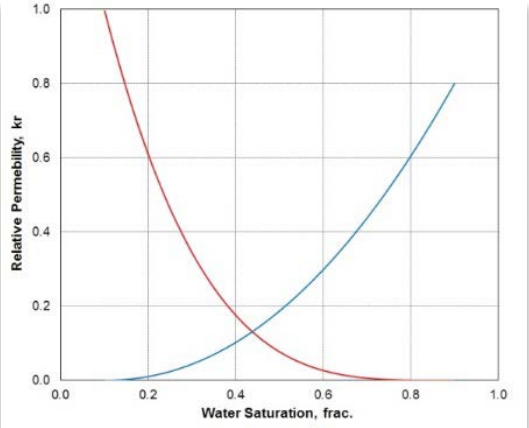


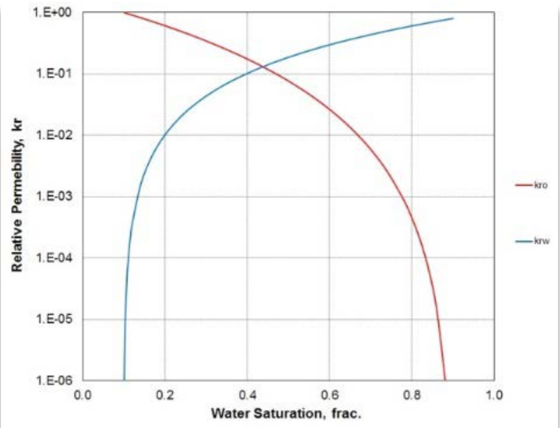
Base (Reference) Permeability

Primary drainage : k_r usually normalised to K_w

Imbibition (& secondary drainage) k_r is referenced to $k_o(S_{wi})$







Data for Reservoir Engineers - Dynamic Simulation

- Water-Oil Relative Permeability(k_{rw}-k_{ro})

  Water drive, water injection

- Gas-Oil Relative Permeability (k_{rg}-k_{ro})

  Solution gas drive

  Gas cap drive

  Gas injection

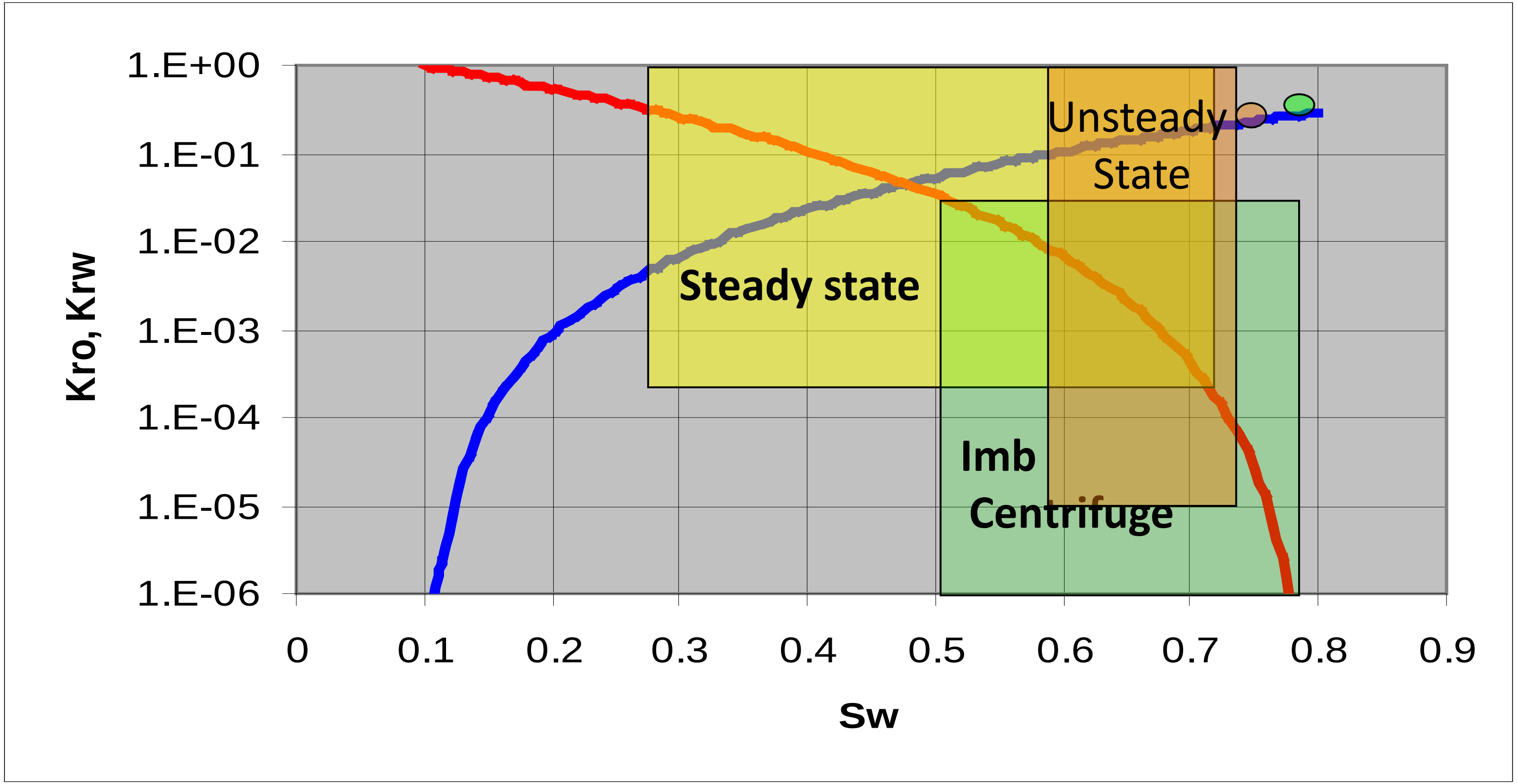
- Water - Gas Relative Permeability (k_{rw}-k_{rg})

  Aquifer influx into gas reservoir

- Gas-Water Relative Permeability (k_{rg}-k_{rw})

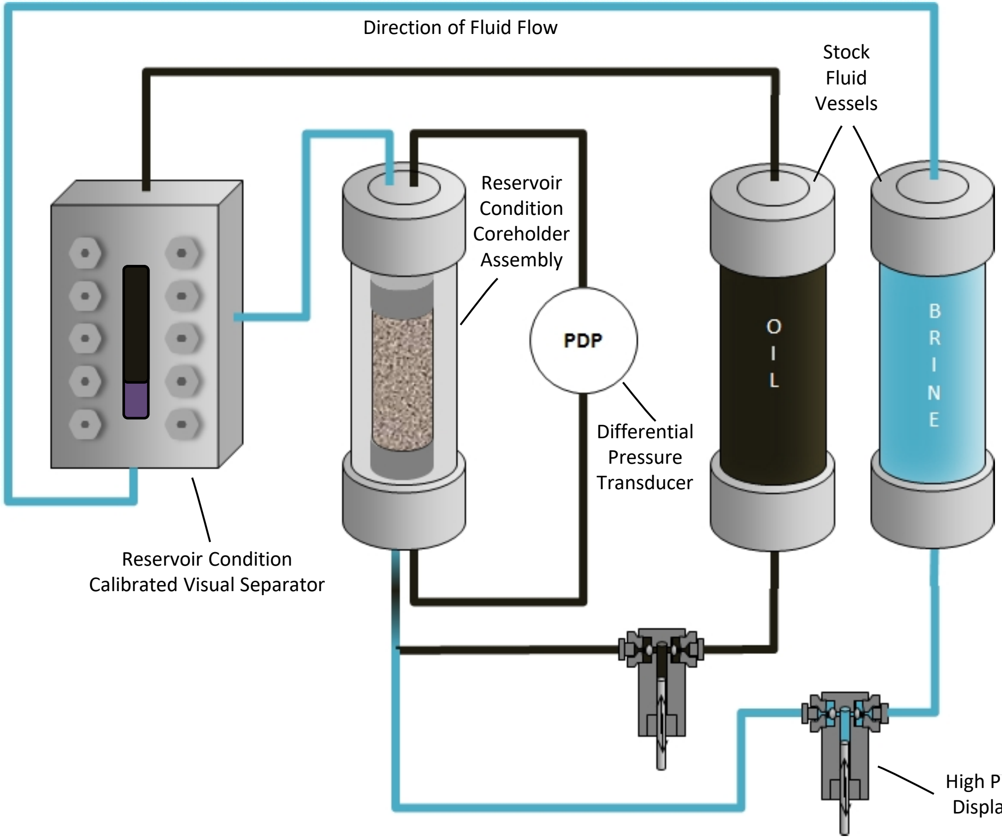
  Gas storage, CO_2 sequestration

Imbibition Relative Permeability



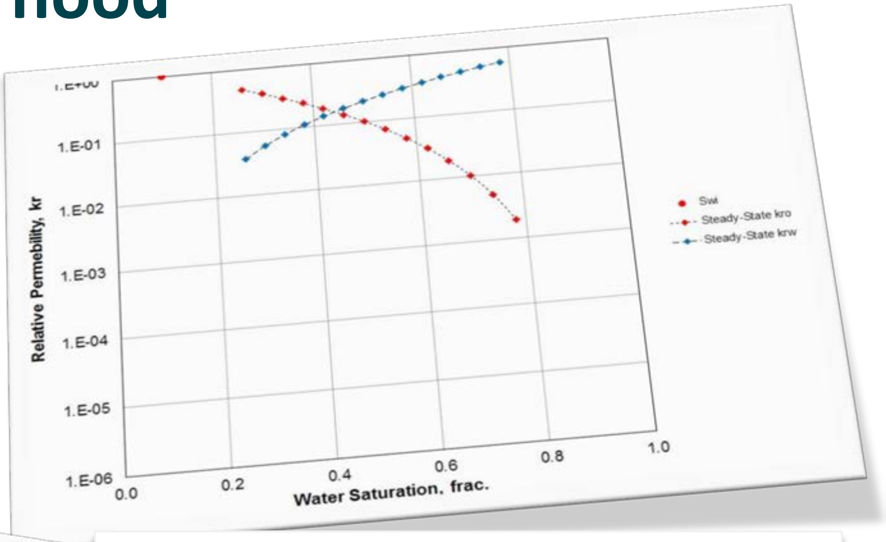
Relative Permeability by Steady State method

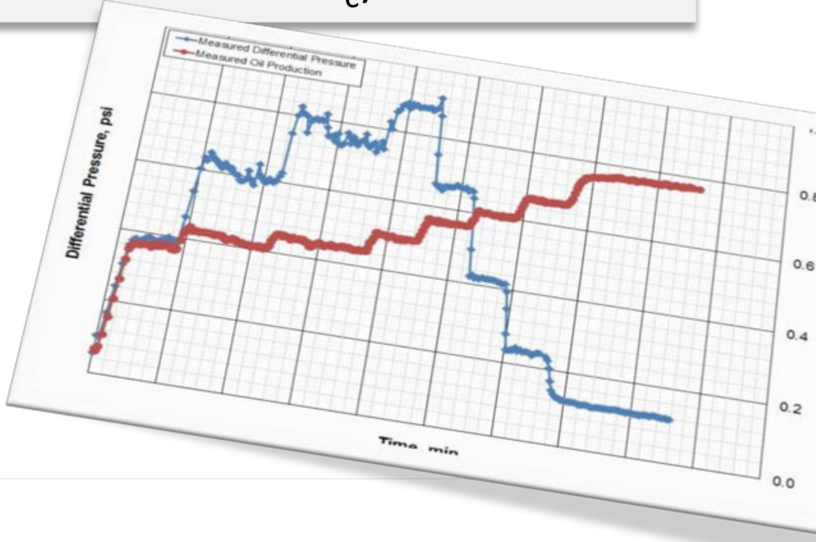
Steady State Coreflood (SS)



Steady State Imbibition Waterflood

- Continuous recirculation of injected brine & oil
- Higher flowrate possible with stable flow (minimise influence of P_c)





- Saturation from ISSM
- Calculate relative permeability directly from equilibrium ΔP and individual phase flowrates

Steady-state Overview

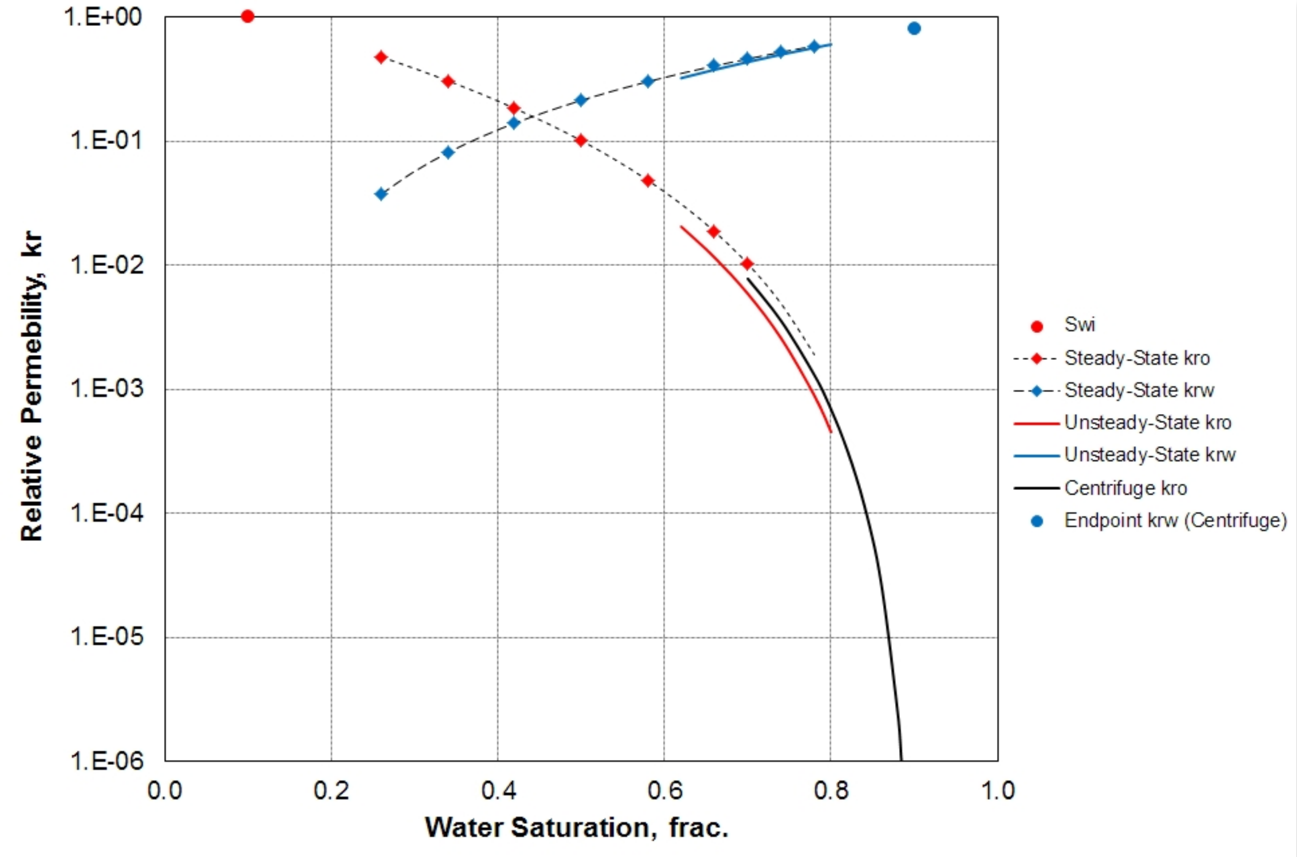
Advantages

- Data interpretation and calculation is (usually) straight forward
- Extended saturation range possible to define relative permeability curve
- Higher flow rates may be used to mitigate laboratory scale capillary pressure
- Suitable for most wettability cases & reservoir oils

Disadvantages

- Longer test required to achieve SS at each f_w (1 to 3 days per f_w)
- Uncertainty as to whether fluid displacement is truly representative of the reservoir process.
- Possible core damage due to large volume throughput (and high flow rate)
- Application of Darcy’s Law is valid only if the saturation in the core is uniform (assumes P_c=0).

Centrifuge + USS + SS



Typical outline

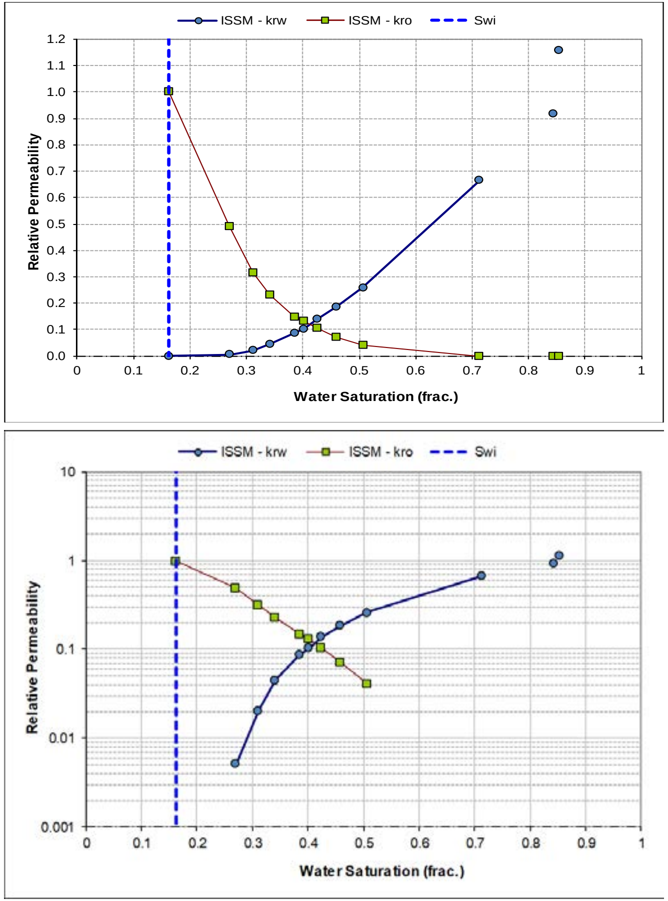
Imbibition water displacing oil Relative Permeability

- Clean and dry core, measure basic properties
- Saturate core with brine, measure K_w
- Desaturate to Swi
- Restore Wettability
- Measure endpoint (base) (multi-rate) permeability

  $k_o(S_{wi})$
- Measure Relative Permeability

  $k_w - k_o$
- Measure endpoint (multi-rate) permeability

  $k_w(S_{or})$



Controlling Factors

A number of factors influence Relative Permeability:

- Initial water saturation, S_{wi}
- Wettability
- Pore structure – homogeneity of core material
- Saturation history (& hysteresis)
- Test procedures
- Laboratory length scale (capillary pressure)
- Mobility ratio

Required Fluids

Preparation of laboratory fluids Includes:

a. Preparation of laboratory synthetic formation water (SFW) – Client to supply composition

b. Preparation of CsCl doped synthetic formation water (dSFW)

c. Preparation of CsCl doped injection water (if different from dSFW) – Client to supply composition

d. Preparation of laboratory oil (Isopar-L) for ambient temperature measurements

Preparation of live oil Includes:

a. Preparation and measurement of Stock Tank Oil (STO) composition. – Client to supply surface oil

b. Calculation & preparation of synthetic gas composition. – Client to supply PVT report

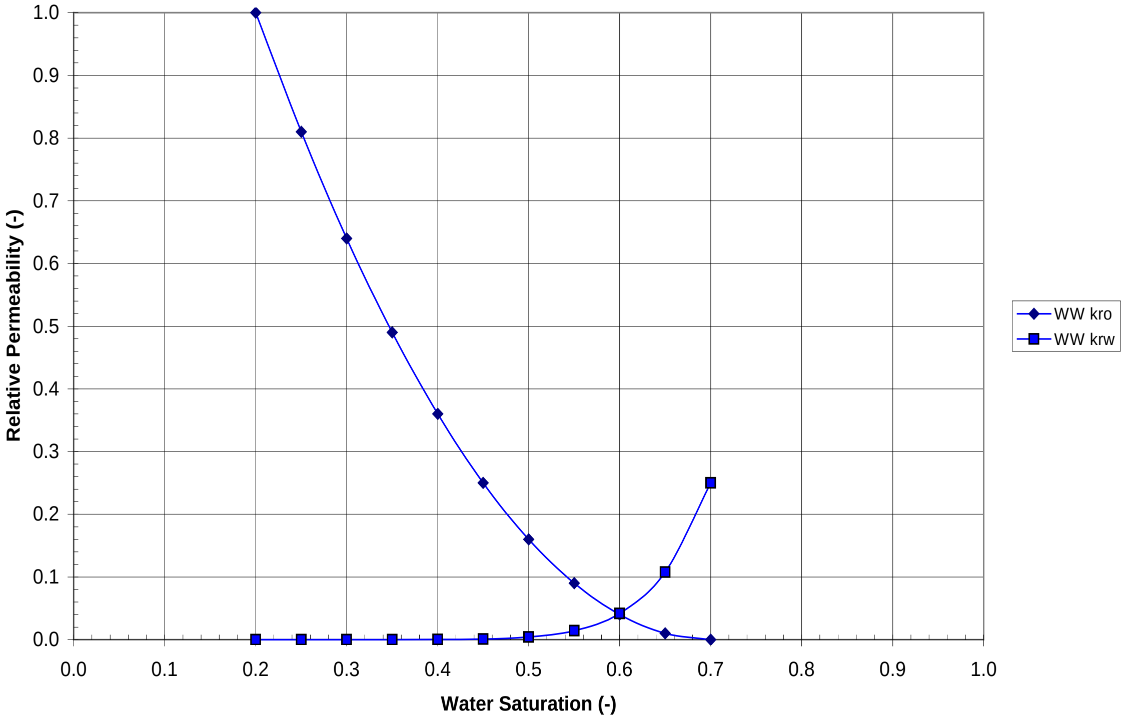
c. Measurement QC of gas composition.

d. Recombination of STO and synthetic gas to a specified B.Pt pressure.

e. Recombined live oil composition, B.Pt, GOR, Bo (measurement QC).

f. Viscosity measurement.

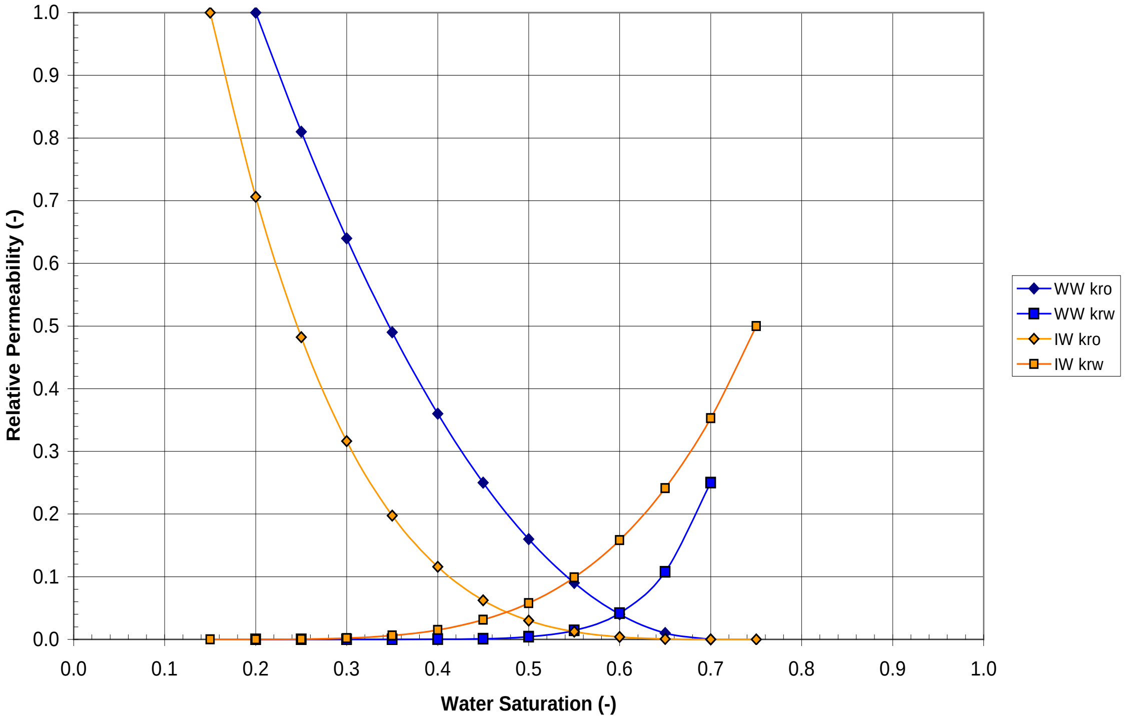
Relative Permeability Curves - Effect of Wettability



Water Wet

- No = 2 Nw = 8
- Swir = 0.20 Sro = 0.30,
- krw’ = 0.25, ultimate recovery = 0.625 OIIP

Relative Permeability Curves - Effect of Wettability



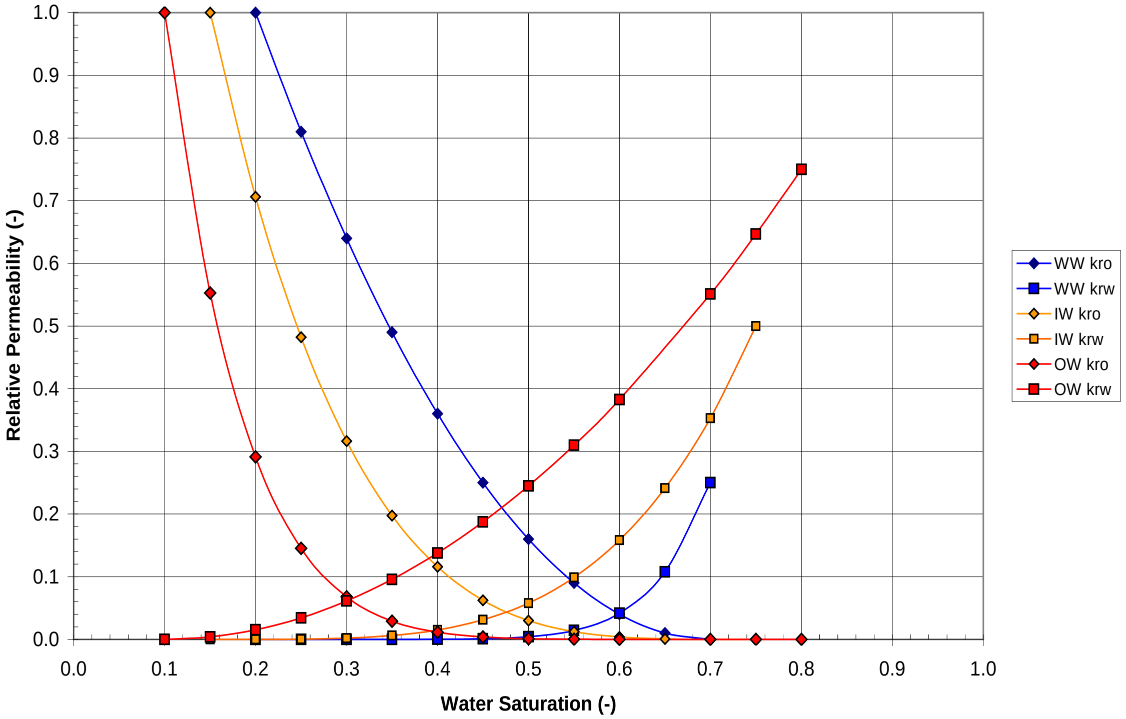
Water Wet

- No = 2 Nw = 8
- Swir = 0.20 Sro = 0.30,
- krw’ = 0.25, ultimate recovery = 0.625 OIIP

Intermediate Wet

- No = 4 Nw = 4
- Swir = 0.15 Sro = 0.25,
- krw’ = 0.5, ultimate recovery = 0.706 OIIP

Relative Permeability Curves - Effect of Wettability



Water Wet

- No = 2 Nw = 8
- Swir = 0.20 Sro = 0.30,
- krw’ = 0.25, ultimate recovery = 0.625 OIIP

Intermediate Wet

- No = 4 Nw = 4
- Swir = 0.15 Sro = 0.25,
- krw’ = 0.5, ultimate recovery = 0.706 OIIP

Oil Wet

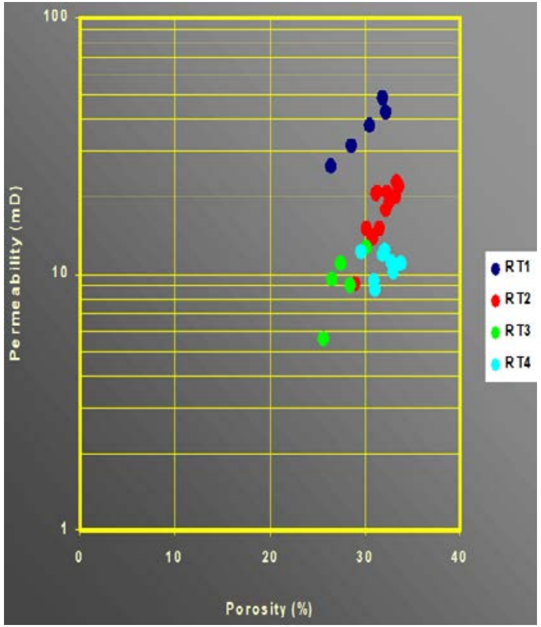
- No = 8 Nw = 2
- Swir = 0.10 Sro = 0.20,
- krw’ = 0.75, ultimate recovery = 0.778 OIIP

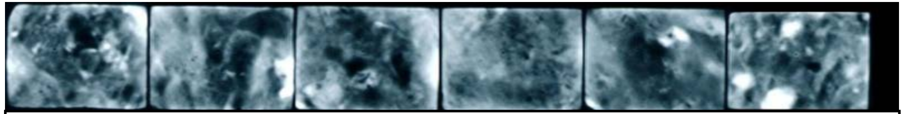
Selection of core material

Select representative homogeneous core material

Samples screening and evaluation is needed to perform a proper selection of suitable and representative samples.

- Homogeneity screening (representativity)
- Characterize rock samples and identify representative lithology/rock type
  - 1 rock type per test
- Location of samples reference to reservoir
- All available information and data should be evaluated to be able to perform a proper samples selection, such as
  - CT scan,
  - Basic properties
  - lithological description, formation/zone, hydrocarbon leg (Gas, Water, Oil)
  - MICP, XRD, etc.





Composite Core

Preparation of core material

Cleaning and drying

Preparation Methods

- Restored State Preparation
- Native State Preparation
- Cleaned State Preparation

Considerations for Preparation

- How was the core drilled? (mud type, coring operations, well-site work)
- How the core was handled and preserved

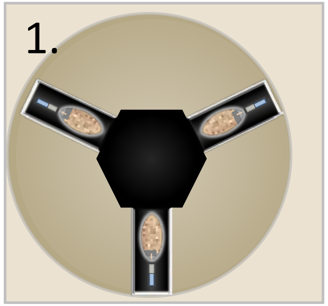
Restored state preparation

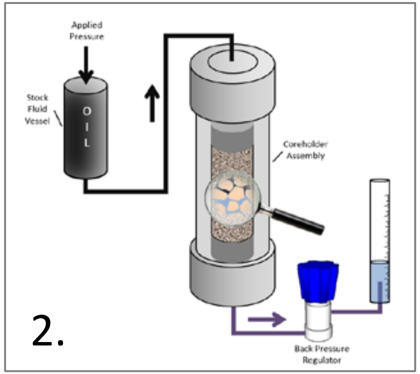
- Cleaning and drying methods adapted to clay content and minerology
- If sensitive clay materials – consider non-drying route
- Saturate with appropriate brine
- Establish representative initial water saturation
- Restore wettability with live reservoir oil

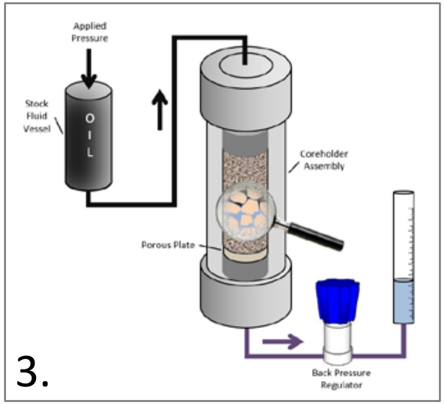
Centrifuge Drainage to Swi

Methods

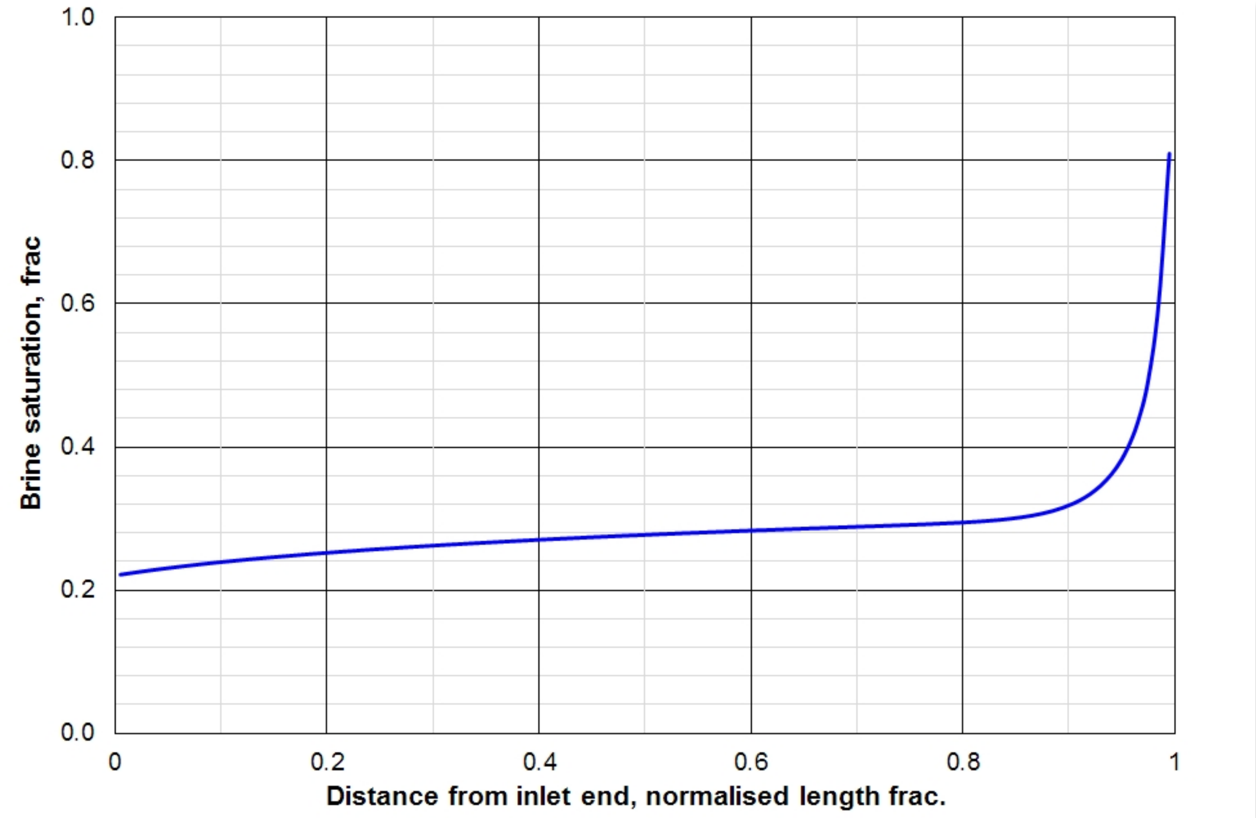
1. Drainage by Centrifuge
    i. Fast, suitable for low permeable core material
    ii. End effect on saturation distribution
2. Drainage by Viscous oil drive
    i. Fast, suitable for unconsolidated core material
    ii. End effect on saturation distribution
    iii. Can give too high Swi
3. Drainage by porous plate – preferred method
    i. Gives homogeneous water saturation
    ii. Pc, limited by porous plate, but suitable for most cases
    iii. Takes longer time – but full PcRI not required when using to prepare for relative permeability measurements



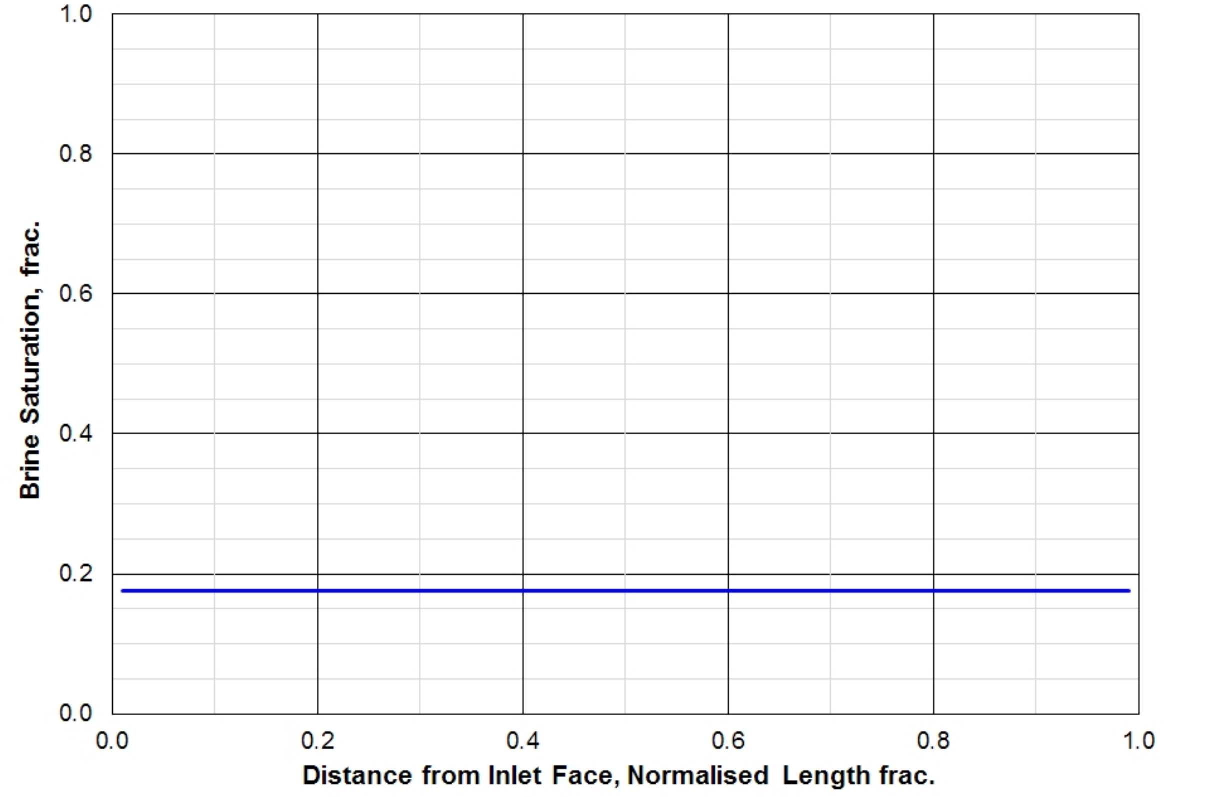




Without Porous Plate



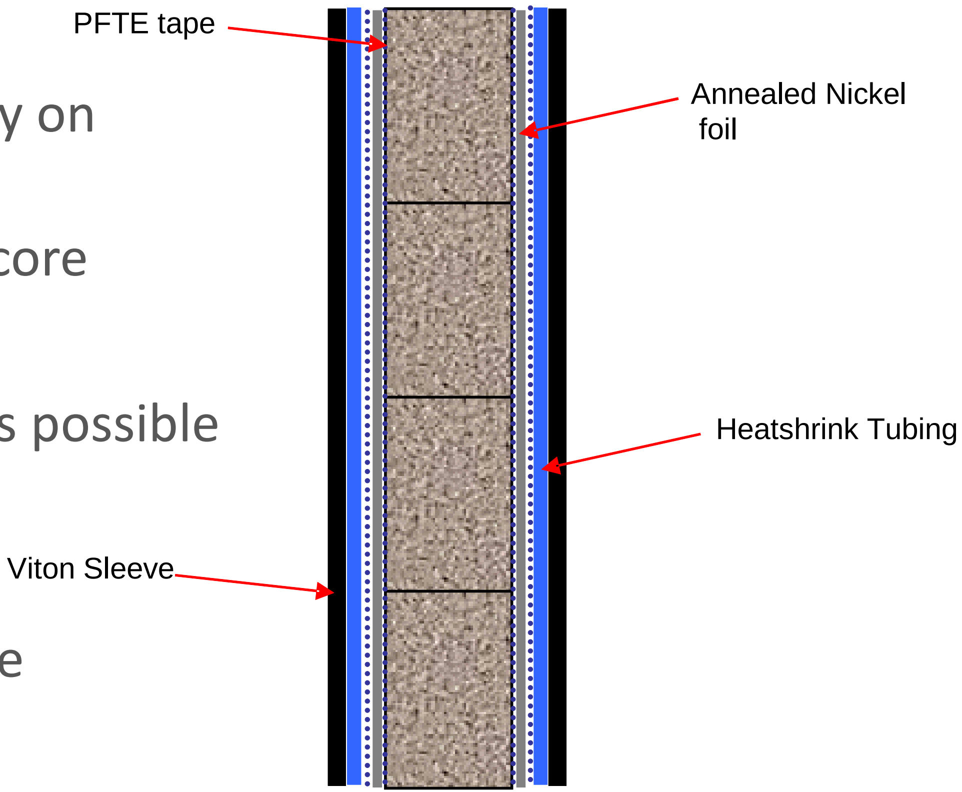
With Porous Plate



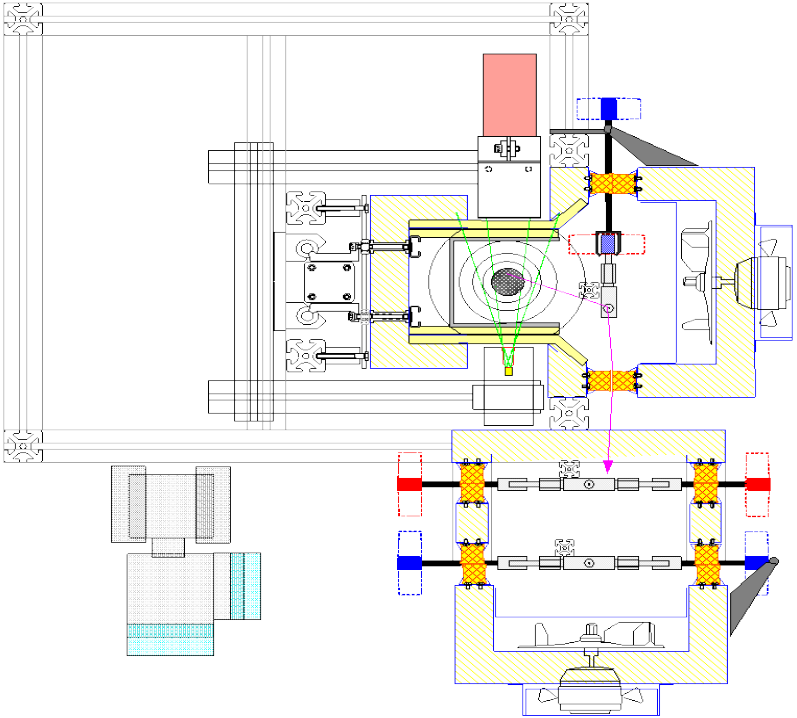
Composite core

Composite core advantages and disadvantages

- For flood type tests
- Larger pore volume, higher accuracy on volumetric measurements
- Higher differential pressure across core
- Less impact of capillary end effects.
- Plug samples should be as similar as possible
  - Porosity, permeability
  - Saturation,
  - Pore size distribution
- Risk of effect of discontinuity in core junctions



Reservoir Condition Core Flood Rig



Core Flooding

Saturation Determined by:

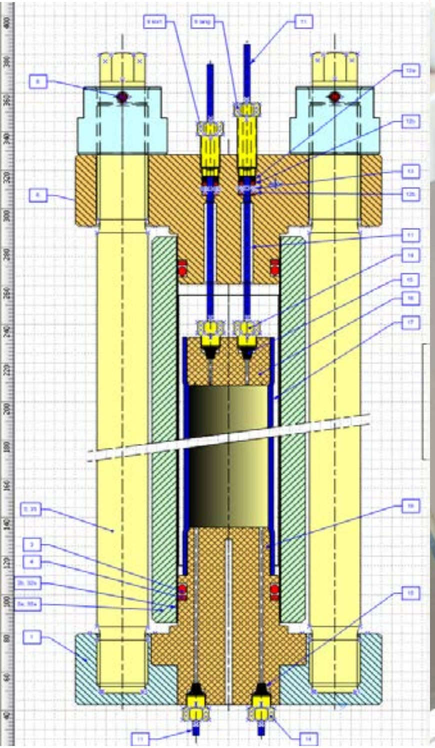
External Methods

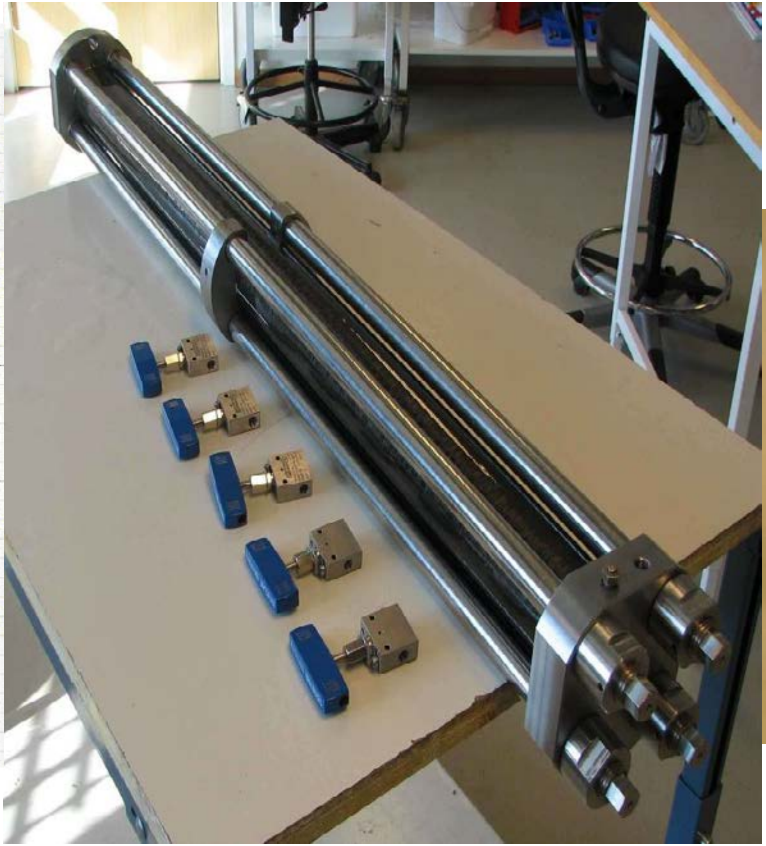
- Volumetric (Visual Cell/Separator)
- Solvent extraction and Karl Fischer titration – end point

In-situ Methods

- Gamma ray attenuation
- Tracer Techniques – end point

Stratum Reservoir Carbon Fibre Core Holders

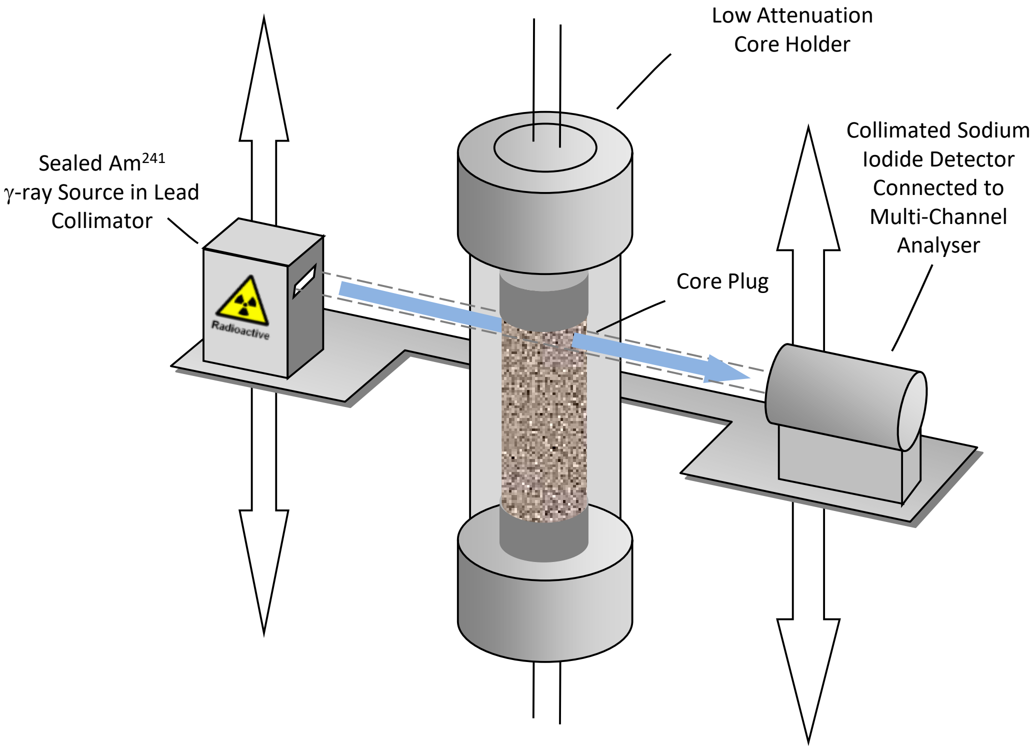




1000bar 170°C Model

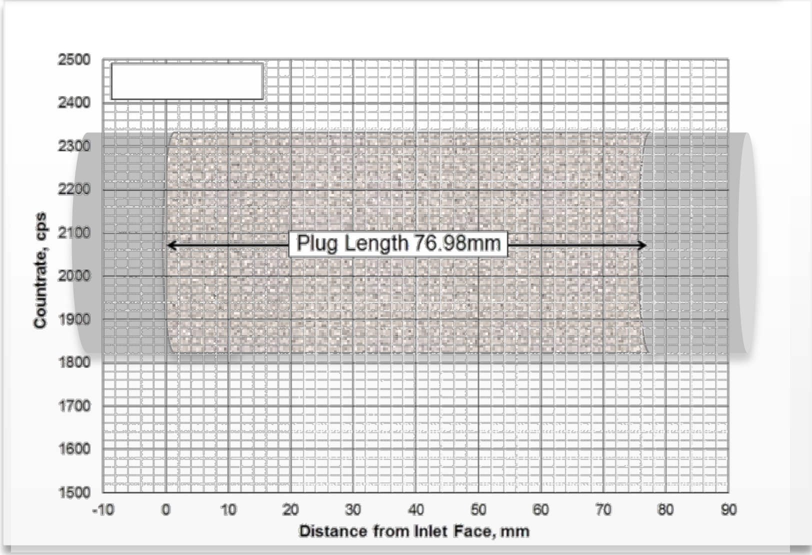
700bar 150°C Model

In-Situ Saturation Monitoring (ISSM)



$$I_{(transmitted)} = I_i \,.\, e^{-\mu x}$$

$$I_{(transmitted)} = I_i \,.\, e^{-\{\mu x(1-\varphi) + \varphi x(S_w \mu_w + S_o \mu_o)\}}$$



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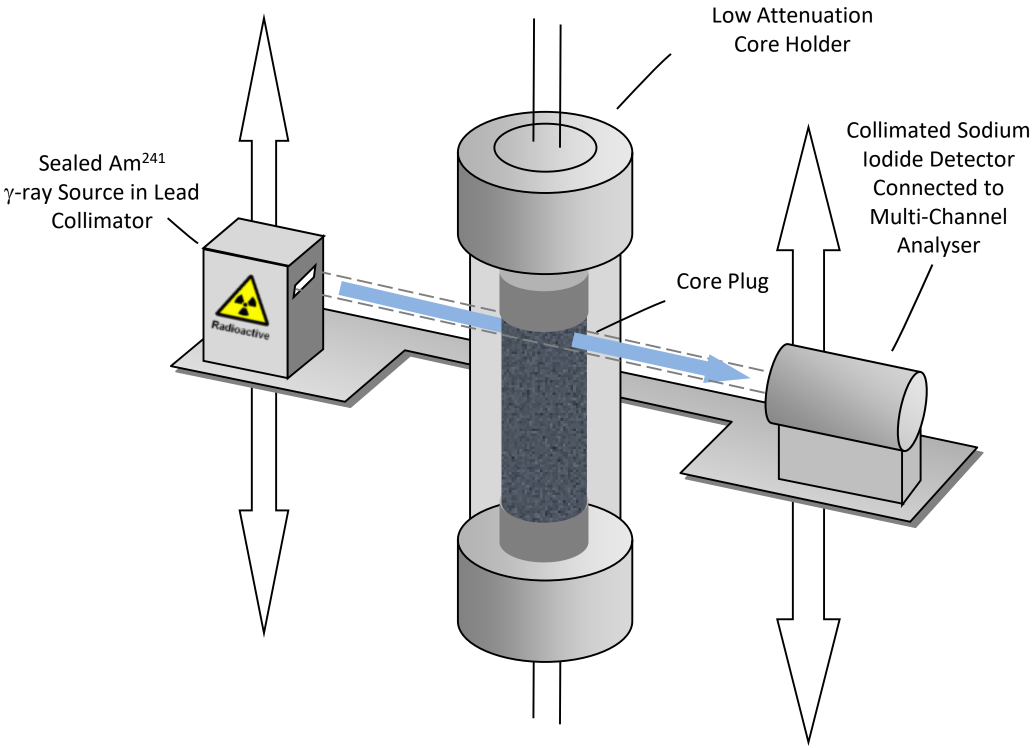


Low Attenuation Core Holder

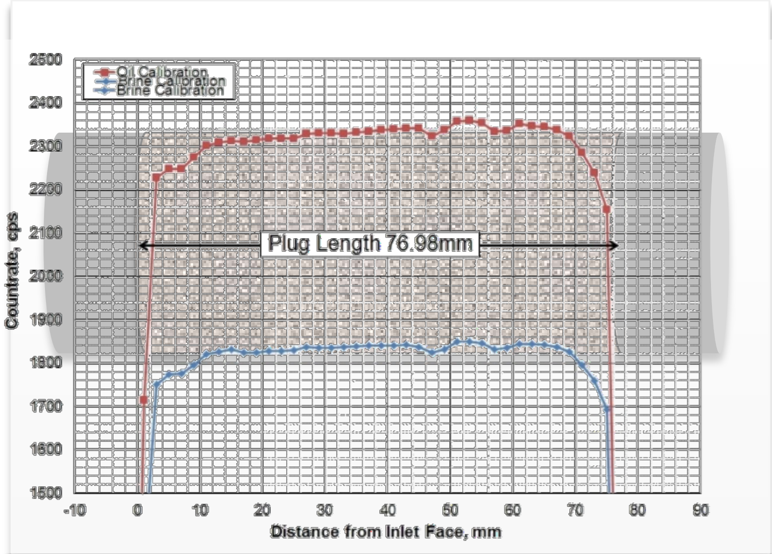
Sealed Am^{241} γ-ray Source in Lead Collimator

Collimated Sodium Iodide Detector Connected to Multi-Channel Analyser

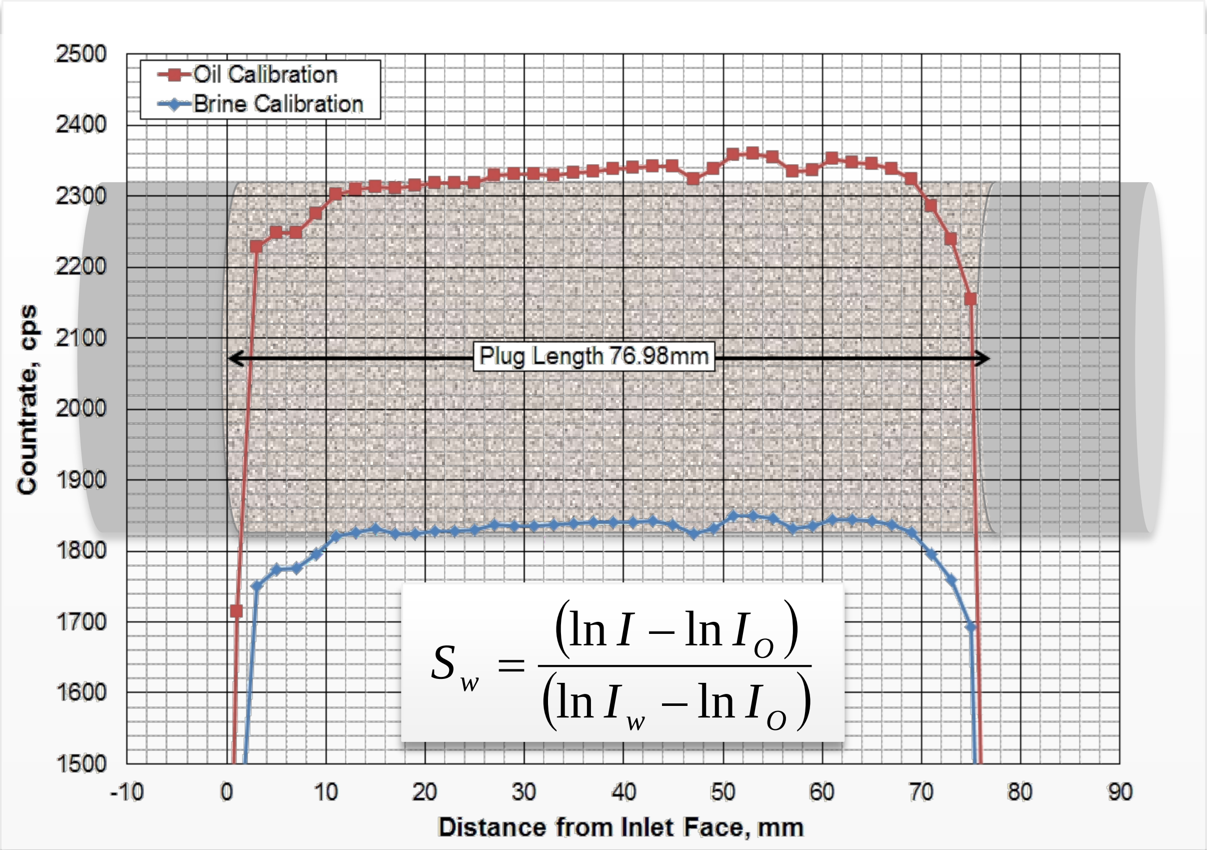
Core Plug

$$I_{(transmitted)} = I_i \, . e^{-\mu x}$$

$$I_{(transmitted)} = I_i \, . e^{-\{\mu x(1-\varphi) + \varphi x(S_w \mu_w + S_o \mu_o)\}}$$

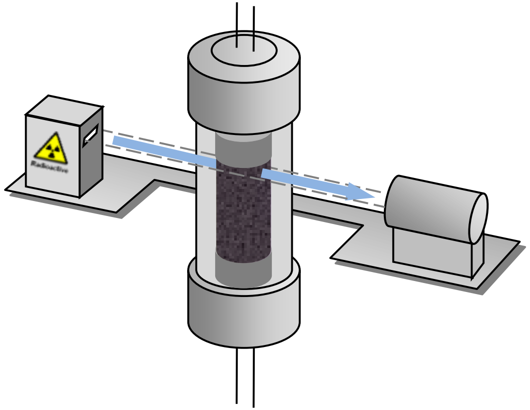


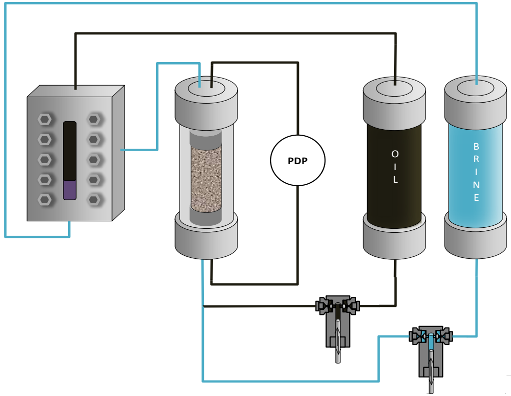
In-Situ Saturation Monitoring (ISSM)

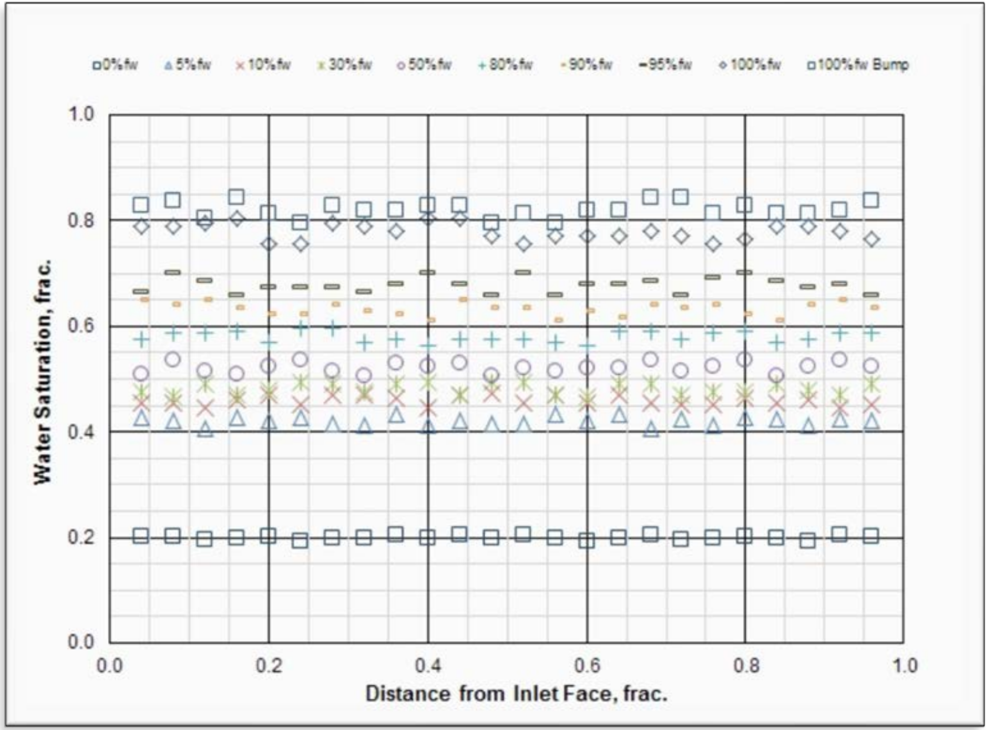


$$S_w = \frac{(\ln I - \ln I_O)}{(\ln I_w - \ln I_O)}$$

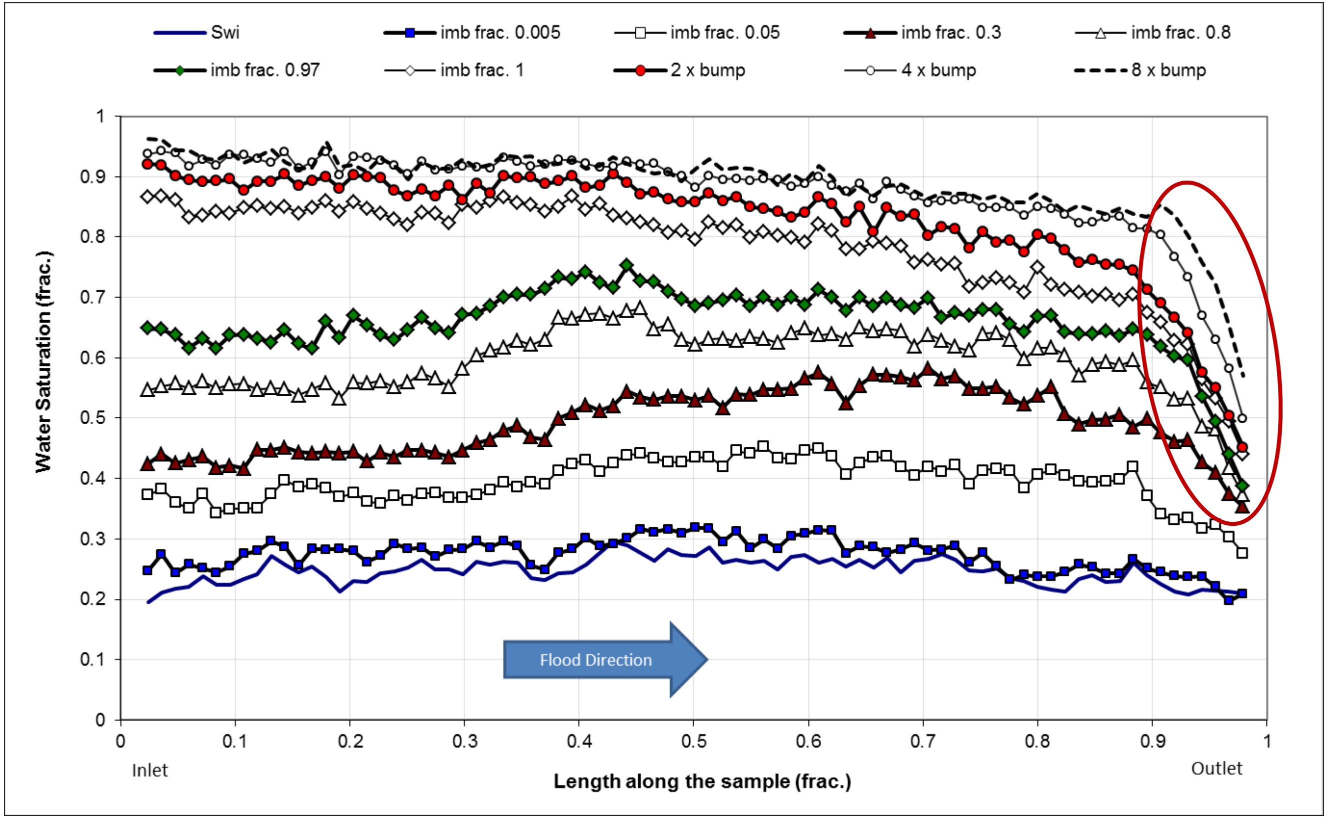
ISSM For Steady-state Core Flooding







Laboratory Effects



Relative Permeability Models

Corey Relative Permeability Model:

$$kron = \frac{kro}{kro'} = Son^{No}$$

k_{ro}’ = end-point kro

$$krwn = \frac{krw}{krw'} = Swn^{Nw}$$

k_{rw}’ = end-point krw

$$Swn = \frac{S_w - S_{wir}}{1 - S_{wir} - S_{ro}}$$

$$Son = \frac{1 - S_w - S_{ro}}{1 - S_{wir} - S_{ro}} = 1 - Swn$$

Typical properies for different wettability conditions

Condition	S_{wi} (%)	S_{or} (%)	k_{rw}'	n_w	n_o
Water wet (WW)	> 20 -25	< 10	0.1 - 0.4	4 - 6	2 - 3
Mixed wet (MW)	15-25	10-15	0.5 - 0.9	2 - 4	3 - 5
Oil Wet (OW)	< 15	> 15	0.8 - 1.0	1.5 - 3	6 - 8

Relative Permeability Models

LET Relative Permeability Model:

$$k_{rw} = k_{rw}^{0} \frac{(S_w^*)^{L_w}}{(S_w^*)^{L_w} + E_w(1 - S_w^*)^{T_w}}$$

$$k_{ro} = k_{ro}^{0} \frac{(1 - S_w^*)^{L_o}}{(1 - S_w^*)^{L_o} + E_o(S_w^*)^{T_o}}$$

$$S_w^* = \frac{S_w - S_{wi}}{1 - S_{or} - S_{wi}}$$

Constraints:

- $L_w \geq 1.0\,,\ E_w \geq 0.5,\ T_w \geq 0.5$
- $L_o \geq 1.0\,,\ E_o \geq 0.5,\ T_o \geq 0.5$

where:

k_{rw} - *water relative permeability*

k_{ro} - *oil relative permeability*

k_{rw}^{0} - *water relative permeability at residual oil saturation*

k_{ro}^{0} - *oil relative permeability at initial water saturation*

S_w - *water saturation*

S_{w*} - *normalised water saturation*

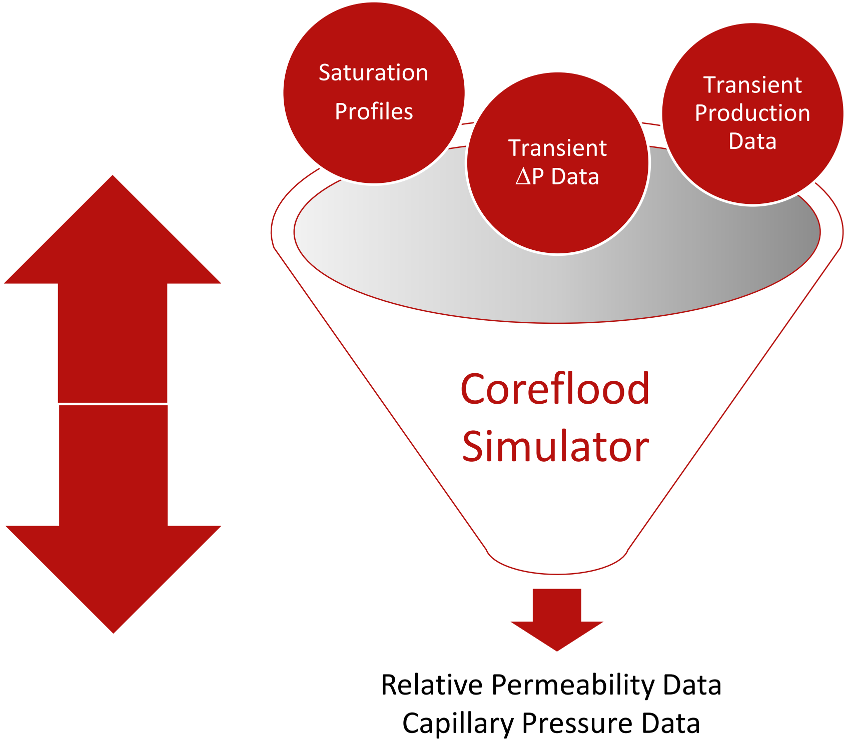
S_{wi} - *initial water saturation*

S_{or} - *residual oil saturation*

L_w, E_w, T_w - *LET parameters for water*

L_o, E_o, T_o - *LET parameters for oil*

History Matching Laboratory Data by Simulation



Quality Control of Laboratory Data

Useful Reservoir Engineering Data

Saturation Profiles

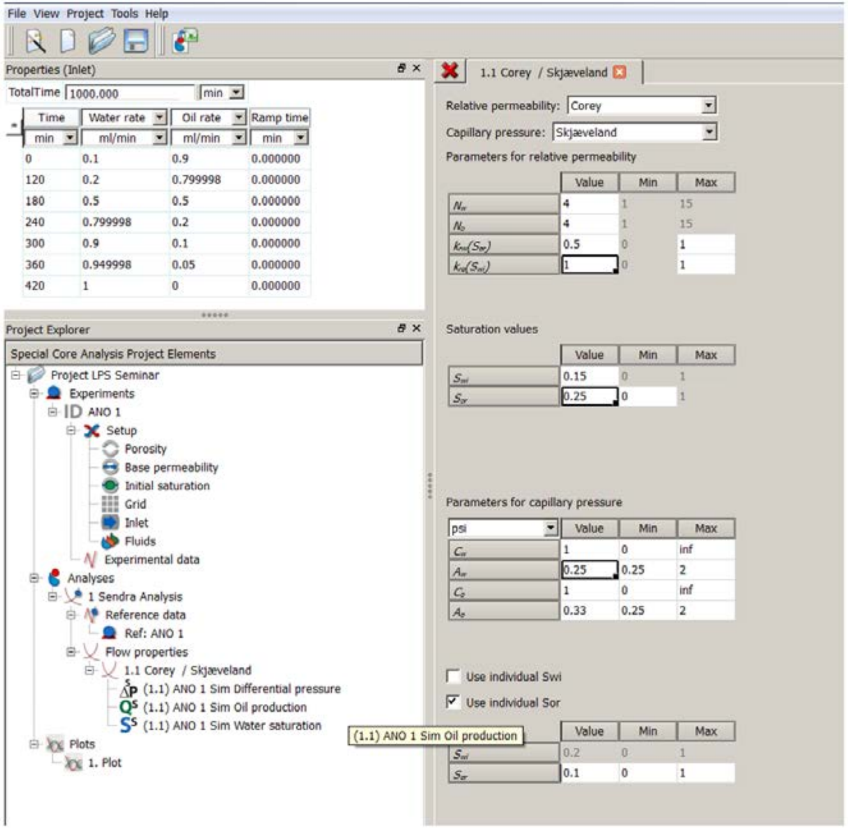
Transient ΔP Data

Transient Production Data

Coreflood Simulator

Relative Permeability Data
Capillary Pressure Data

Core Flood Simulator



Properties (Inlet)

TotalTime 1000.000 min

Time	Water rate	Oil rate	Ramp time
min	ml/min	ml/min	min
0	0.1	0.9	0.000000
120	0.2	0.799998	0.000000
180	0.5	0.5	0.000000
240	0.799998	0.2	0.000000
300	0.9	0.1	0.000000
360	0.949998	0.05	0.000000
420	1	0	0.000000

Project Explorer

Special Core Analysis Project Elements

- Project LPS Seminar
  - Experiments
    - ANO 1
      - Setup
        - Porosity
        - Base permeability
        - Initial saturation
        - Grid
        - Inlet
        - Fluids
      - Experimental data
  - Analyses
    - 1 Sendra Analysis
      - Reference data
        - Ref: ANO 1
      - Flow properties
        - 1.1 Corey / Skjæveland
          - (1.1) ANO 1 Sim Differential pressure
          - (1.1) ANO 1 Sim Oil production
          - (1.1) ANO 1 Sim Water saturation
  - Plots
    - 1. Plot

(1.1) ANO 1 Sim Oil production

Relative permeability: Corey

Capillary pressure: Skjæveland

Parameters for relative permeability

	Value	Min	Max
N_w	4	1	15
N_o	4	1	15
$k_{rw}(S_{or})$	0.5	0	1
$k_{ro}(S_{wi})$	1	0	1

Saturation values

	Value	Min	Max
S_{wi}	0.15	0	1
S_{or}	0.25	0	1

Parameters for capillary pressure

psi	Value	Min	Max
C_w	1	0	inf
A_w	0.25	0.25	2
C_o	1	0	inf
A_o	0.33	0.25	2

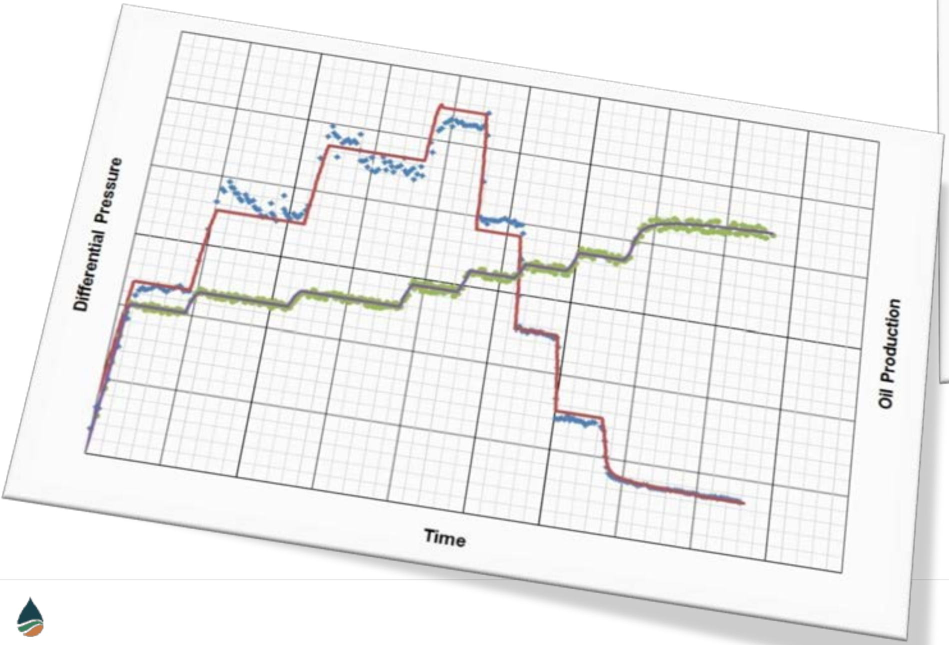
☐ Use individual Swi

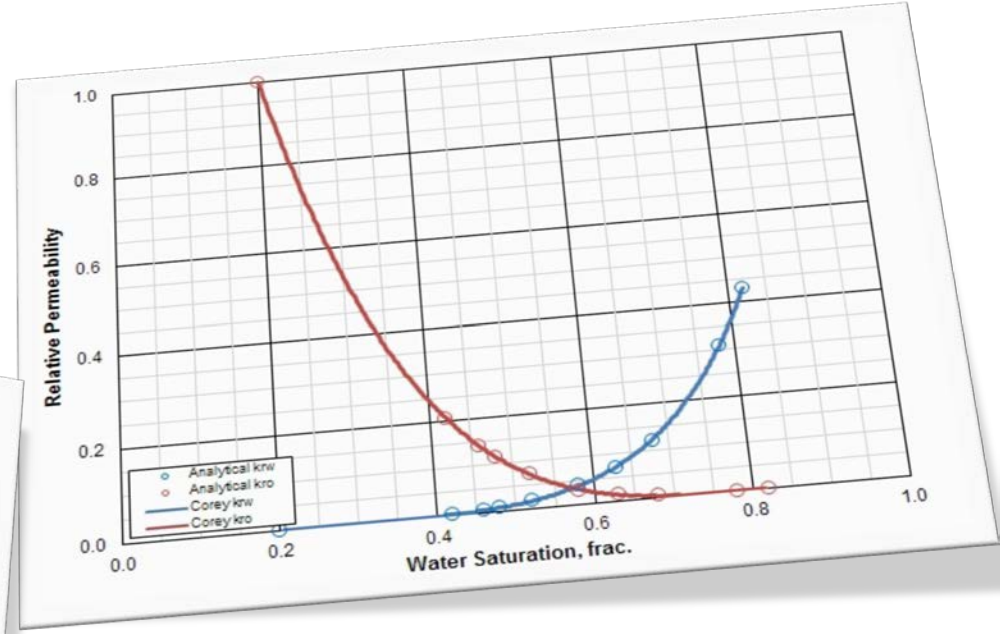
☑ Use individual Sor

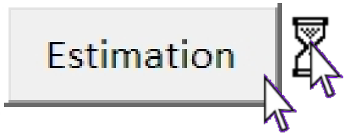
	Value	Min	Max
S_{wi}	0.2	0	1
S_{or}	0.1	0	1

Simulation of Transient Data

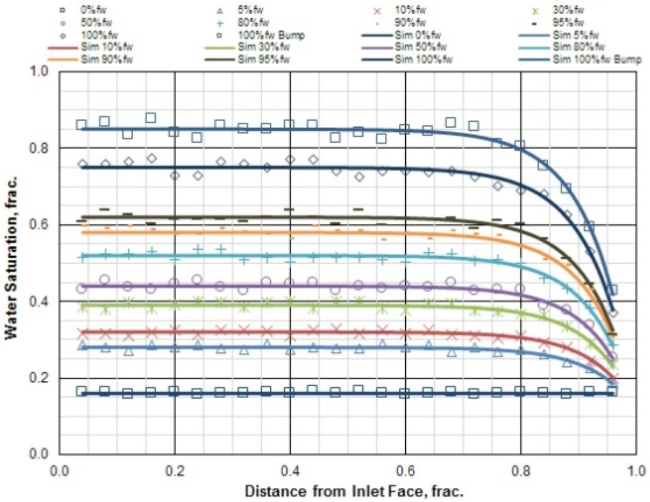
History matching of oil production and ΔP transient data to derive k_{rw} & k_{ro}

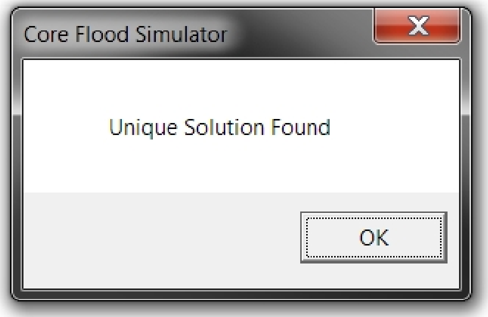




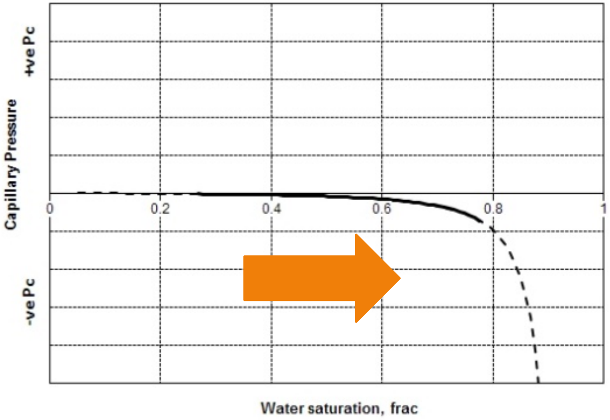


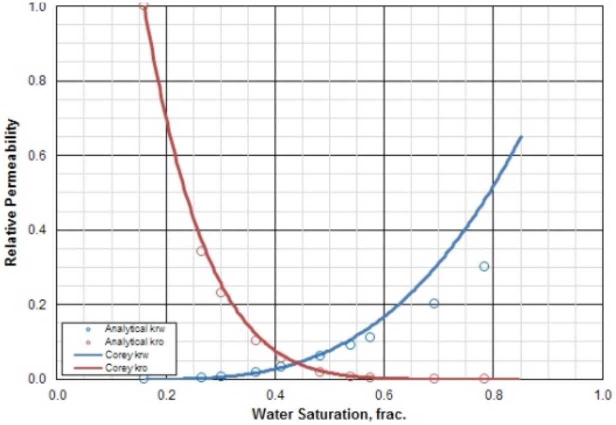
Case History 2 (Negative Imbibition Pc; Oil Wet)



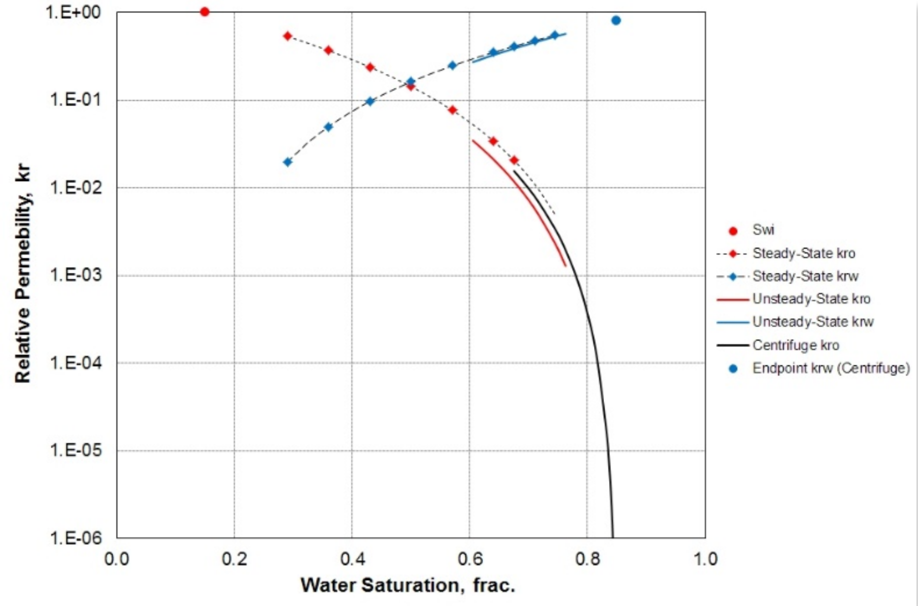


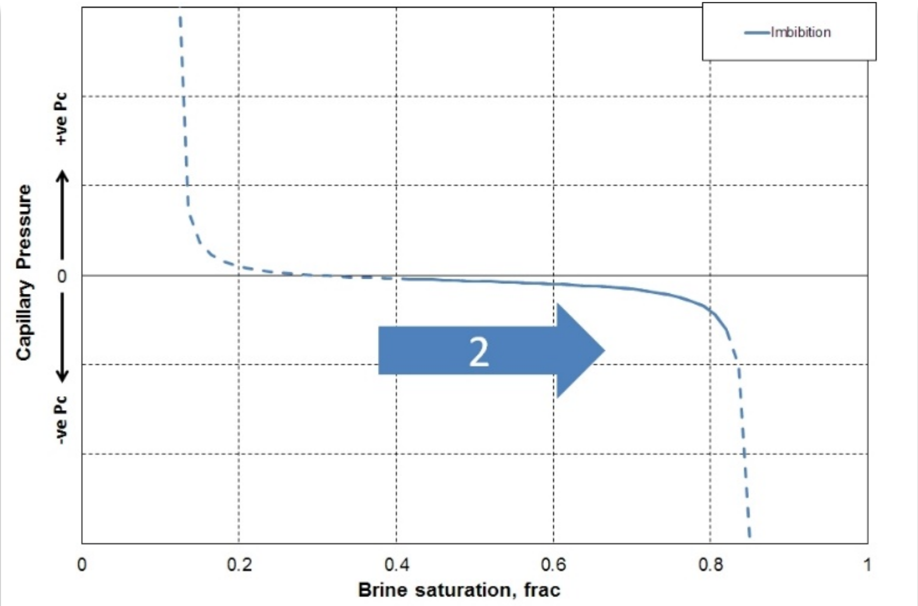
Unique Solution Found





Data for the Reservoir Engineer





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Thank you!

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Questions?

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