PVT Analysis & EoS Modeling

2022

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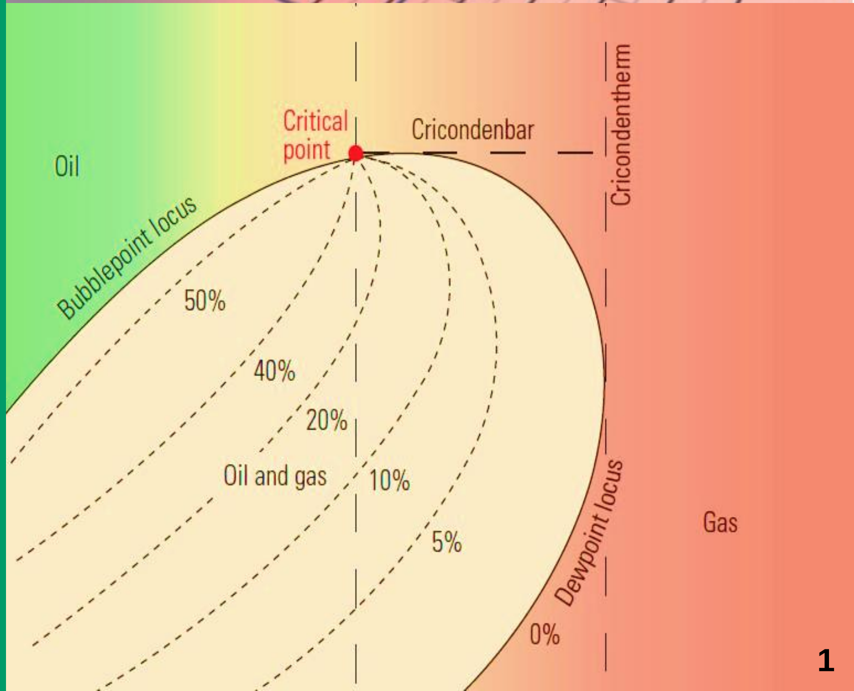
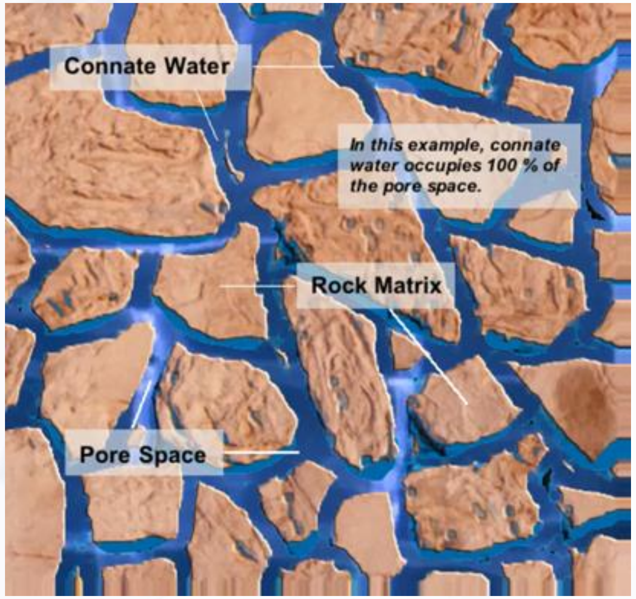


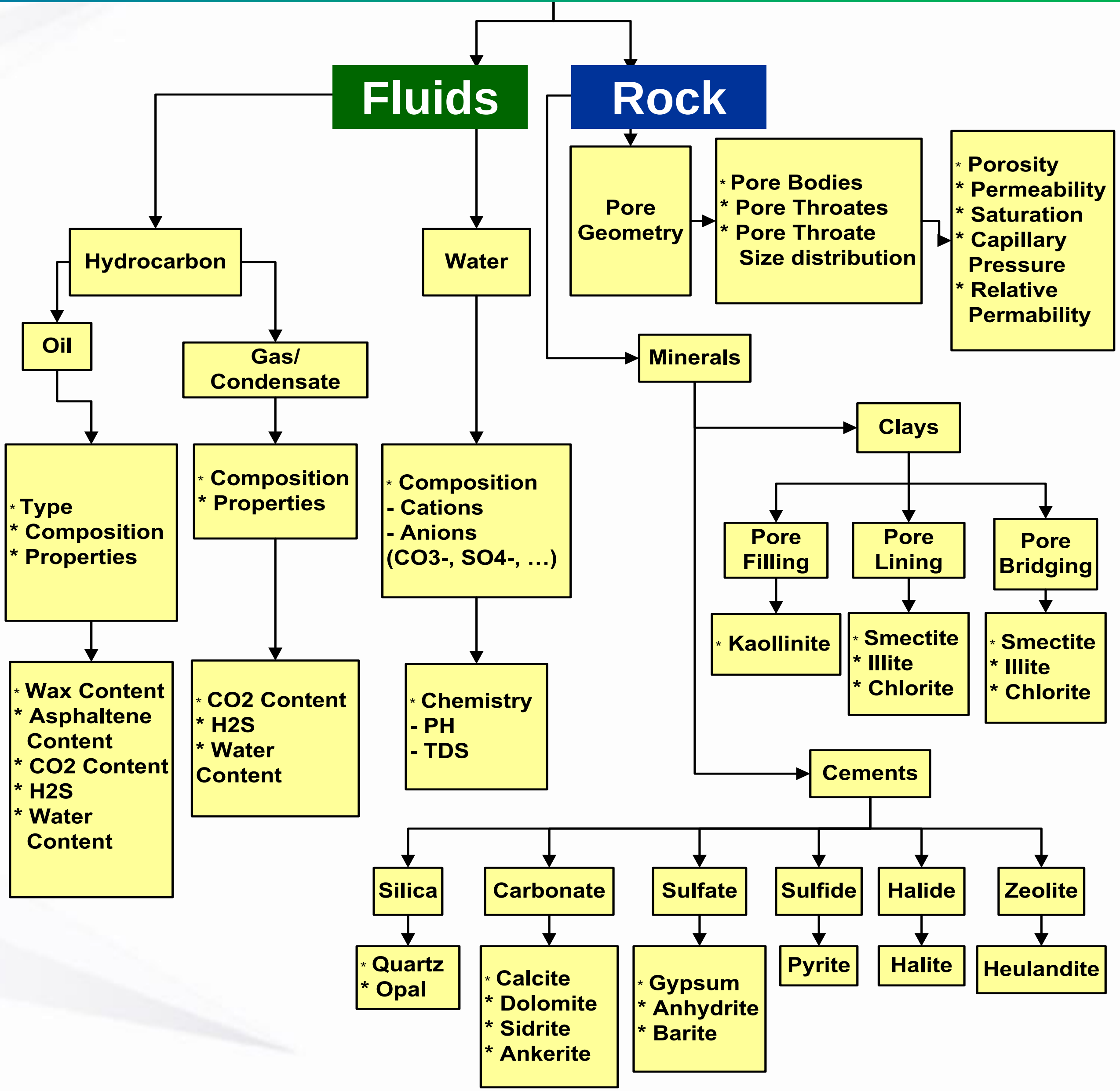
Agenda

- Applications of Fluid Data
- Reservoir Fluid Sampling (Bottom and Surface)
- Types of Reservoir Fluids
- Laboratory Reservoir Fluid Studies
- PVT Analysis Workflow
- Simulation Considerations for PVT Modeling
- Black Oil vs. Compositional Models
- Equation of State (EoS) Modeling

Reservoir System

- Reservoir fluids are combination of:
  - Gas
  - Oil
  - Water





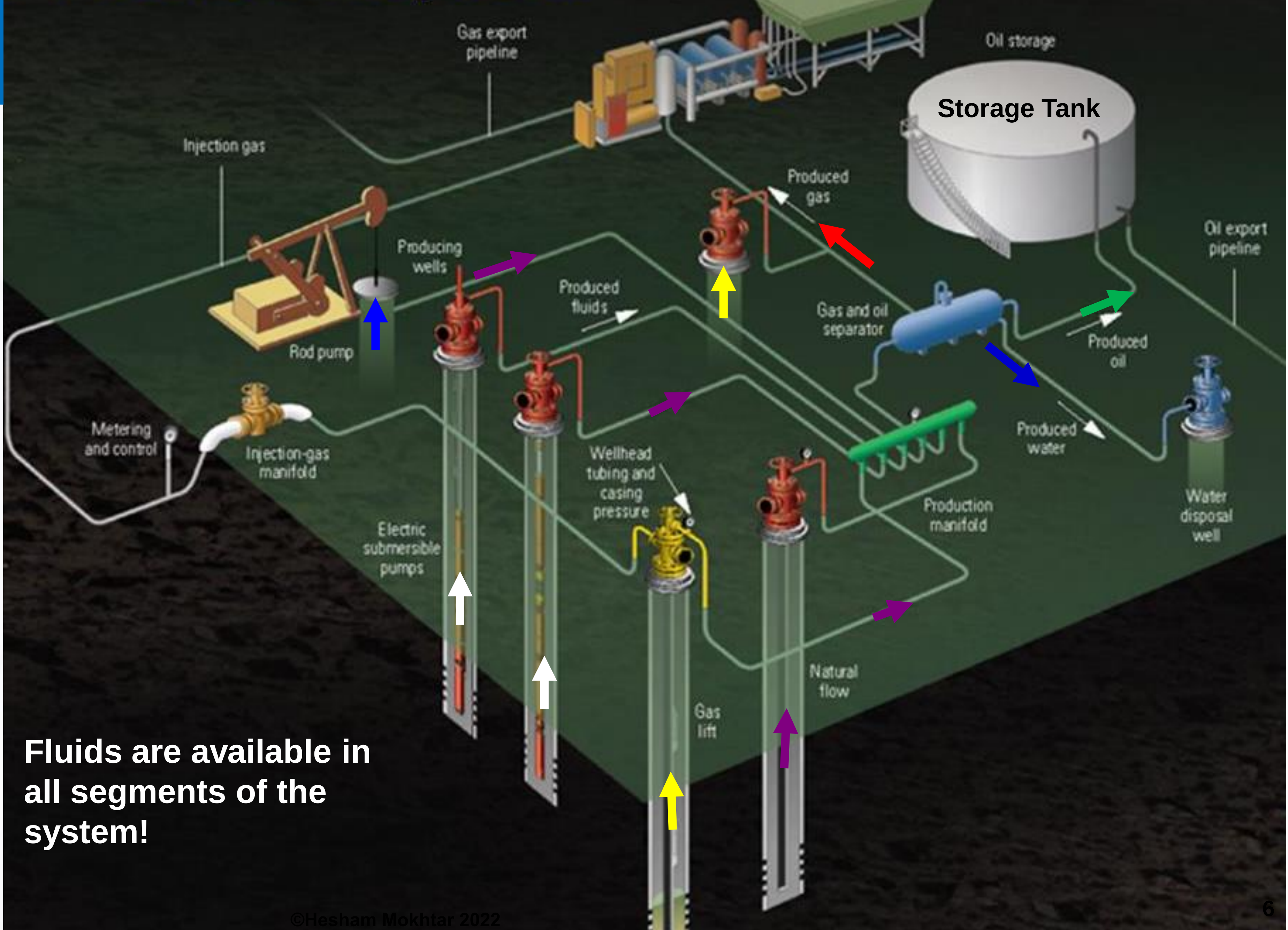
Full Field Modeling

It involves:

1. Fluid flow in a porous media.
2. Flow through wellbore (production tubing).
3. Flow through surface pipes.

- **Reservoir rocks can NOT be brought to surface, but fluids can!**
- **Reservoir fluids are representing the heart of the production system.**

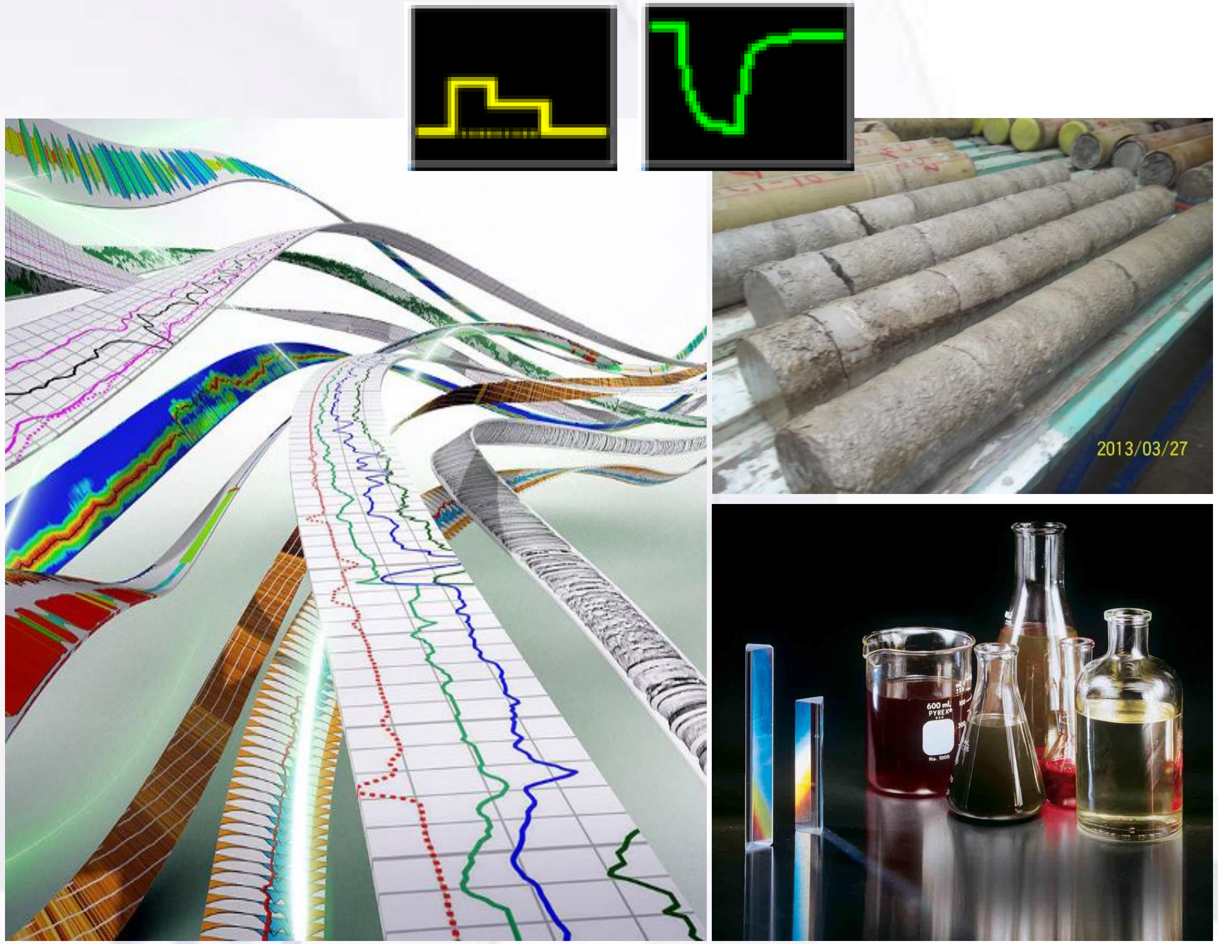
Production System

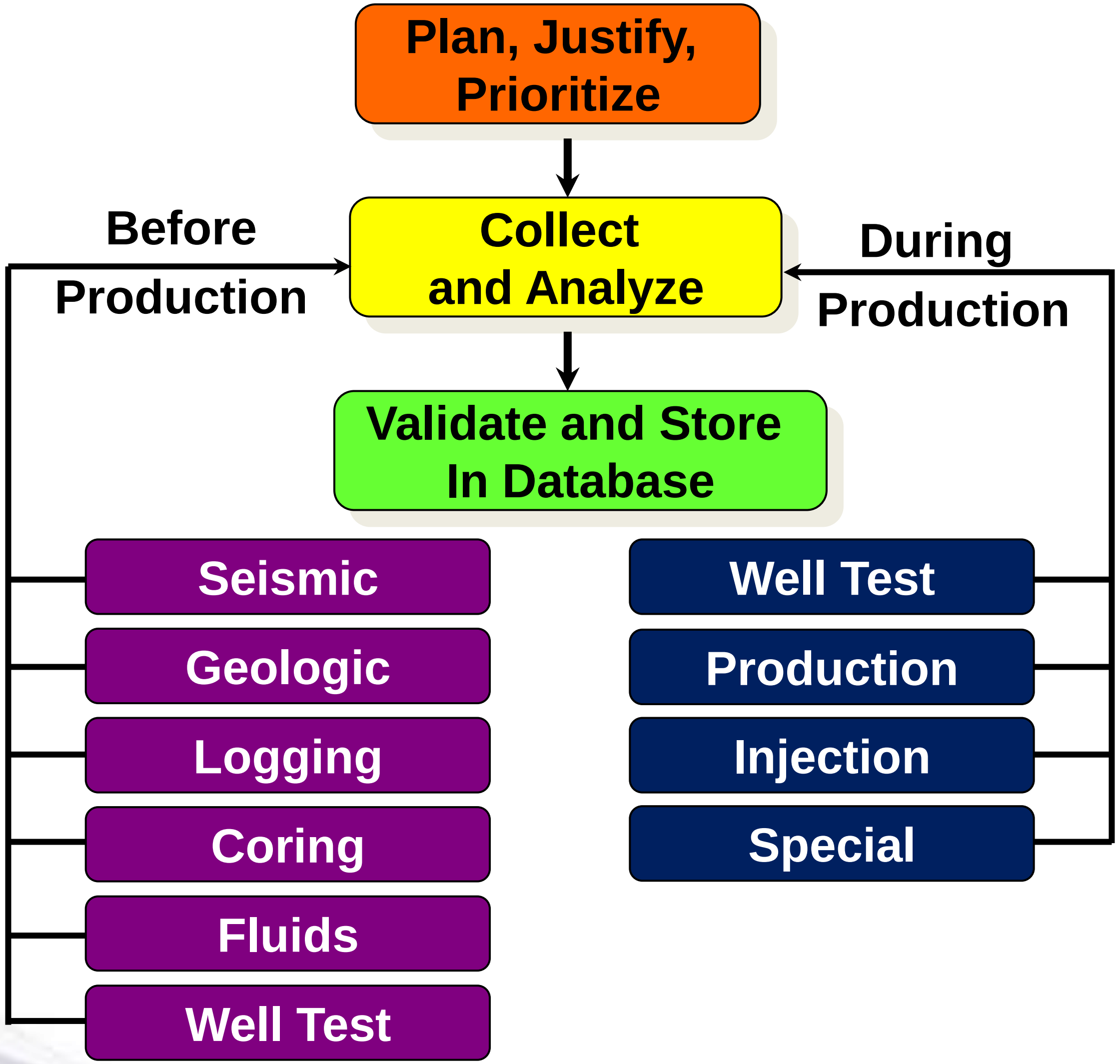


Fluids are available in all segments of the system!

Reservoir Management Plan Components

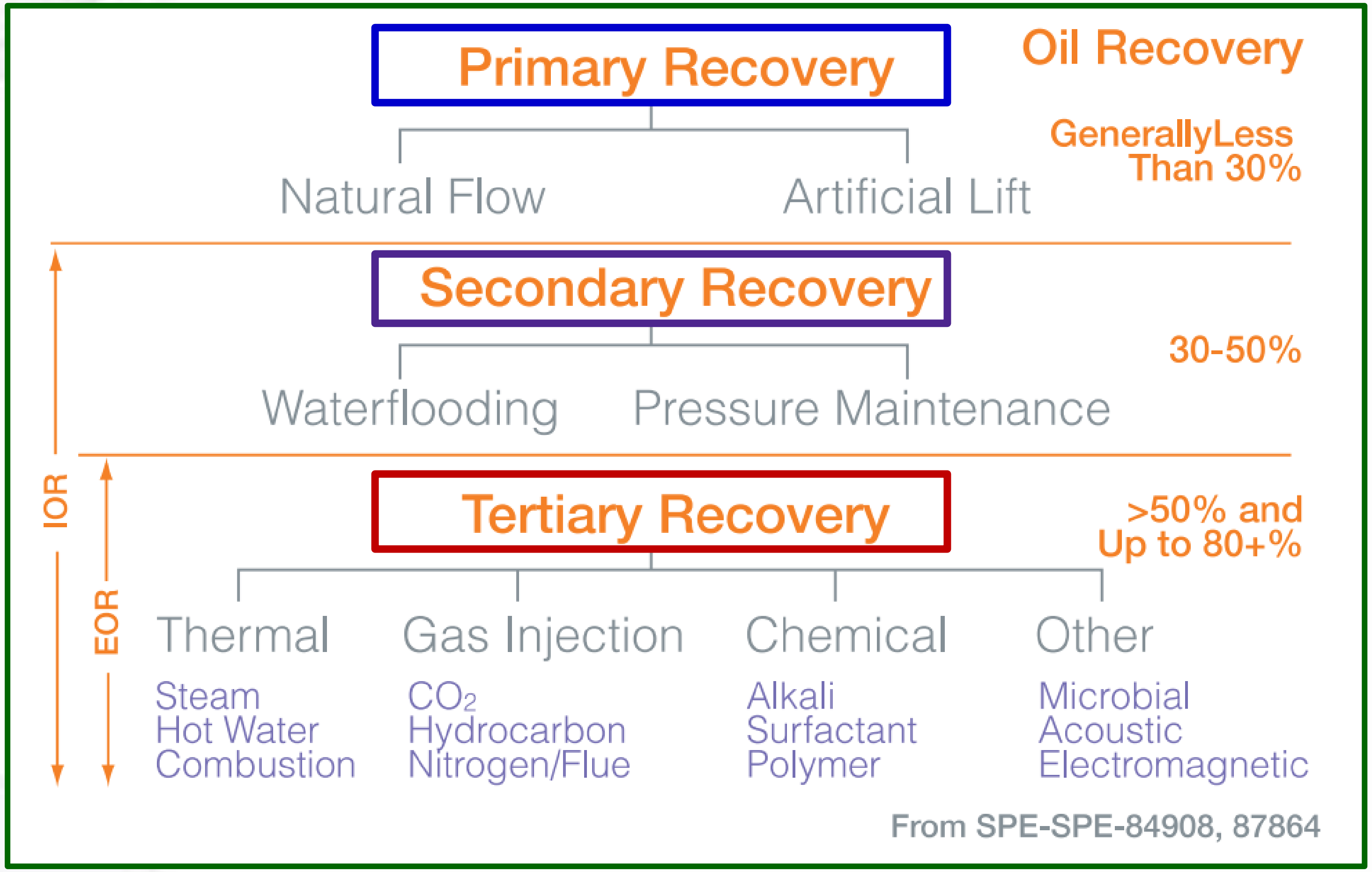
Data Acquisition and Analysis





Oil Recovery Techniques?

- **Natural reservoir energy (primary recovery)**
- **Improved recovery methods:**
  - Pressure maintenance (Gas injection & Waterflooding)
  - Thermal recovery
  - Chemical flooding
  - Miscible flooding



EOS modeling plays a significant rule in EOR applications

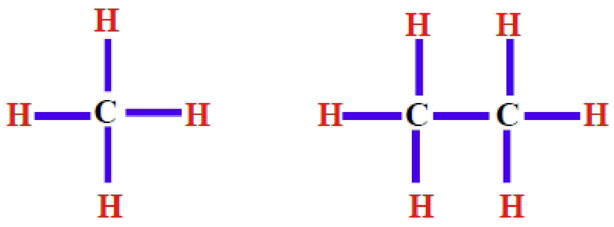
Introduction: Reservoir Fluids

- A reservoir normally contains **either water or hydrocarbon or a mixture.**
- The specific hydrocarbon produced depends on the reservoir pressure and temperature.
- The formation water may be fresh or salty.
- The amount and type of fluid produced depends on the initial reservoir pressure, rock properties and the drive mechanism.
- **Thermodynamics: PVT**
  - Three main parameters required to relate reservoir volumes to surface volumes (P, V, T).
  - Characteristic parameters of the fluids (**density, compressibility, viscosity, solubility, etc.**) are changing with P & T.
  - Fluids need special lab measurements (PVT analysis).

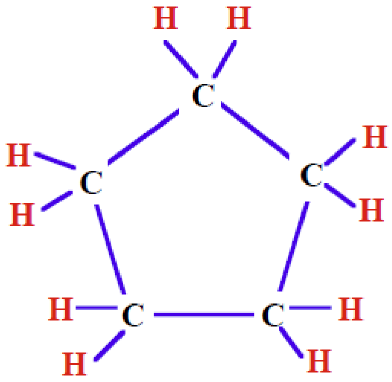
Hydrocarbon Structure

- The simplest and most abundant is the **paraffin** series, chains of **Carbon** atoms with **Hydrogen** attached.
- The chemical formula for this type of structure is C_nH_{2n+2}.
- The major constituent of hydrocarbons is **paraffin**.
- They range from a **dry gas** which is mostly C1 (methane) to **tar** which is mostly the heavier fractions.
- The black oil normally found is between the two extremes, C1 and heavier fractions (C7+).
- The hydrocarbon extracted from reservoirs varies in **composition from place to place**.

- The more complex ring structures, **Naphthalene** and **Benzenes** occur in varying proportions.

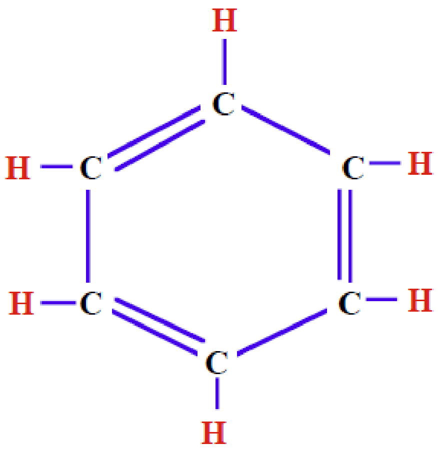


PARAFFIN SERIES, METHANE AND ETHANE



NAPTHALENE SERIES

CYCLOPENTANE



AROMATIC SERIES

BENZENE

Petroleum Fluid Phases

- **A fluid phase is a homogeneous and physically distinct part of a system that is separated from other parts by definite boundaries (e.g. oil, gas, water).**
- **Equilibrium**: a condition at which a material appears to be at rest (no change in volume or changing phase).

- **Component**: A component is an entity, consistent, a given compound, or substance (e.g. C1, C2, N2, etc.).

- The behavior of a reservoir fluid is analyzed using 3 dependent parameters; **Pressure, Volume, and Temperature (P-V-T).**
- **There are 2 common ways of showing this:**
  - **P** vs. T, while keeping V constant.
  - **P** vs. V, while keeping T constant.

Petroleum Production Flow Path

RESERVOIR

IOR/EOR
4D-SESMICS

WELL BORE

-ARTIFICIAL LIFT
-EXTENDED REACH
- FLOW ENHANCING SOLUTIONS

WELLHEAD

-XMAS TREE
-INJECTION SYSTEM

PIPELINE

-PRESSURE LOSS
- FLOW REGIME/SLUGS
-TEMPERATURE
-CORROSION
-EROSION
-NASTIES;WAX,SCALE.. ,ETC
-PIPELINE INTEGRITY

MANIFOLD

-CONNECTORS
-VALVES
-INSTRUMENTS
-METERING
-FRAME

SS BOOSTING

-MPH PUMPS
-SS SEP`N+ PUMP.
-GAS COMPRESSION

PIPELINE

AS ABOVE

SLUG CATCHER

-SLUG CATCHER
-L.PUMPING

RISER

-SLUGGING
-DP
-INTEGRITY

TOPSIDE PROCESS

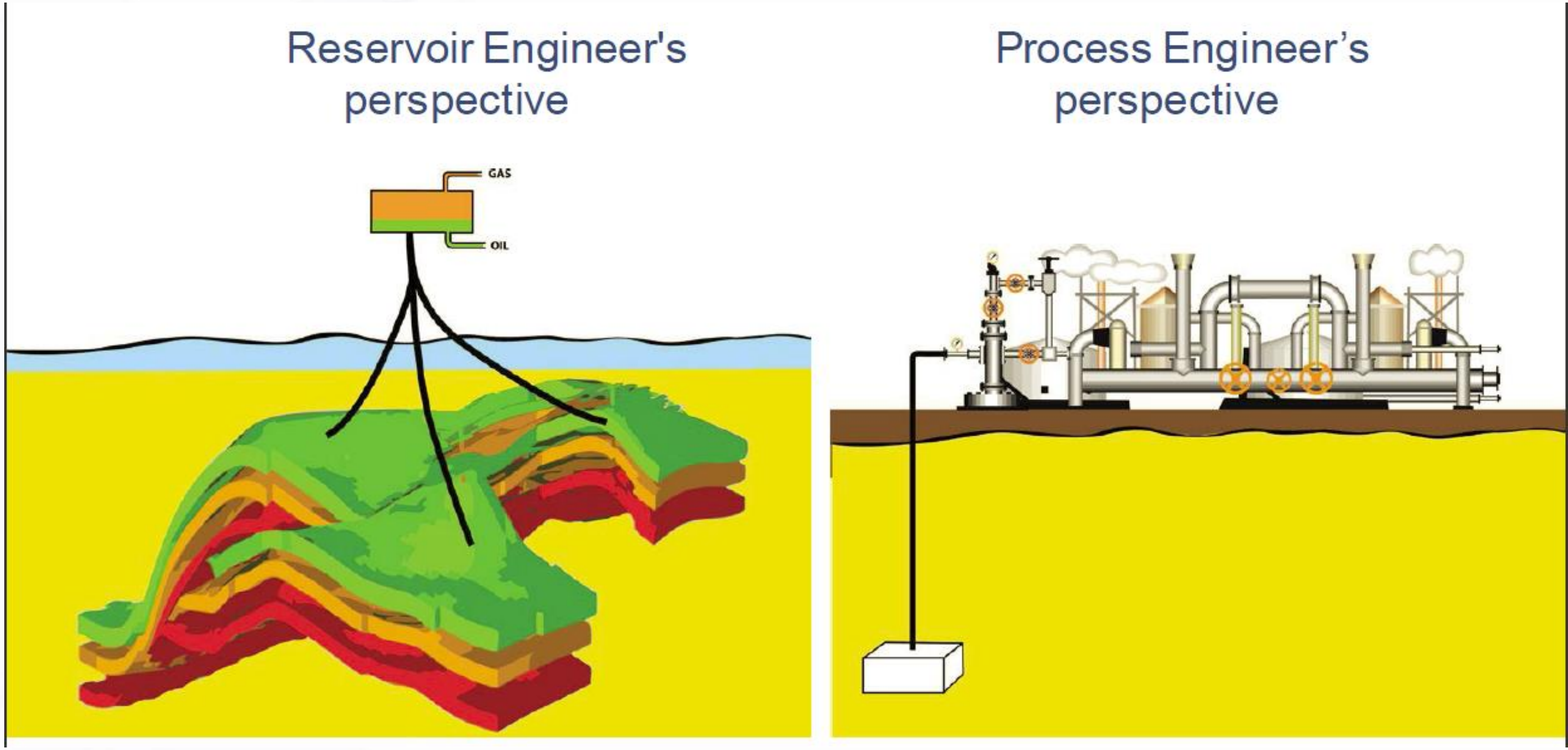
-PROCESS
-BOOSTING SYSTEMS

EXPORT

-PUMPING COMP`N

Different Prospects for Fluid Modeling

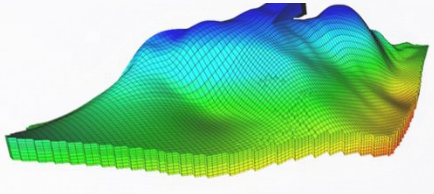
- Subsurface engineers are considered with PVT data analysis for fluid flow calculation and simulation modeling.
- Production & processing engineers are concerned with flow assurance issues.
- Conversion difficulties in transferring from reservoir modelling software to processing modelling software!



Applications of Reservoir Fluid Data

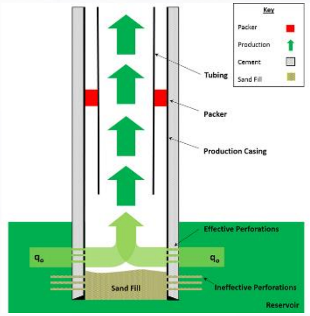
Drilling

Sample Validation (especially MDT)	OBM Contamination	Well Construction
P_{sat}, GOR, μ, ρ, C12+, C36+	STO C36+	H_2S, CO_2, H_2O



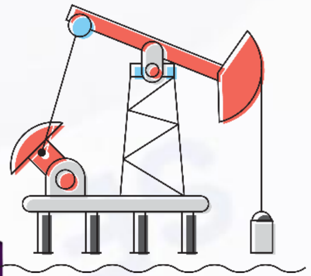
Reservoir

Steady Separator Conditions	Multi-Flow Meter Rates Vx	Well Test Interpretation	Natural Drive Mechanism	Material Balance	Reservoir Simulation & Reserve Estimates
C12+, GOR	ρ_o, ρ_w, ρ_g, w_i, l_i, y_i	μ, ρ, k	P_{sat}, ρ, P_{grad}	GOR, B_o, B_g, Z_{factor}	Full PVT



Completion

Artificial Lift Calculations	Completion Design	Material Specification	Subsea Applications
μ_o, μ_ω, ρ_o, ρ_w, GOR	H_2S, CO_2, H_2O	H_2S, CO_2, H_2O	C36+, μ, ρ, H_2S, FA

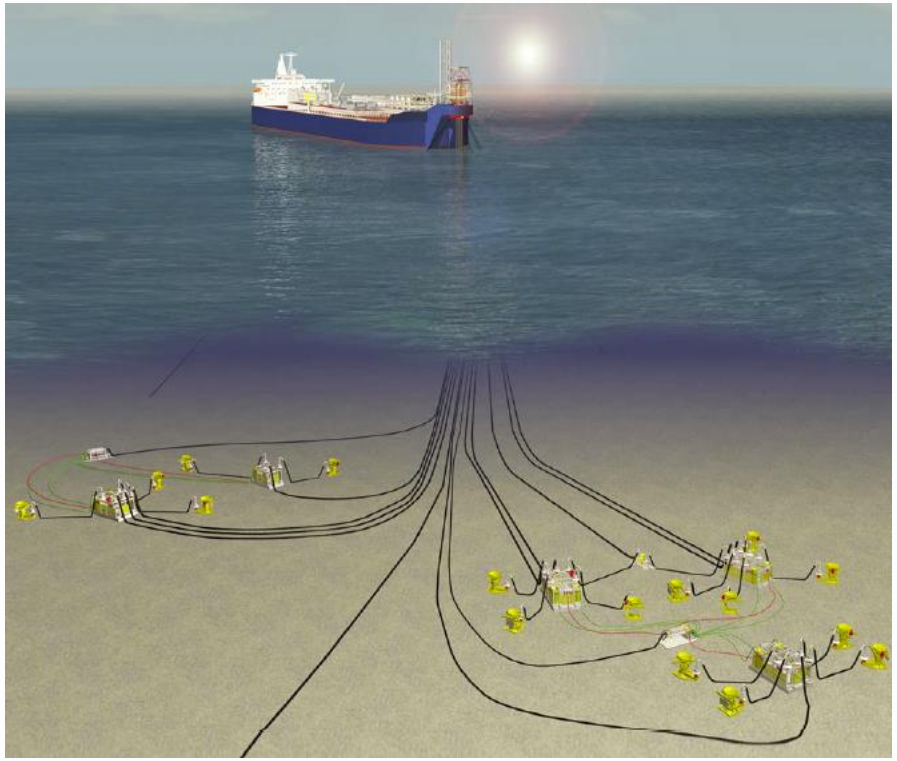


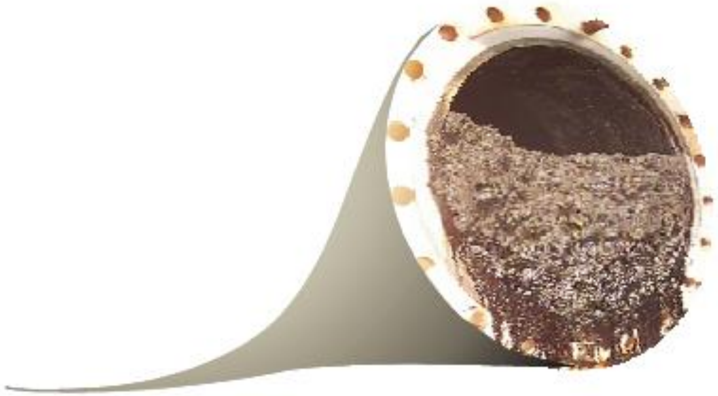
Production

Multi-Flow Meter Rates Vx	Production Facility Design	Production Forecasts	Production Log Interpretation
ρ_o, ρ_w, ρ_g, w_i, l_i, y_i	GOR, CVD, R_s, ST	Full PVT	GOR, ρ_o, ρ_w, μ

Flow Assurance

- **Flow assurance is to take precaution to ensure deliverability and operability.**
- **To assure flow and maintain production by managing these elements:**
  - Asphaltene
  - Waxes
  - Hydrates
  - Emulsions/Slugs
  - Scales/Sulfur
- **Asphaltene**: Alkane insoluble components of oil & precipitate $\Delta(P, T \& x)$
- **Wax**: Normal paraffin from C15 to C75 and become solid $\Delta(T\&P)$
- **Hydrate**: Inclusion compounds formed by water and small molecular gases (C_1, C_2, C_3, CO_2, H_2S) at low T and high P conditions.





How Much Oil Is In Place?

- **STOIIP (N)**
- **Original oil reserves (N_{pa})= N*RF**

- **GIIP (G)**
- **Original gas reserves= OGIP*RF**

$$N = \frac{7758Ah\phi(1-S_{wi})}{B_{oi}}$$

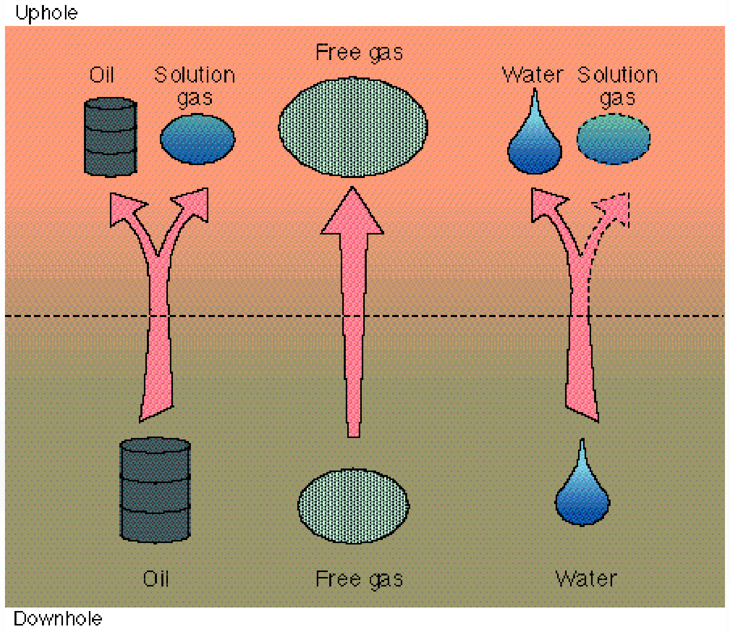
$$GIIP = \frac{7758Ah\phi(1-S_{wi})}{B_{gi}}$$

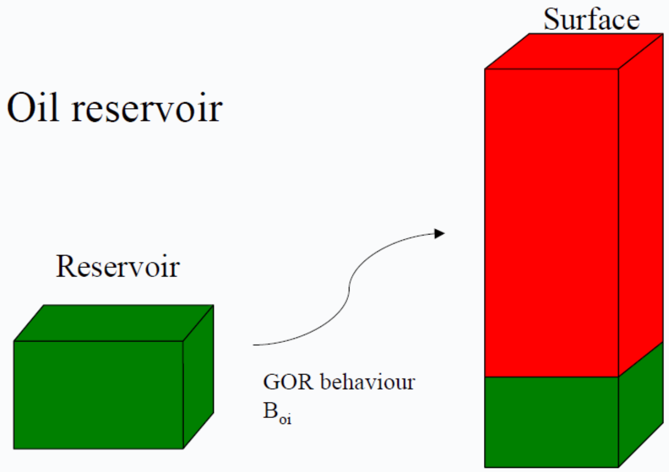
$$SGIP = N * R_{soi}$$

$$RF = 1 - \frac{B_{gi}}{B_{ga}}$$

Surface

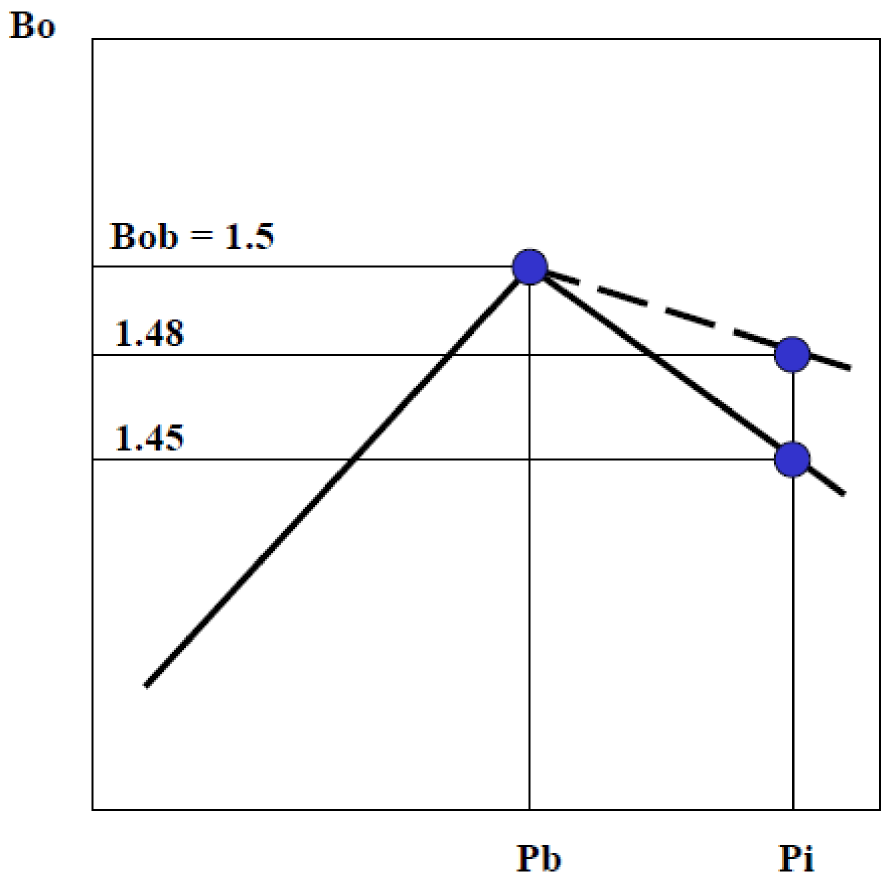
Subsurface





Errors of PVT Data, How Much Does It Cost?

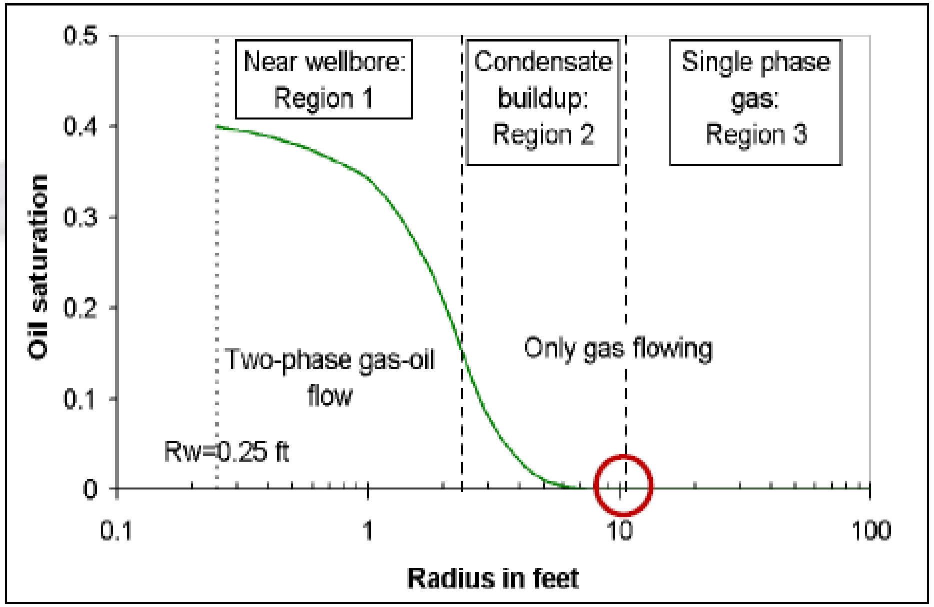
- Expansion of the oil above Pb determines how much of the oil in place will be produced?
- B_{ob} = 1.5 & **B_{oi} = 1.48 bbl/STB**
- **But, it's wrongly evaluated as 1.45!**
- **Error on PVT may lead to large errors in estimates of reserves :(1.48 – 1.45) / (1.5 – 1.45) = 60%**
- Hence, on the evaluation of the reserves, is ≈**60%!!!**

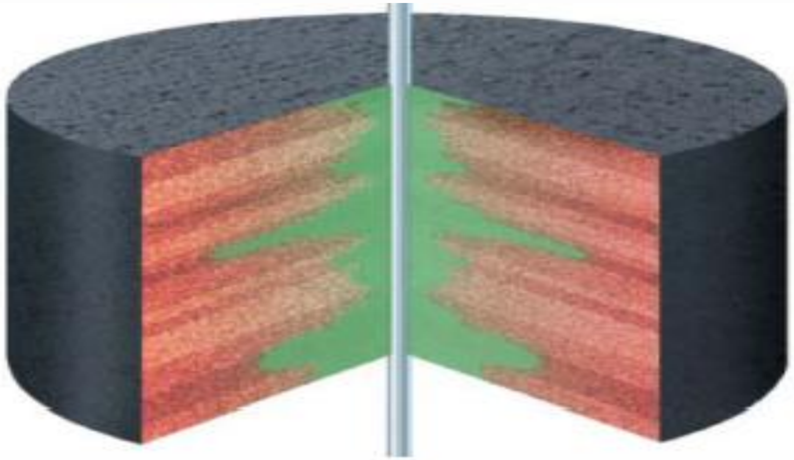


Importance Of Reservoir Fluid Identification

Prediction of future productivity problems and their solutions

- **Condensate blockage in gas-condensate reservoirs**
  - ❑ Reducing production delta P By enhancing productivity through acidizing or fracturing.
  - ❑ Gas recycling to vaporize condensate and produce it.
- **Flow assurance examples:**
  - ❑ Using corrosion inhibitor in case of H2S existence.
  - ❑ Using Asphaltene dispersant in case of Asphaltene problems.





PVT Analysis Workflow

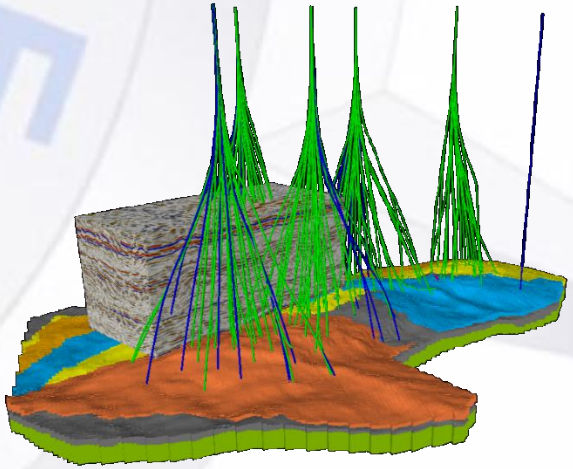
Sample
- Reservoir Fluid Modelling
- Fluid Characterisation
- PVT Experiments
- Compositional Data
- Black Oil Analysis

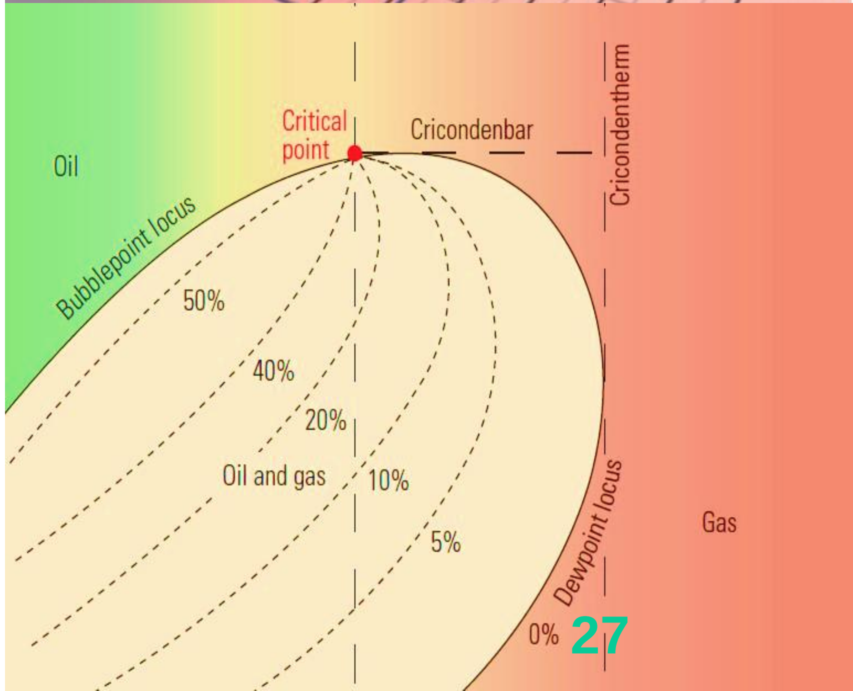
Validate
- Sample QC
- Mud Cleaning
- Model Tuning
- Physical and Transport Properties

Predict
- Phase Behaviour
- Hydrates Formation
- Wax Separation
- Asphaltene Flocculation
- Physical and Transport Properties

Simulate
- Flow Assurance Strategies
- Process Engineering
- On Line Flow Metering
- Embedded Solutions
- From Reservoir to Refinery

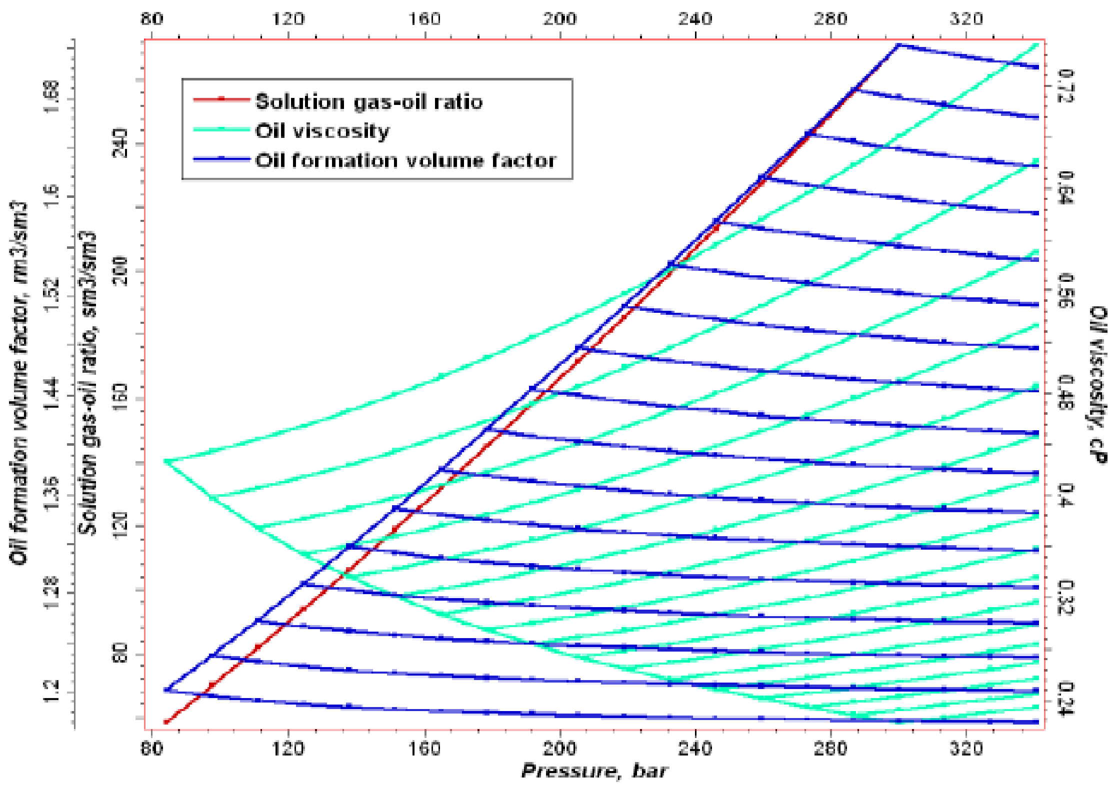
Dynamic Reservoir Model (Fluid Model)





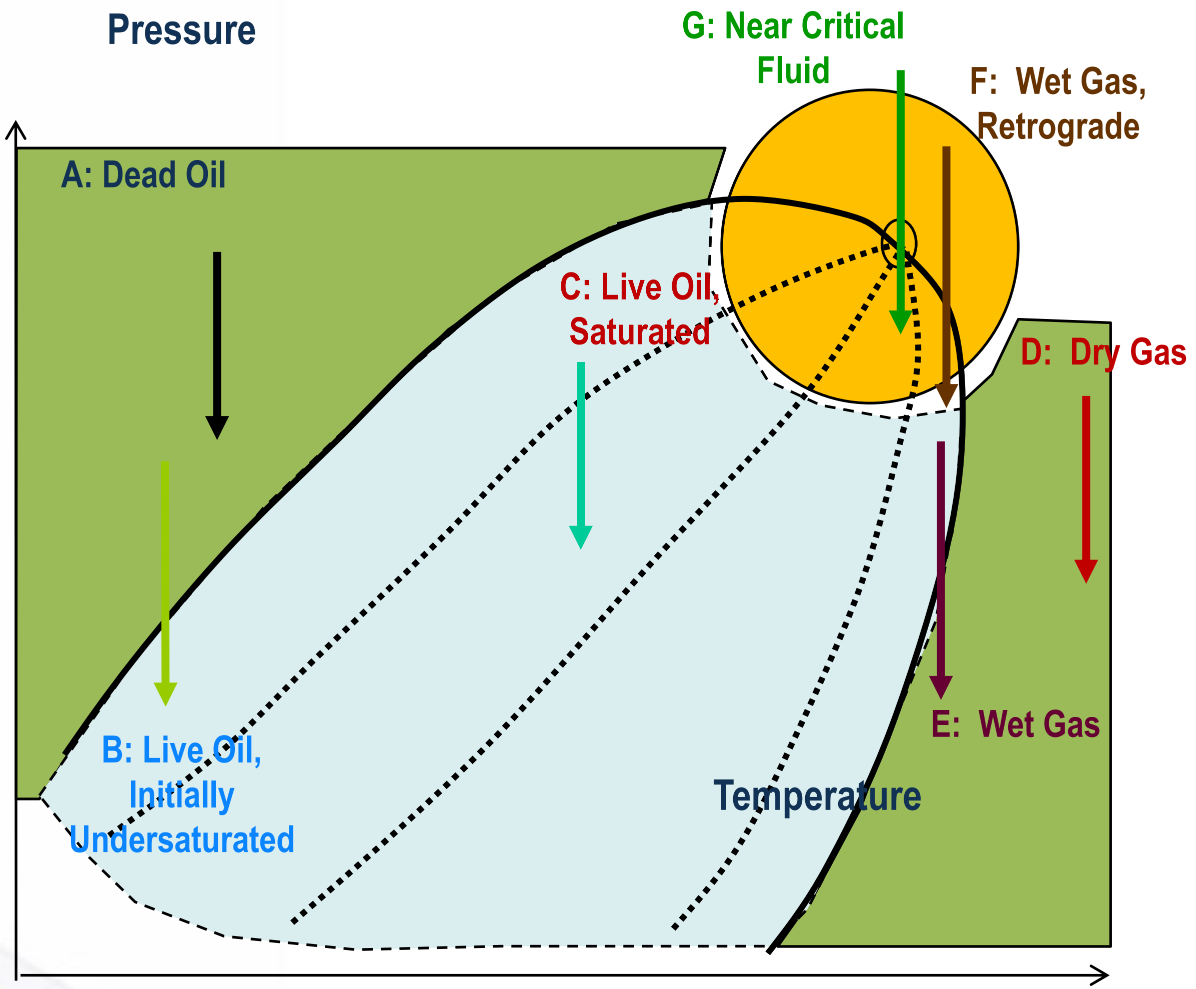
Fluid Properties & PVT Analysis

- **Why is PVT needed?**
  - Mass balance is a key equation in simulation
  - Produced volumes must be translated to reservoir conditions
  - Reservoir volumes must be converted to mass
- **Where does PVT come from?**
  - Laboratory experiments: Equation of State Model
  - Correlations: Available in Petrel
- **Fluid data required?**
  - Fluid PVT as a function of pressure
  - Density & Gravity at surface conditions
- **RE should:**
  - QC of PVT reports.
  - Developing EOS model and matching the lab data.
  - Generating Black oil / compositional PVT input for the simulator.
  - If PVT data is not directly available, then use offset data or empirical correlations.



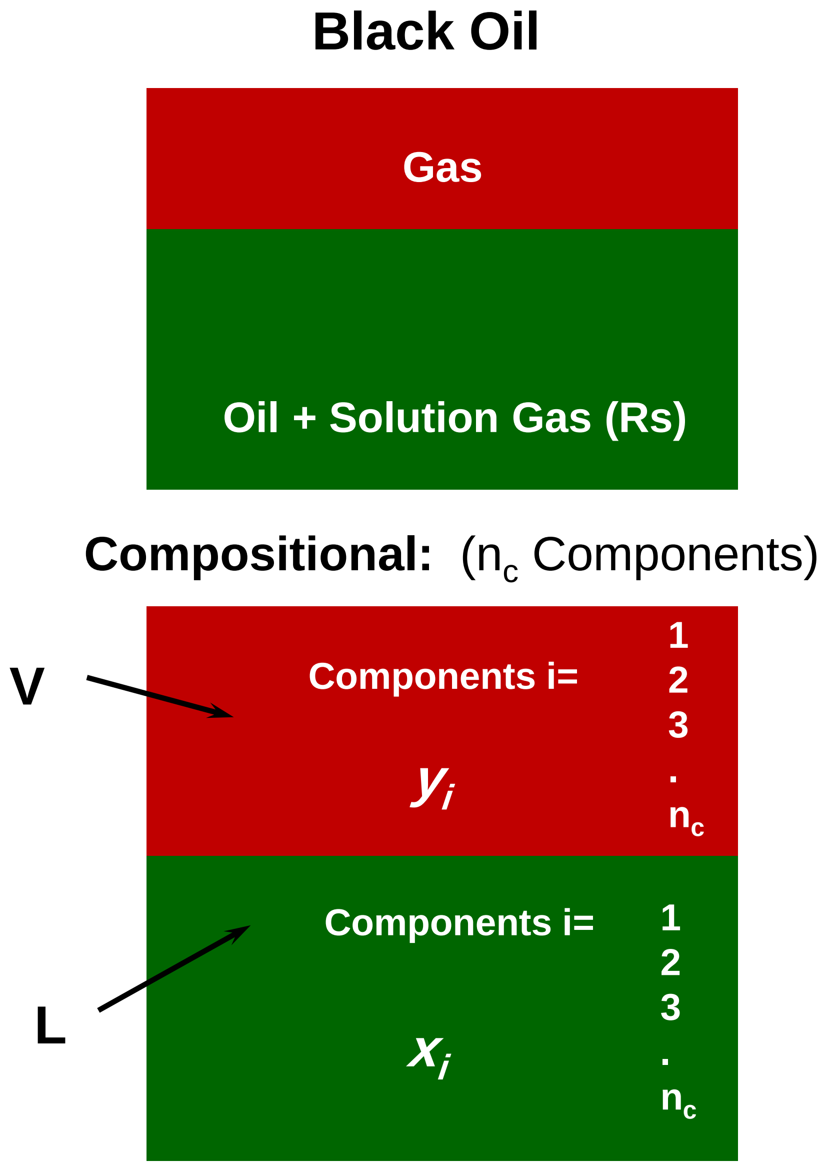
Fluid Models

- Fits the Black Oil model.
- Unsuited for black oil simulation (use Compositional simulation).
- Approximated by Black Oil varying gas/oil and oil/gas ratios to mimic small compositional changes.



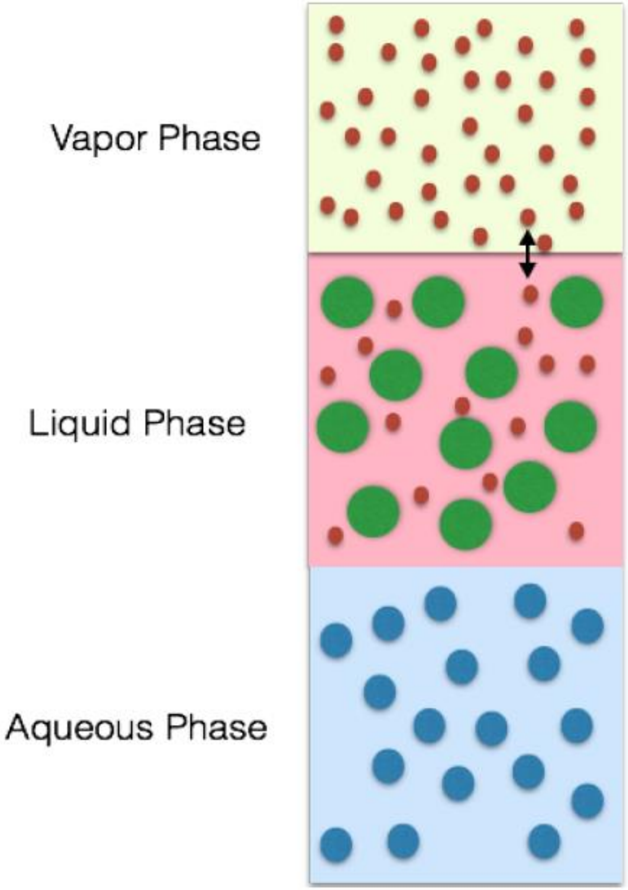
Black Oil and Compositional Models

- **Black oil simulators:**
  - Oil and gas phases are represented by **ONE component**.
  - Assumes composition of gas and oil components are **CONSTANT** with pressure and time.
- **Compositional simulators:**
  - Oil and gas phases are represented by **multi-component mixtures**.
  - Assumes the reservoir fluids at all **P, T, compositions, and time** can be represented by an **Equation of State (EOS).**



Black Oil Model

- **The black oil model is based on simple interpolation of PVT properties as a function of pressure.**
- Water is modeled explicitly together with **2 hydrocarbon components (oil phase and gas phase).**
- At standard P/T, hydrocarbon components are divided into a gas component and an oil component in a stock tank
- **No mass transfer occurs between the water phase and the oil/gas phases**



Black Oil vs. Modified Black Oil PVT

Black Oil Simulation	Modified Black Oil Simulation
B_g	B_g
B_o	B_o
μ_o	μ_o
$f(p)$	$f(p)$
μ_g	μ_g
	R_v
R_s	R_s

Compositional Simulation

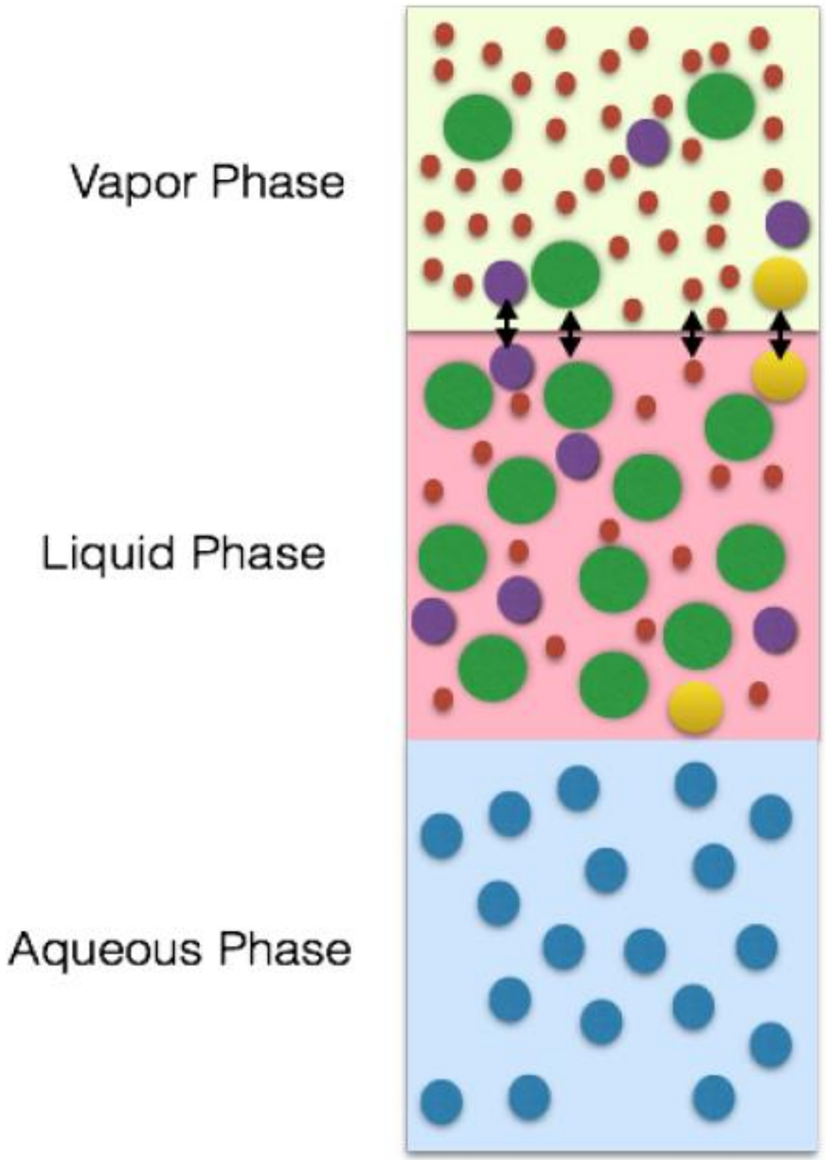
Compositional simulation models are needed in the following cases:

- **Miscible and near-miscible displacements (IFT changes)**
- Gas cycling
- Compositional gradient
- Monitoring of production stream composition
  - Surface separation design
  - Gas plant calculations
- Changing separator conditions with time

	Gas	Oil	Water
Comp 1	X	X	
Comp 2	X	X	
•••	X	X	
•••	X	X	
Comp n	X	X	
Water			X

Compositional Model

- In reservoirs containing light oil, the hydrocarbon composition affects fluid properties a lot.
- **A compositional model is based on a thermodynamically-consistent or equation of state (EOS) model.**
- Each hydrocarbon component (arbitrary number) is handled separately.
- More unknowns than the black oil model:
  - j is the molar density of phase j
  - Xij is the molar fraction of component i in phase j
  - Ni is the overall molar density of component i



Black Oil vs. Compositional Models

Three phases are presented

Black Oil	Compositional

$$\left.\begin{Bmatrix} B_o \\ B_g \\ R_s \\ \mu \end{Bmatrix}\right. = f\,(p)$$

Table Values

$$\left.\begin{matrix} K_i = \dfrac{y_i}{x_i} \\ \mu \\ \rho \end{matrix}\right\} f\,(p, x_i, y_i)$$

EoS Flash

- Assumes Composition of Gas and Oil Phases CONSTANT with Pressure and time.

- Assumes EoS represents fluids at all T, P, Composition
- Need PVT package (e.g. PVTi) to regress EoS.
- The process of deciding how many phases are present is called a "Flash"

Black Oil vs. Compositional Models

Three phases are presented

Black Oil

$$\begin{pmatrix} P \\ S_w \\ S_g \end{pmatrix}$$

No gas -> Rs instead Sg
No oil -> Rv instead So

- **Unknowns (3 Phase System):**
  - **(3) variables per grid block**

Compositional

$$\begin{pmatrix} P \\ Z_w \\ Z_i \end{pmatrix}$$

Molar density of Water

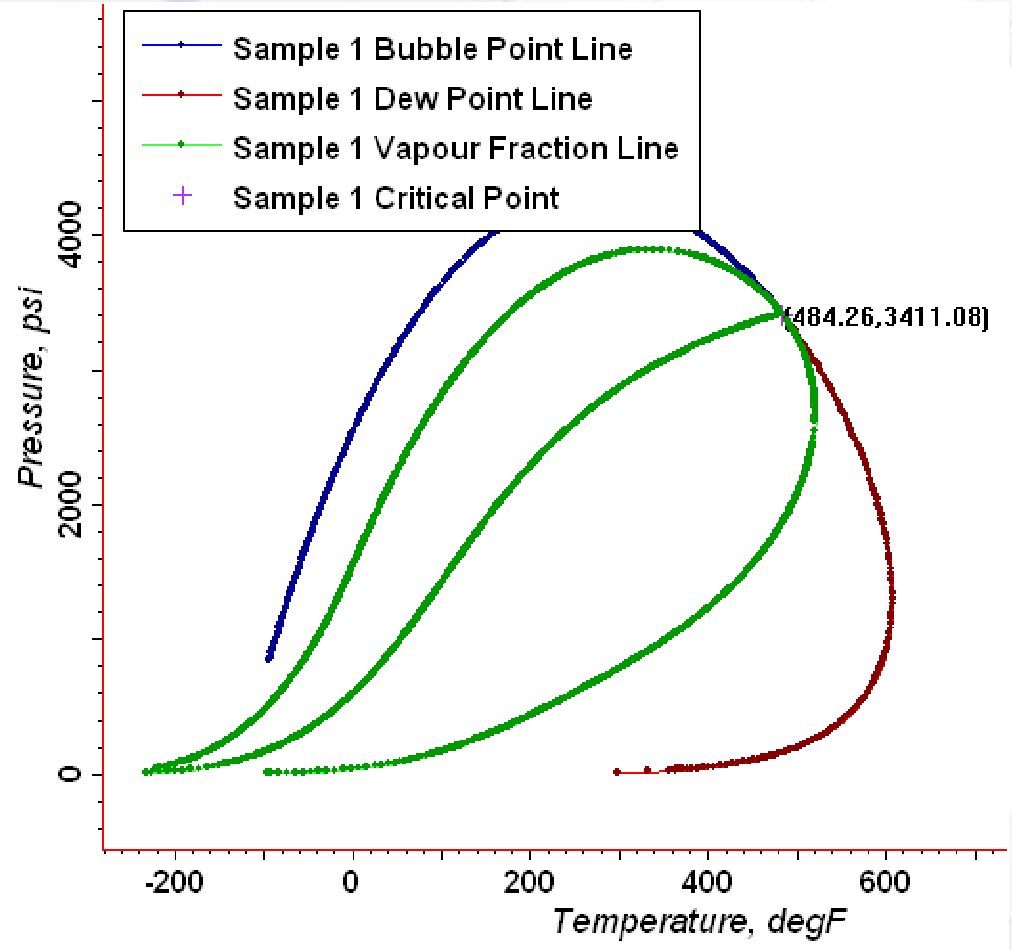
Molar densities of each hydrocarbon component

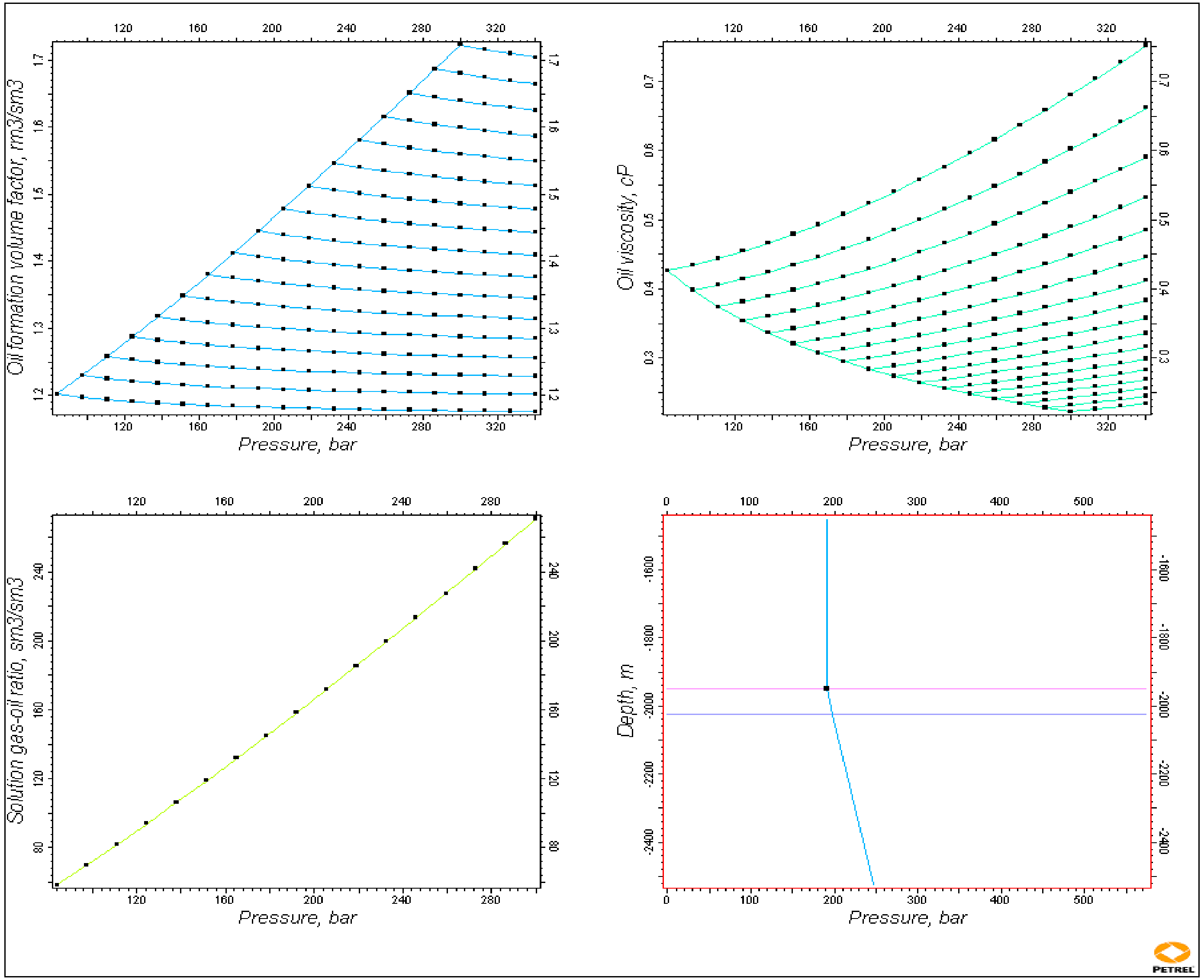
i = 1, ... N_c (molar density) instead than S_i

- **Unknowns (3 Phase System):**
  - **(N_c+2) variables per grid block**

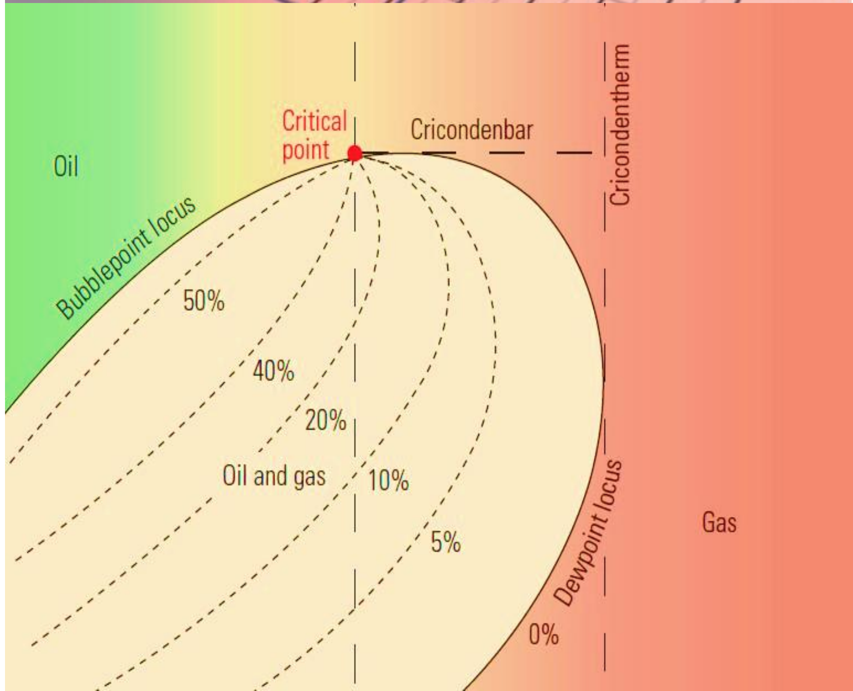
- **For instance,**
  - To model hydrocarbon fluid with (7) components then we will have (9) variables, instead of (3) in a black oil model.

Black Oil Model





Reservoir Fluid Sampling



Fluid Sampling Methods

- **Types:**
  - **Bottomhole sampling**
    - Wireline & DST sampling & production well sampling.
  - **Surface sampling**
    - Wellhead sampling
    - Separator sampling
- **Initial reservoir fluid characterization (MDT & RDT tools):**
  - **Applications of single-phase sampling (BHS)**
  - **Reservoirs above Psat (Pb & Pd)**
- **Water samples:**
  - **Aquifer sampling**
  - **Source of water: connate or breakthrough**

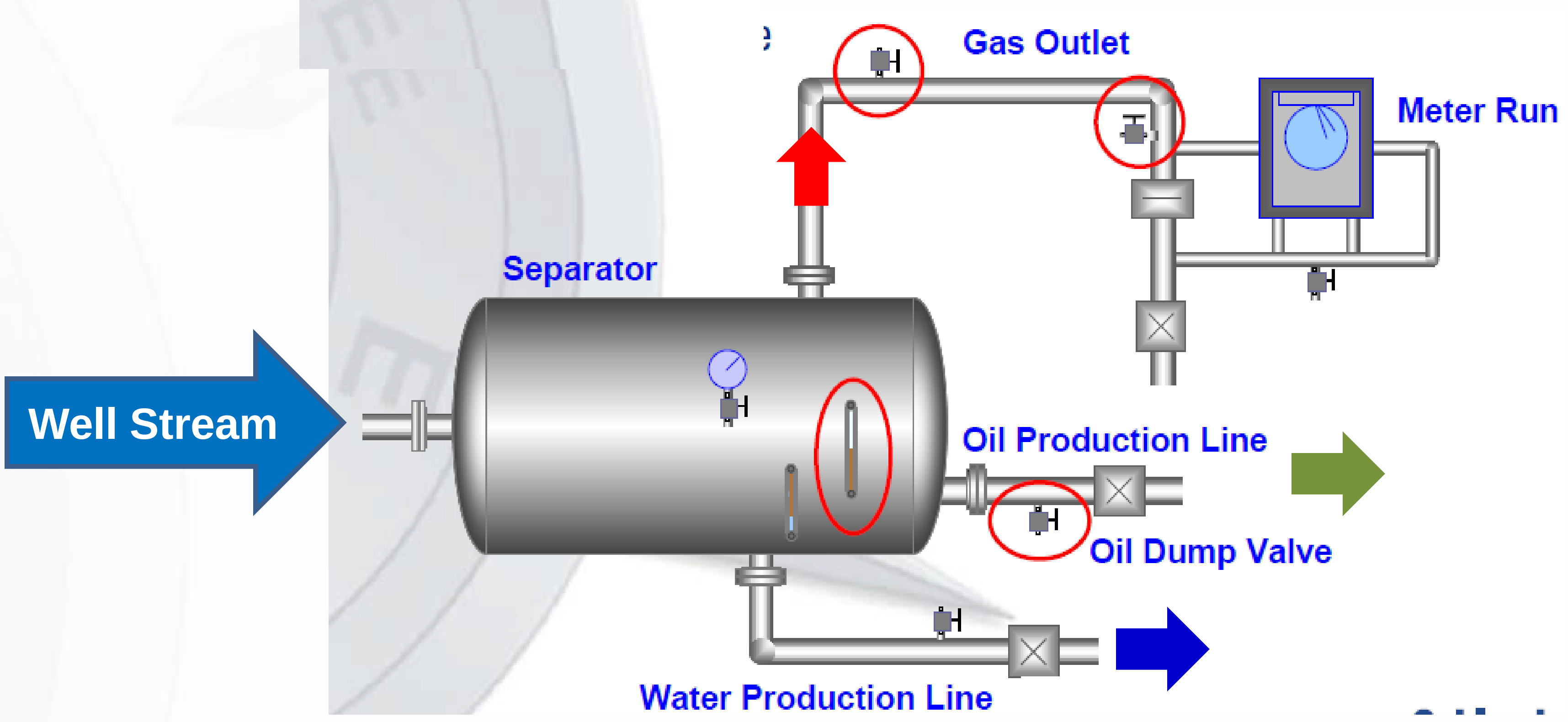
Fluid Sampling

- **Factors governing the sampling method:**
  - Volume of sample required.
  - Type of reservoir fluid to be sampled.
  - Degree of reservoir pressure depletion.
  - The mechanical condition of the well (completion design).
  - The type of available gas oil separation equipment.
- **Fluid samples, is it representative?**

1. Timing: Sample early in order to address the original/right reservoir fluid.
2. The environment: Avoid generating a two-phase condition:
   - Bubble point systems: solution gas
   - Dew point systems: condensate
   - Waxes and Asphaltene
3. Level of contamination & well conditioning

Separator Sampling Points

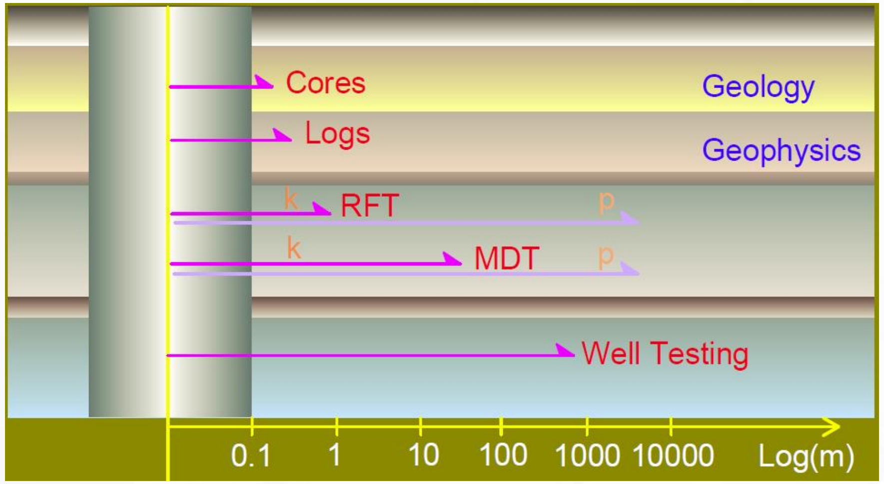
- The surface oil and gas samples are recombined in the laboratory on the basis of the producing GOR.
- In the case of two or three stage separation, the samples are taken from the high pressure separator.

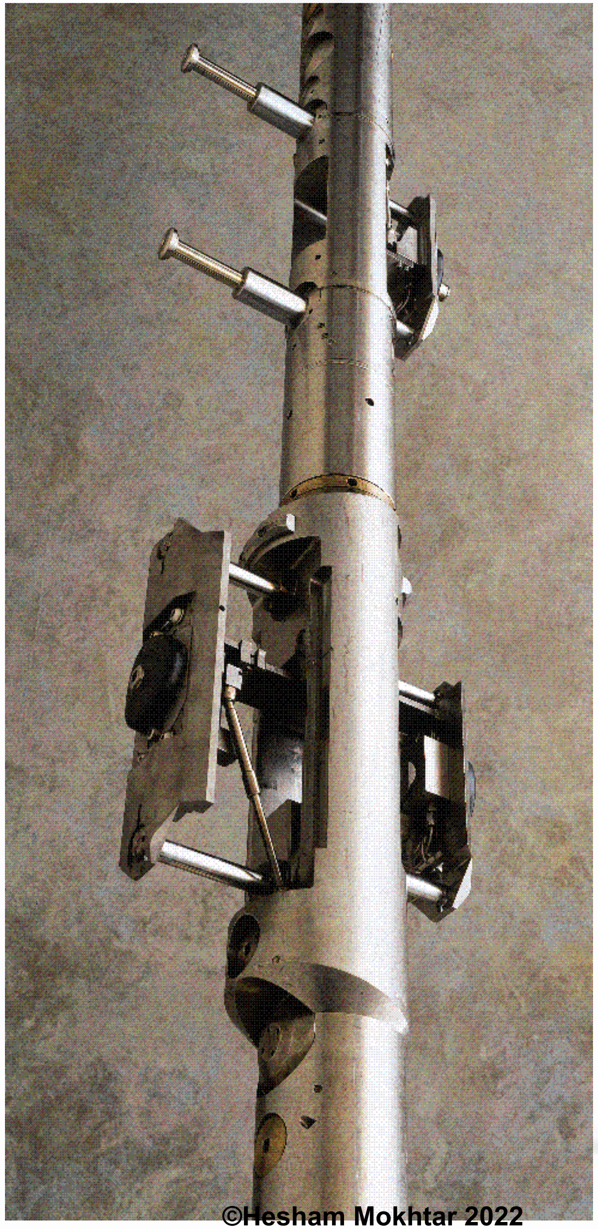


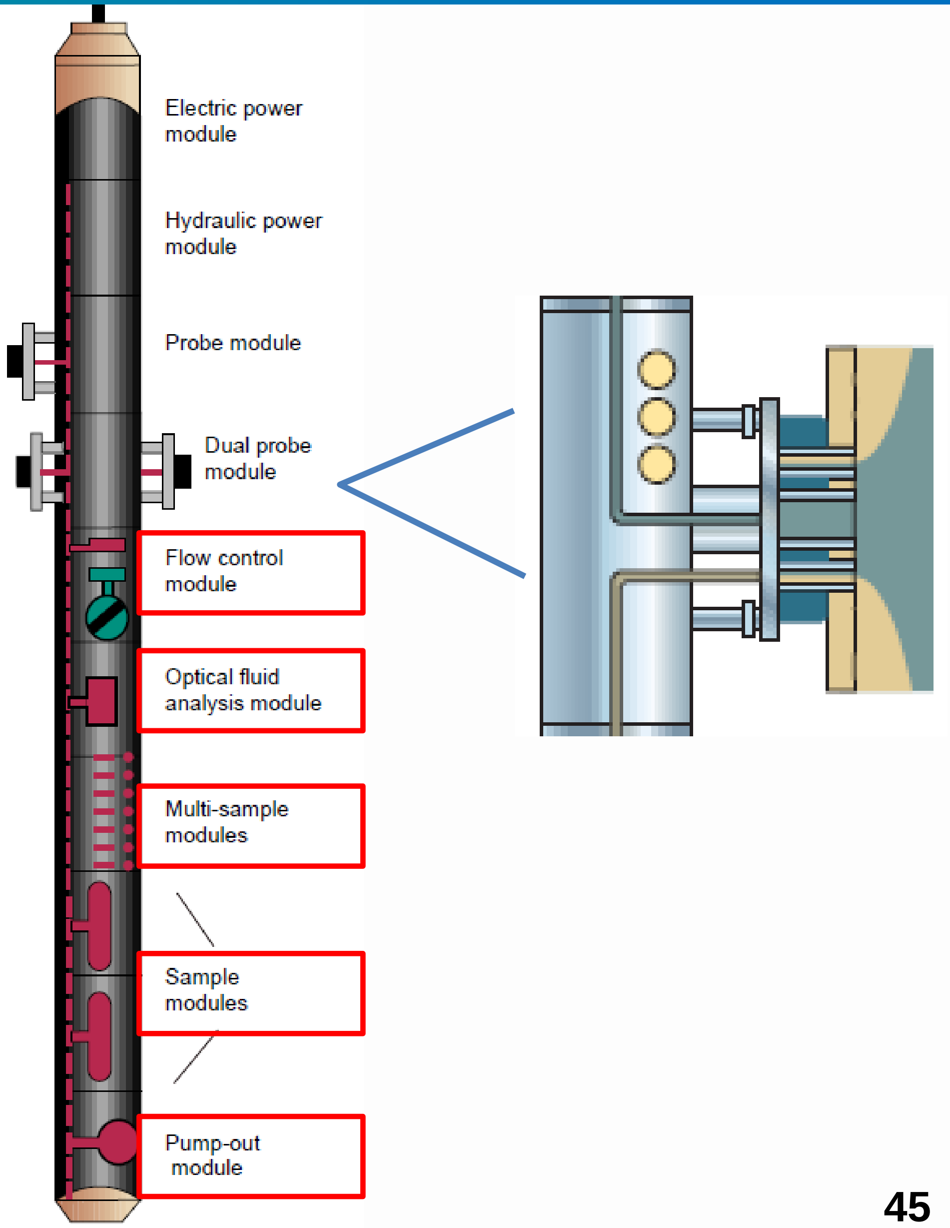
Typical Wireline Sampling Tool

MDT:
Modular Formation Dynamics Tester

Depth of Investigation

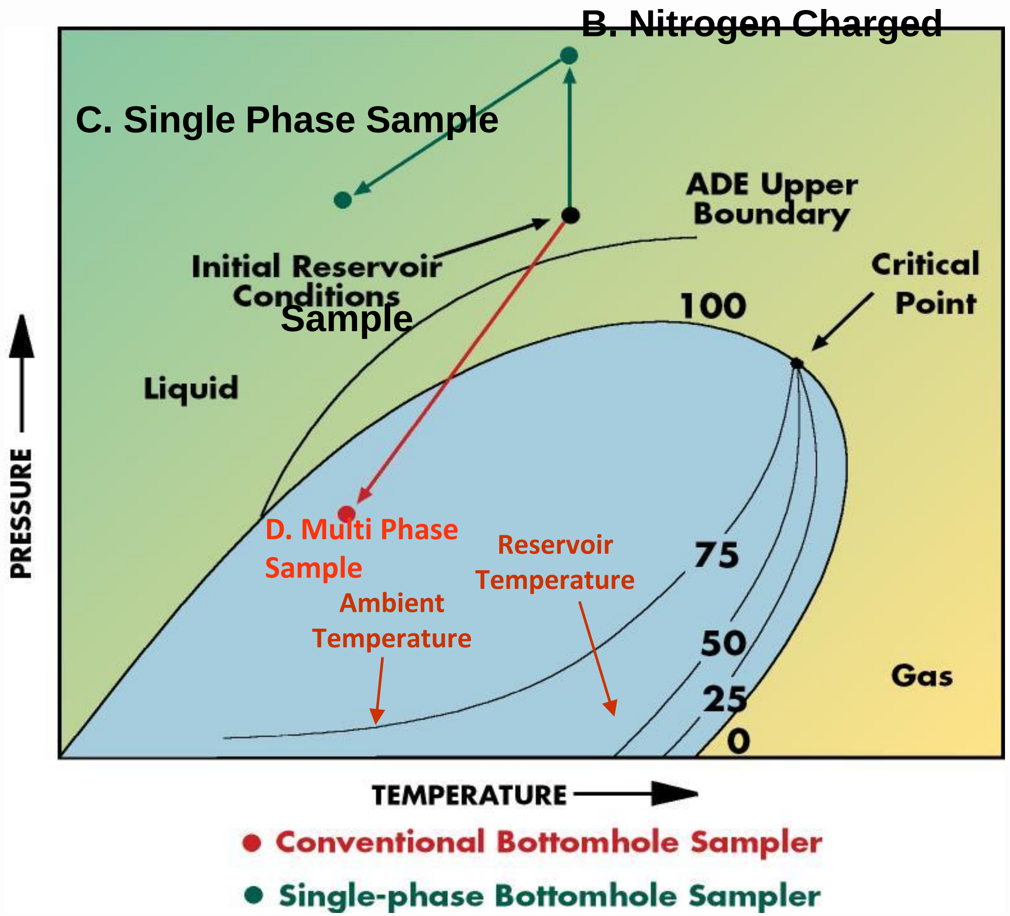






MDT Single Phase Sampling

- The sampling pressure is usually higher than the reservoir. P by almost (2500-3000) psi
- How does it work?
  - Nitrogen charge increases sample pressure above Pres, so the sample pressure will be **always** above Pb even if Pressure drops on return to surface (lower T).
- **Single-Phase Sampling?**
  - Accurate compositional and PVT analysis of formation samples requires the recovered sample to **remain** in downhole formation conditions.



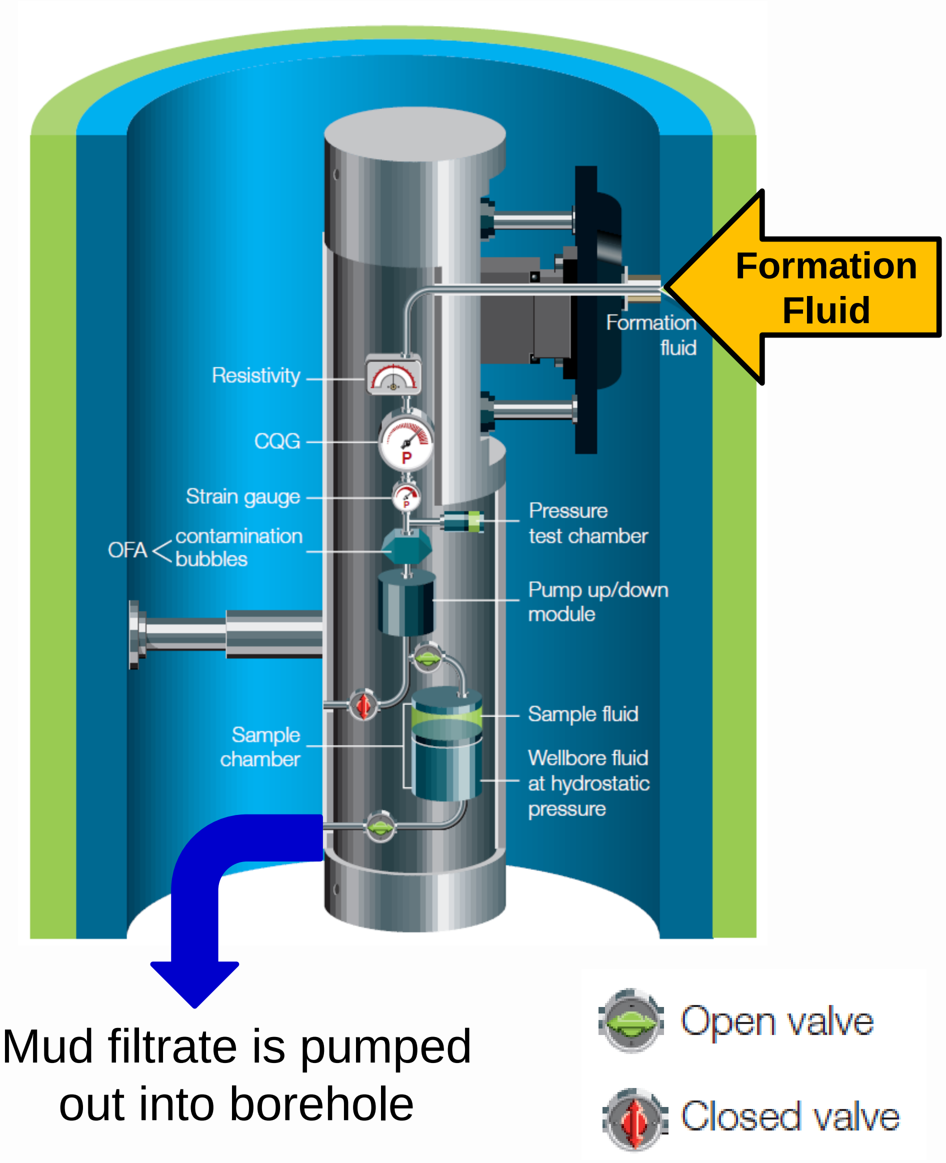
Wireline MDT Tool Configuration

- **MDT (Modular Formation Dynamics Tester) modules:**
  - **Pump-out**: To **pump** the mud filtrate from the formation until reservoir fluid is identified with the resistivity cell or OFA.
  - **Fluid Analysis (OFA & LFA)**: To **differentiate** mud filtrate, water, HC during cleanup and sampling.
  - **Multi Sample Module**: Modular Reservoir Multi-sample Module (MRMS), Has six **450 cc bottles** (SLB).

- Before the sample chamber is opened, the pump-out module flushes filtrate from the formation back to the wellbore.

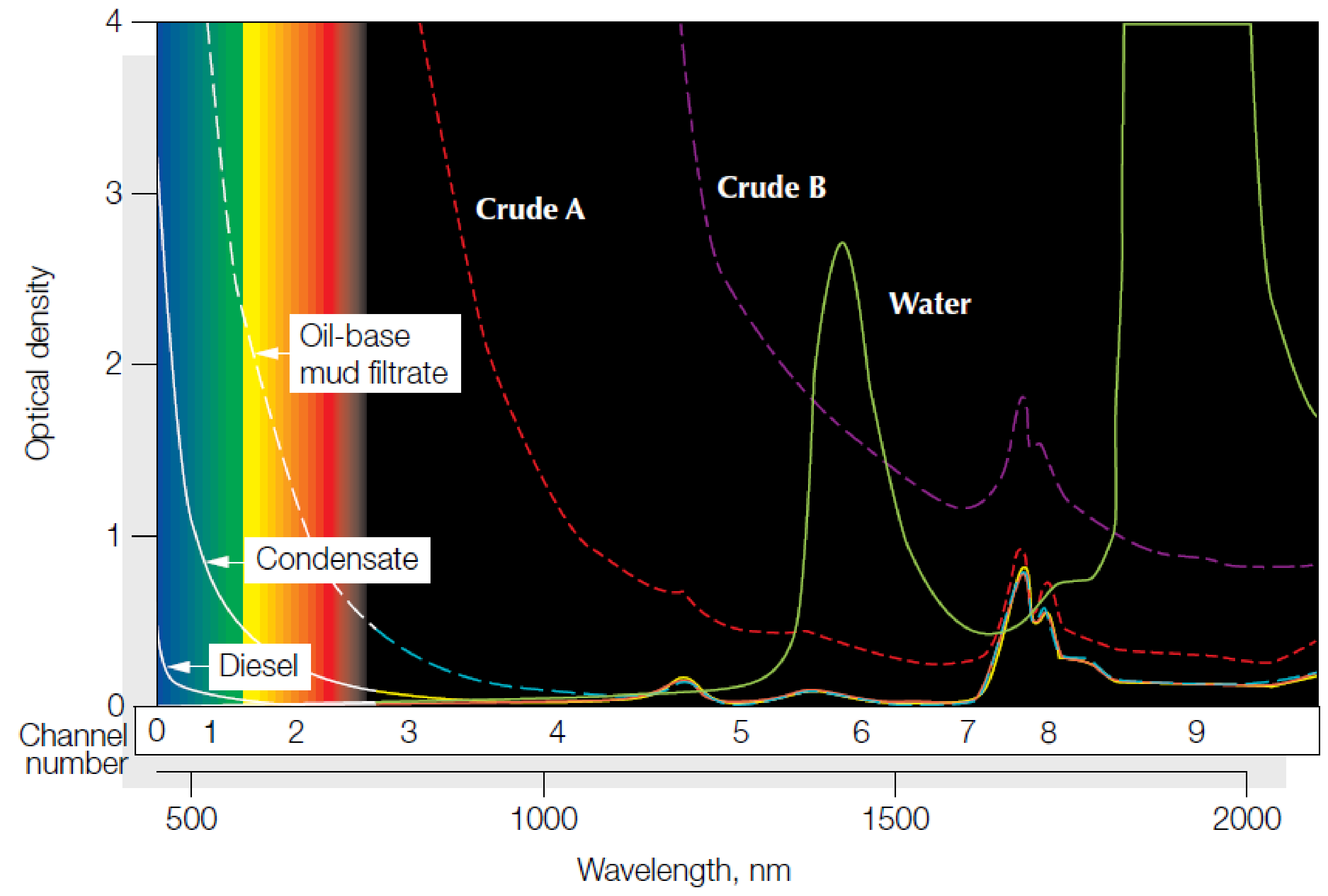
- The **flowline fluid** can be monitored using **Resistivity cell & OFA** module.

- **Once the reservoir fluid is confirmed, the fluid flow can be diverted into a sample chamber.**



Optical Properties of Wellbore Fluids

- **Water contains 2 significant absorption peaks seen in the OFA spectrometer at 1445 and 1930 nm.**
- **Oil contains a strong absorption peak at 1725 nm (this peak corresponds to exciting molecular vibrations involving hydrogen-carbon bonds).**
- Variations in the aromatic molecular components in different oils lead to differences in color—caused by increasing absorption at shorter wavelengths—that differentiate one oil from another.



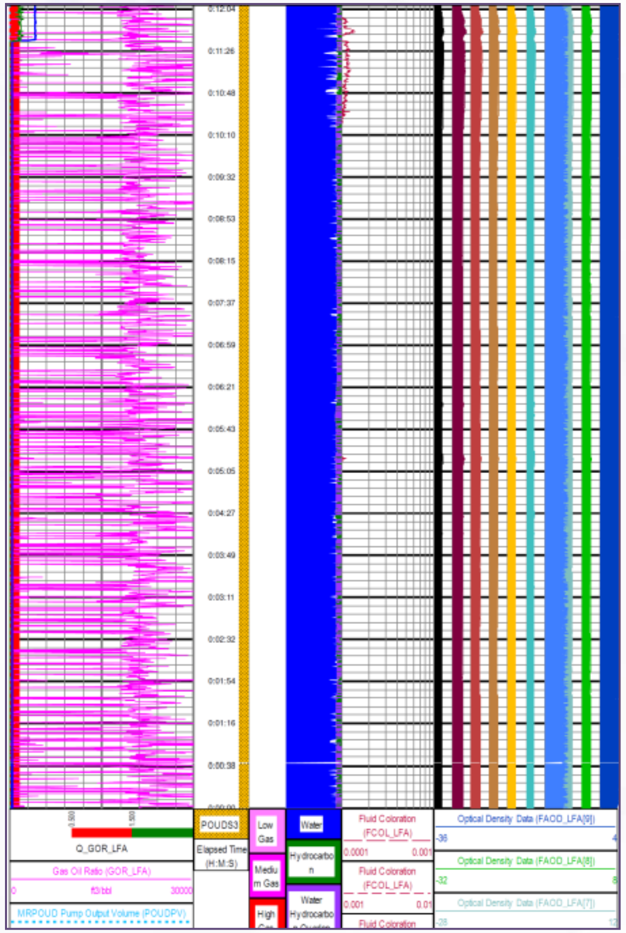
- **Oil and water can be readily differentiated by virtue of their different absorption peaks.**

Risks of Wireline Fluid Sampling

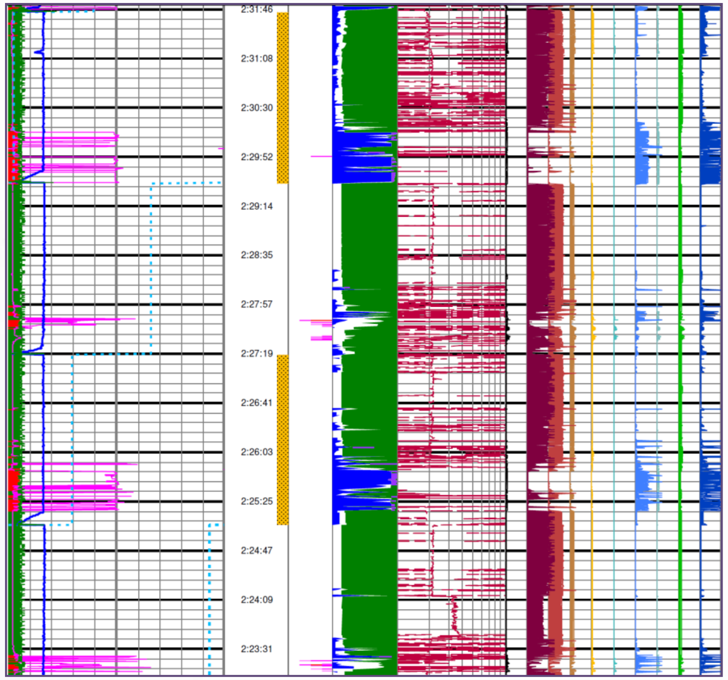
- **Pressure drawdown can change composition**
  - Gases can come out of liquids: **volatile oils**
  - Liquids can come out of gases: **condensates**
  - Solids can come out of liquids: **Asphaltene, waxes**

- **Mud filtrate can add extra ingredients to composition**
  - Significant WBM filtrate might be tolerable in and oil sample
  - Worst case: OBM filtrate in liquid which drops out of a condensate

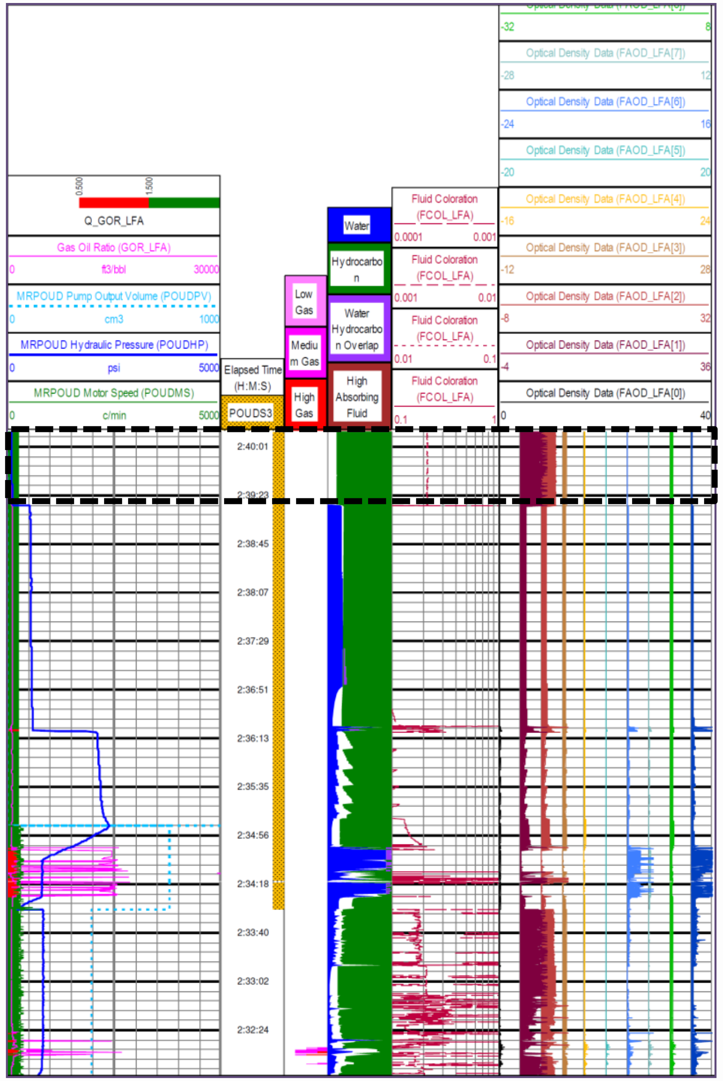
MDT Tool OFA Log Example



1 At the start of pump-out

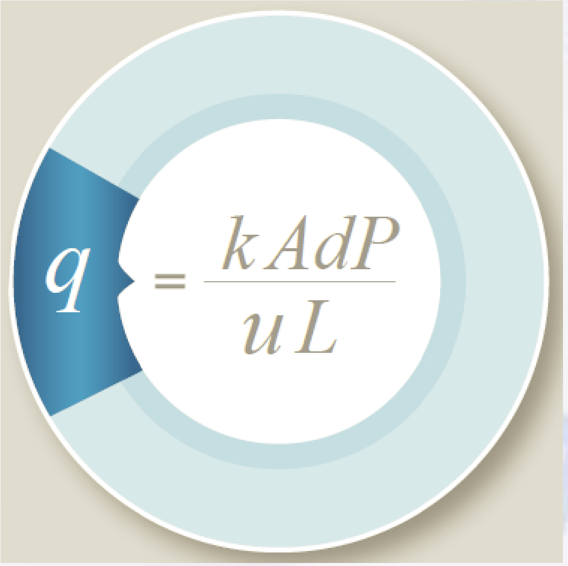


2 While pumping-out

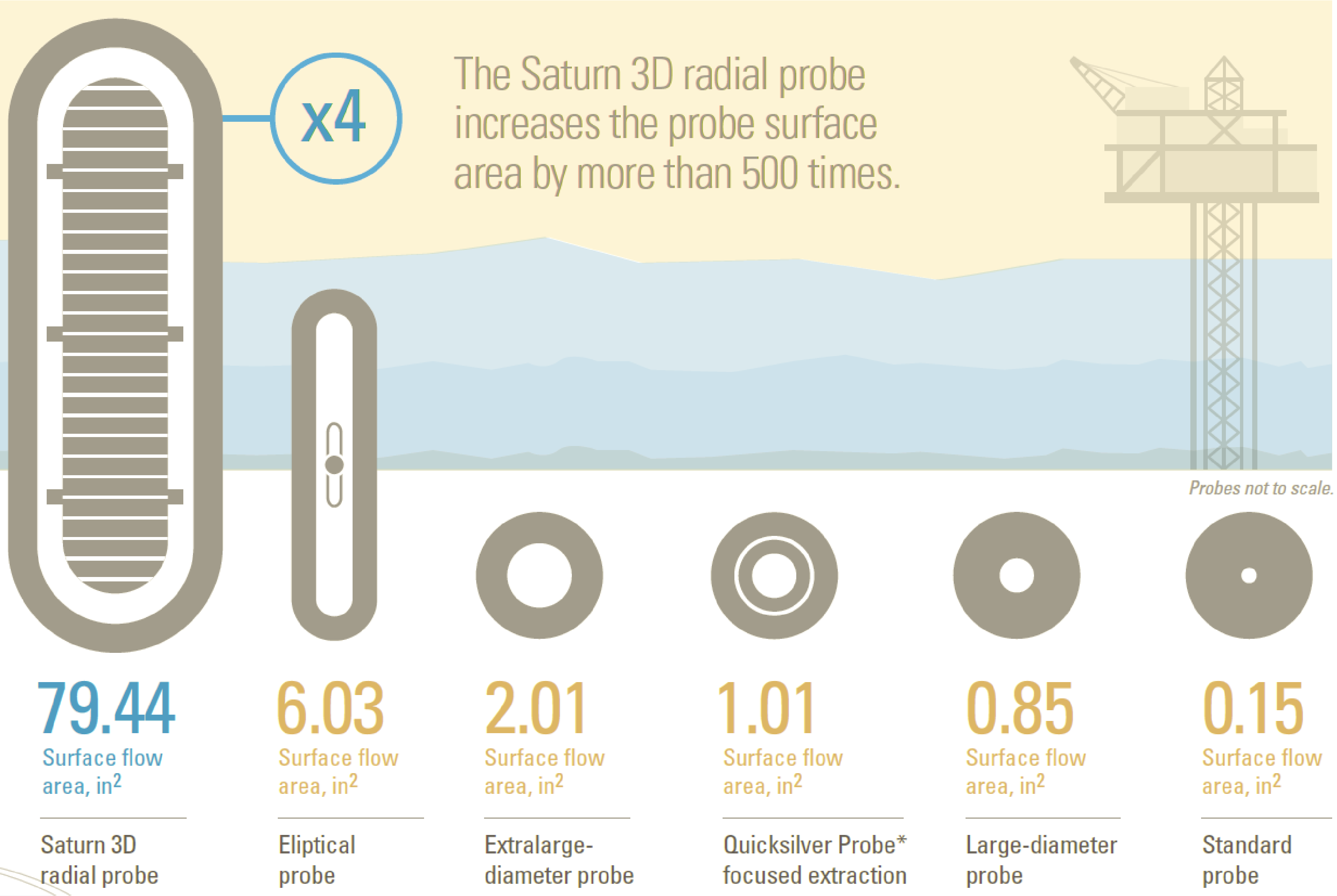


3 While sampling

Comparison Between Different Probes



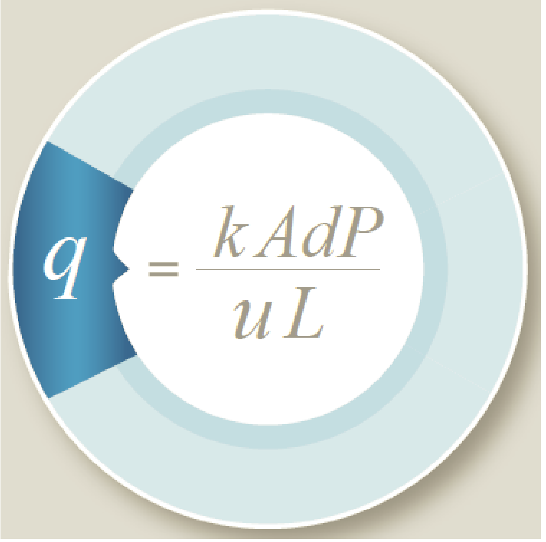
$$q = \frac{k\,A\,dP}{u\,L}$$

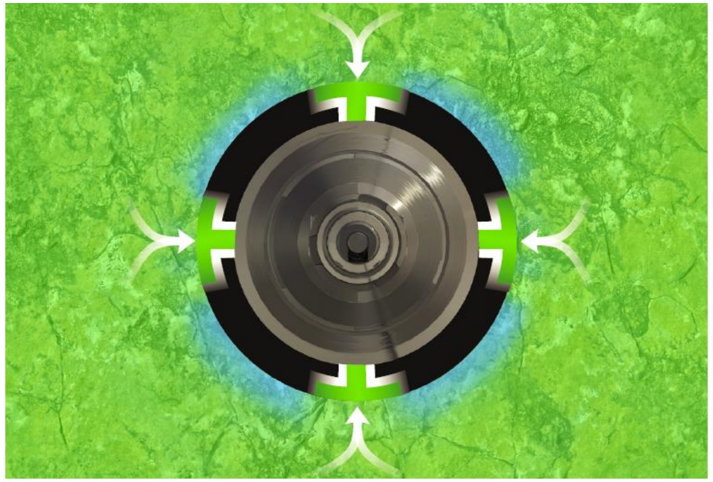


Saturn 3D Radial Probe

- It establishes and maintains true **3D circumferential flow in the formation around the borehole.**
- Enabling highly accurate pressure measurement, downhole fluid analysis, sampling, and permeability estimation in challenging conditions for conventional wireline formation testing:
  - Extremely low-permeability
  - Unconsolidated formations
  - Heavy oil or near-critical fluid types
- The Saturn probe's fast setting and retracting times.
- **Largest flow area of 79.44 in^2 facilitate efficient operations across a wide permeability range in a single trip.**

Each self-sealing port incorporates a filter to capture any dislodged matrix and prevent plugging.



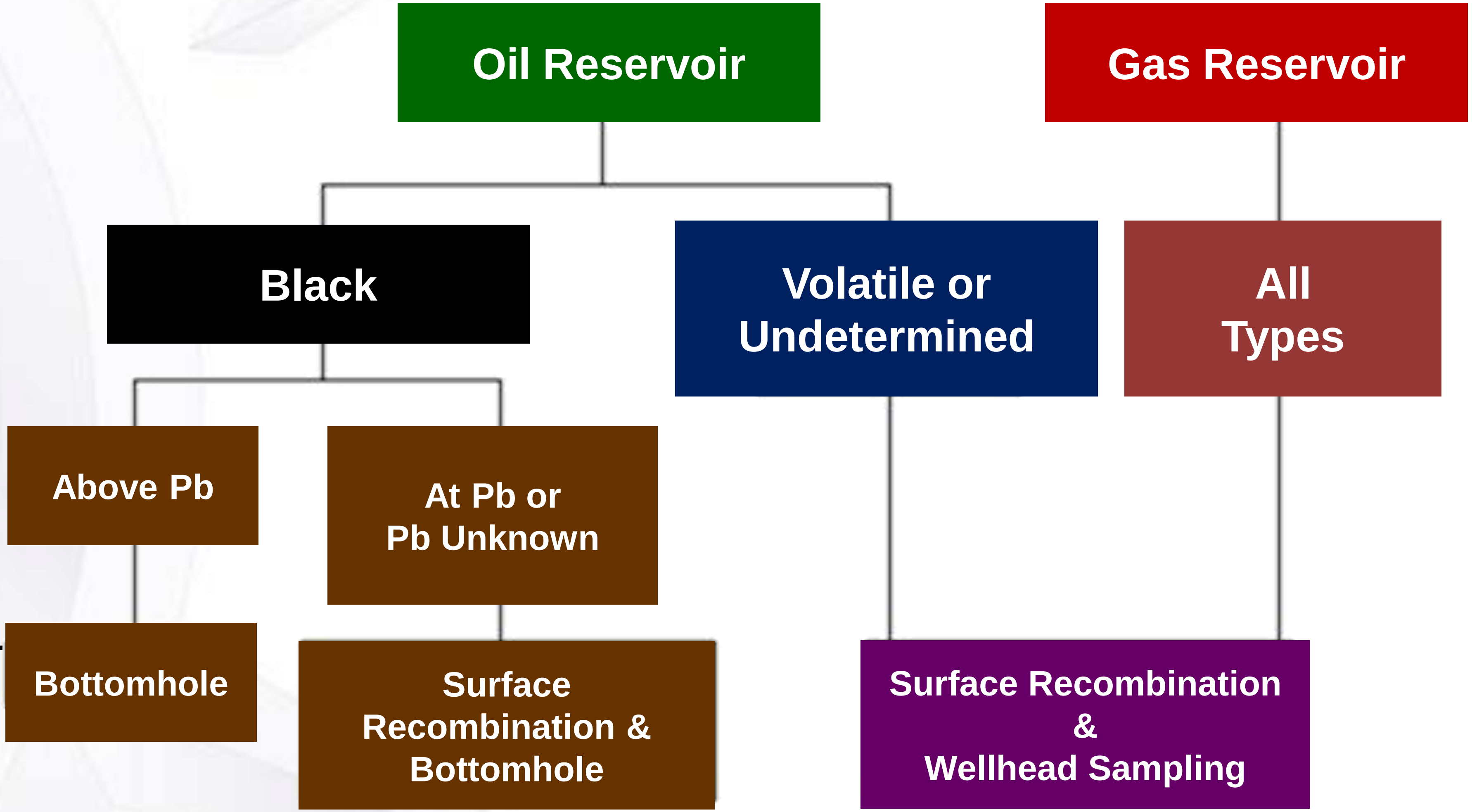


The four Saturn ports efficiently establish circumferential flow from the formation to quickly remove filtrate-contaminated fluid and flow uncontaminated, representative fluid for DFA, sampling, and pressure measurements.

Sampling Techniques Choice Diagram

Factors affecting fluid sampling

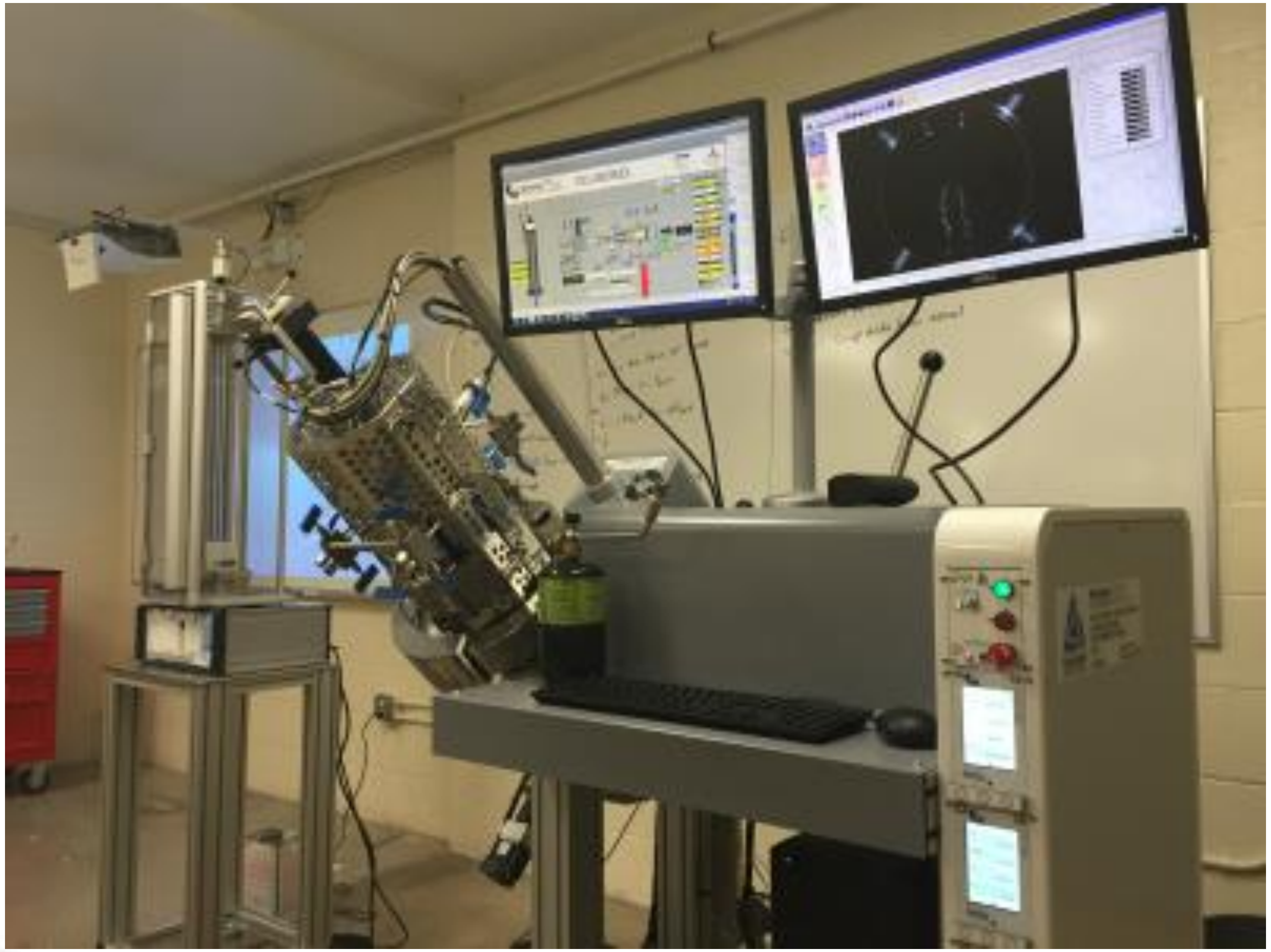
- **Type of sample**
  - Bottom Hole/Surface
- **Sampling conditions**
  - Stability of Pressure, Temperature, and Flow rate
  - Mixture of Fluids
- **Laboratory and equipment**
  - Leakage during Transfer / Transport, Calibration, Sample Size, Selection, Recombination Ratio, Variation of Techniques, etc.



Laboratory PVT Experiments

The Major Laboratory Procedures

- **All are performed after the validity check:**
  1. Compositional measurement (Xi & Yi)
  2. Flash vaporization (CCE/FV)
  3. Differential vaporization (DL/DV)
  4. Separator tests (SEP)
  5. Oil viscosity measurement (VIS)



Validity Check

- The sample is heated to reservoir T, **agitated** and **allowed to stabilization**.
- The opening pressure, air content, hydrocarbon liquid, and water were determined.
- **The samples are valid, even if we have a small amounts of mud filtrate associated.**

Validity Check for BHS

No	Cylinder Number	Depth, m	Fluid Type	Reservoir P, Psia	Reservoir T, F	Laboratory opening P at reservoir T, Psia
1	2253	1813.9	Water	2257.68	164.05	2242
2	2655	1810	Oil	2111.96	166.28	2098
3	4304	1692.9	Gas	1810.39	161.24	1750

PVT Analysis Workflow

Black Oil:

- Pressure Volume (P-V) relationship, Differential Vaporization (DV) experiments, pressurized viscosity determinations and separator (SEP) test analysis.

Volatile Oil:

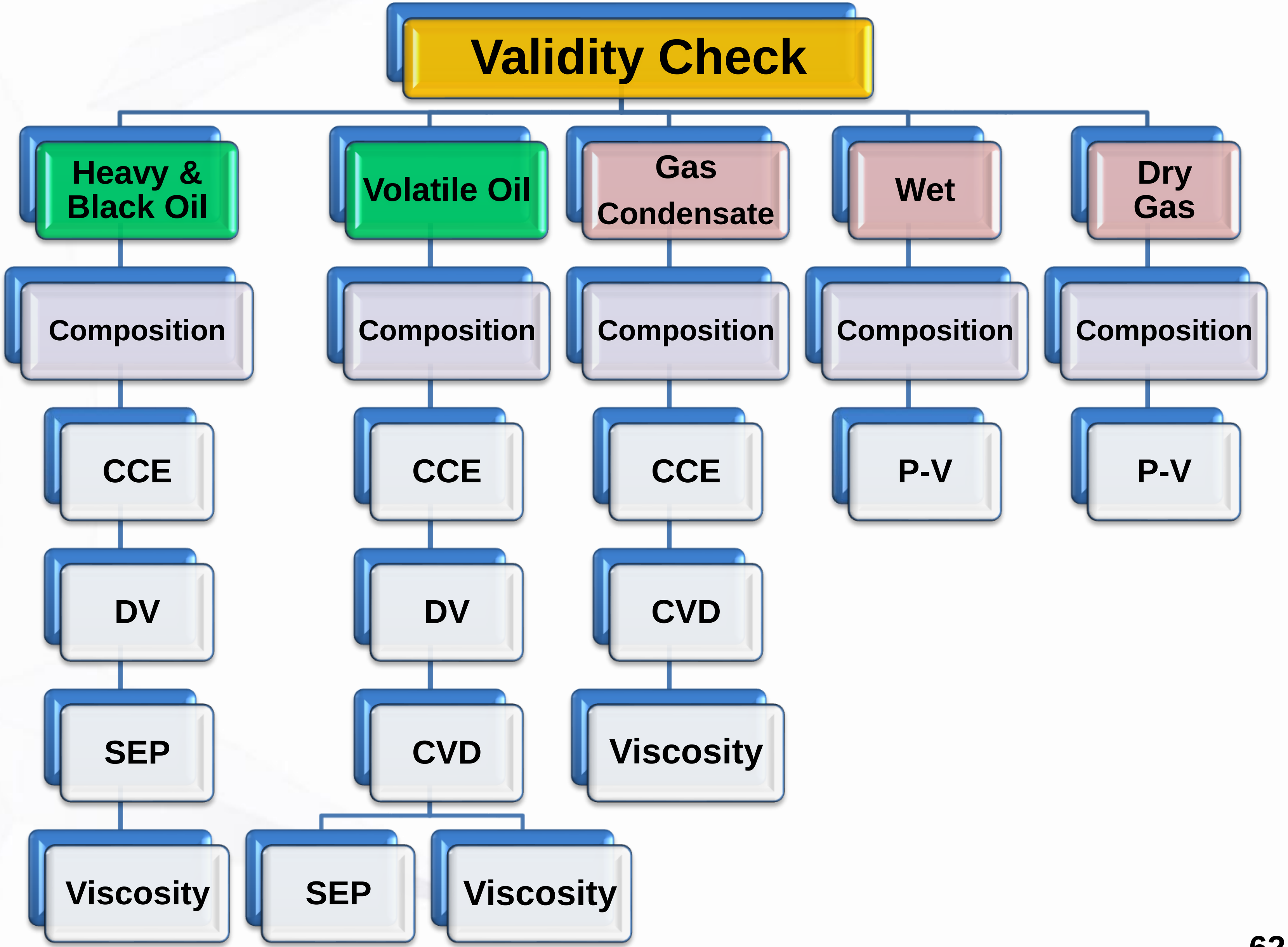
- Constant Composition Expansion (CCE) measurement, while Constant Volume Depletion (CVD) is optional.

Gas Condensate:

- CCE & CVD measurements.

Dry & Wet gases:

- CCE (P-V) measurements is intended not to find out the saturation pressure (Pd), but it's designed to calculate **Z-factor** and **Bg.**



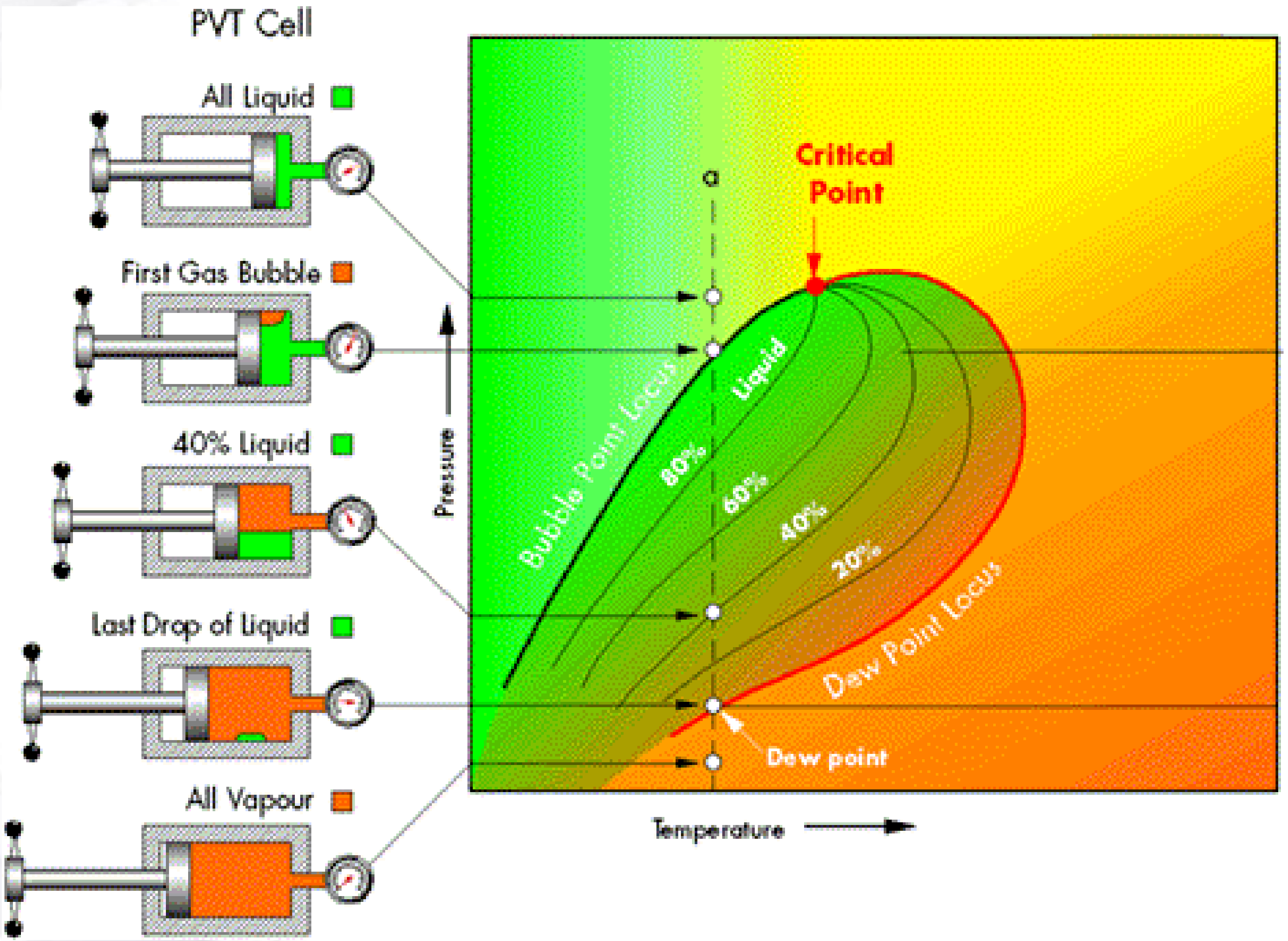
Hydrocarbon Classifications

- **Defined 7 types of fluid systems:**

1. Bitumen
2. Tar or Heavy oil
3. Low shrinkage oil or black oil
4. High shrinkage oil or volatile oil
5. Retrograde condensate gas
6. Wet gas
7. Dry gas

Typical P-T Phase Diagrams (Envelope)

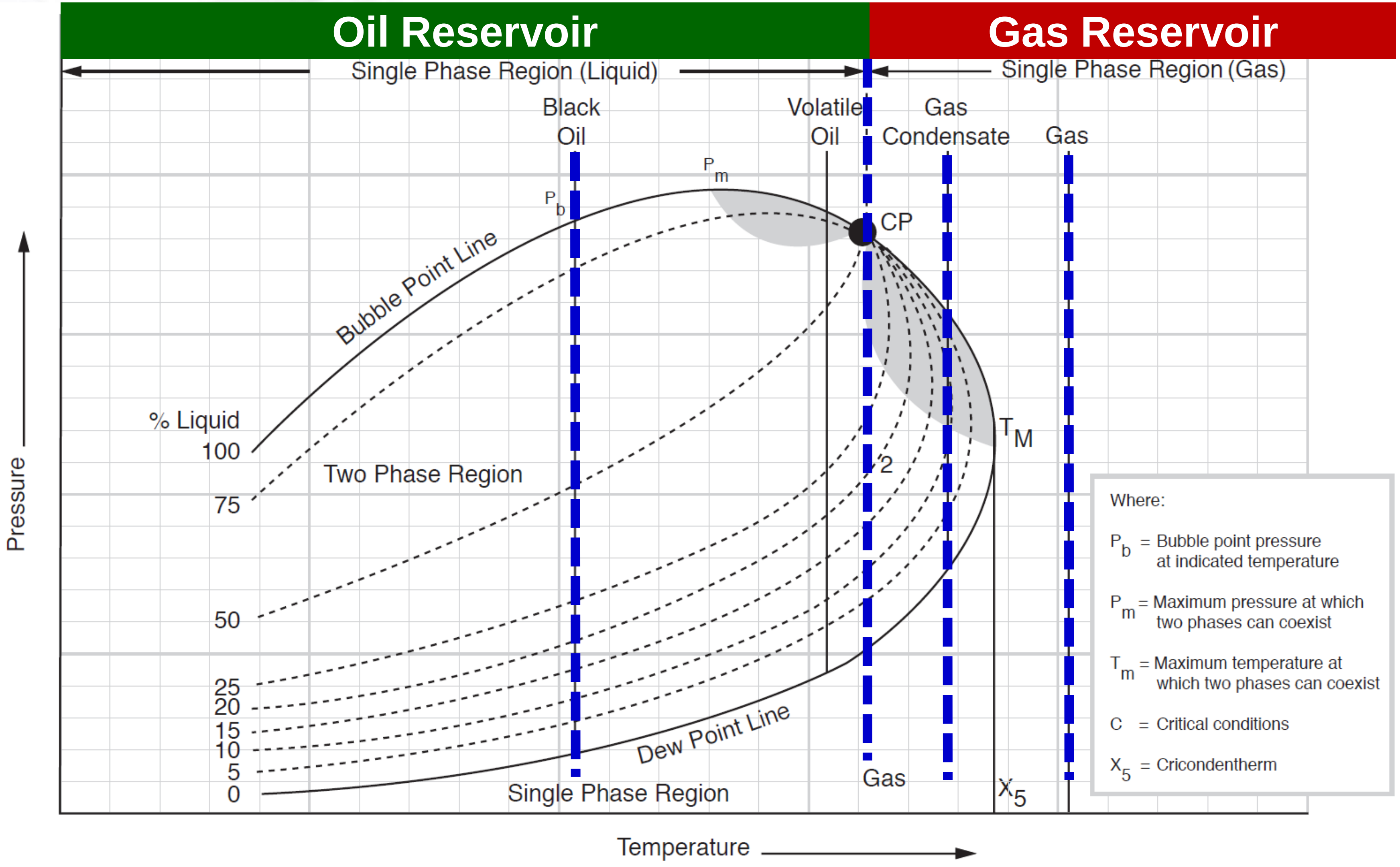
- The study of reservoir fluid under varying conditions (**P**ressure, **V**olume, and **T**emperature)
- **Considering the reservoir as an isothermal system**, T is normally held constant @ reservoir T.
- Depletion vs. volume, while measuring of:
  - **Physical properties (Oil FVF, Density, Viscosity, GOR, etc.)**
  - **Composition (vapor and liquid)**



Schematic PT & PV diagram for a reservoir fluid system.

Reservoir Fluid Types

- A reservoir with T less than the critical point is defined as an **oil reservoir**.
- A reservoir with T between the critical temperature and the cricondentherm is defined as a **gas condensate reservoir.**
- If reservoir temperature is higher than the cricondentherm then the reservoir is defined as a **gas reservoir.**



The Five Reservoir Fluids

Black Oil

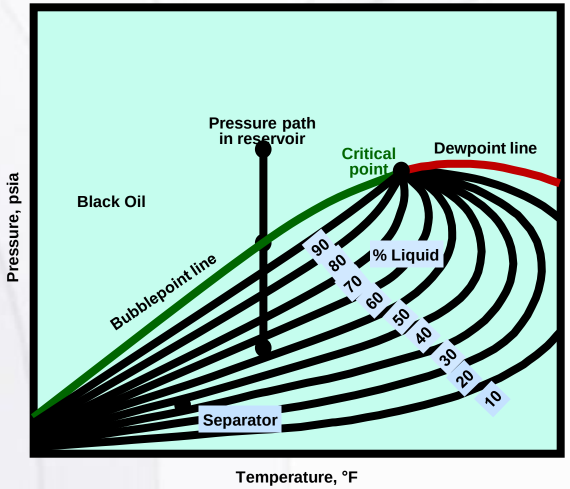
Volatile Oil

Retrograde Gas

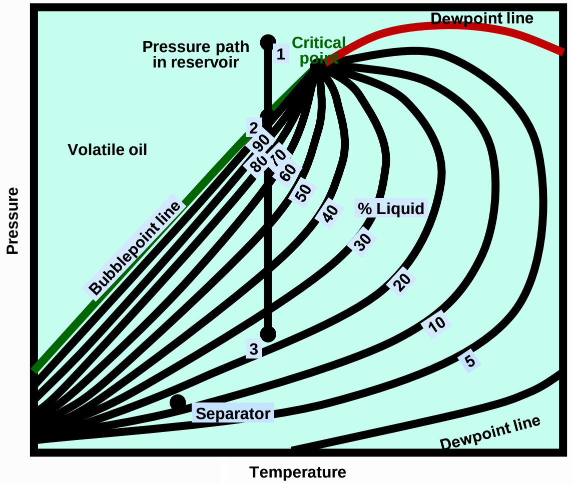
Wet Gas

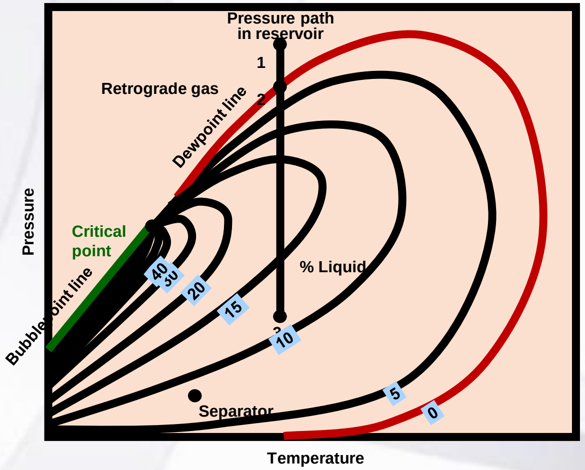
Dry Gas

Black Oil

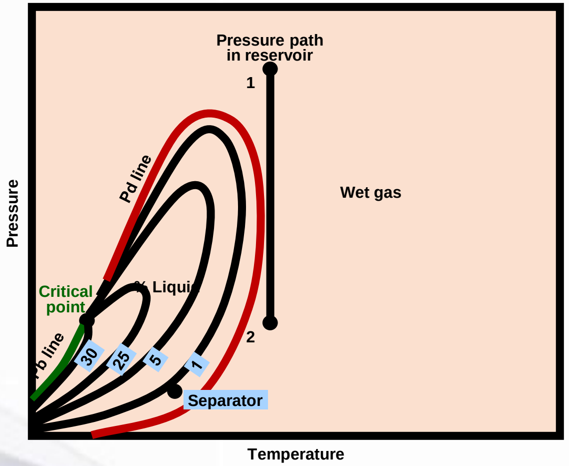


Volatile Oil

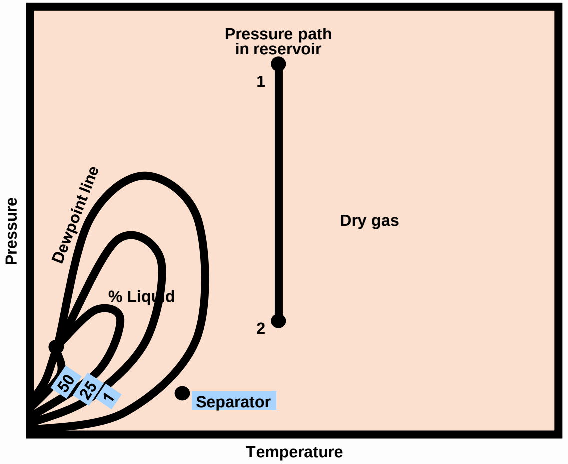




Retrograde Gas



Wet Gas



Dry Gas

Categories of Reservoir Hydrocarbons

- The standard components quantified in petroleum reservoir fluids include:
  1. Non-Hydrocarbons N2 CO2 H2S
  2. Hydrocarbons C1 C2 C3 to C7+ or C20+

Component/Property	Dry Gas	Wet Gas	Condensate	Volatile Oil	Black Oil
CO_2	0.10	1.41	2.37	1.82	0.02
N_2	2.07	0.25	0.31	0.24	0.34
C_1	86.12	92.46	73.19	57.60	34.62
C_2	5.91	3.18	7.80	7.35	4.11
C_3	3.58	1.01	3.55	4.21	1.01
iC_4	1.72	0.28	0.71	0.74	0.76
nC_4	—	0.24	1.45	2.07	0.49
iC_5	0.50	0.13	0.64	0.53	0.43
nC_5	—	0.08	0.68	0.95	0.21
C_{6s}	—	0.14	1.09	1.92	1.16
C_{7+}	—	0.82	8.21	22.57	56.40
GOR (SCF/STB)	∞	69,000	5965	1465	320
CGR (STB/MMSCF)	0	15	165	680	3125
γ_{API}	—	65.0	48.5	36.7	23.6
M_{7+}	—	132	184	240	274
γ_{7+}	—	0.750	0.816	0.864	0.920

Reservoir Fluid Identification

- The **1,750 scf/STB** break between black & volatile oils is not sharp - could be **±250** scf/STB
- The **20 mole%** C7+ break between black & volatile oils is not sharp - could be **±2.5%.**

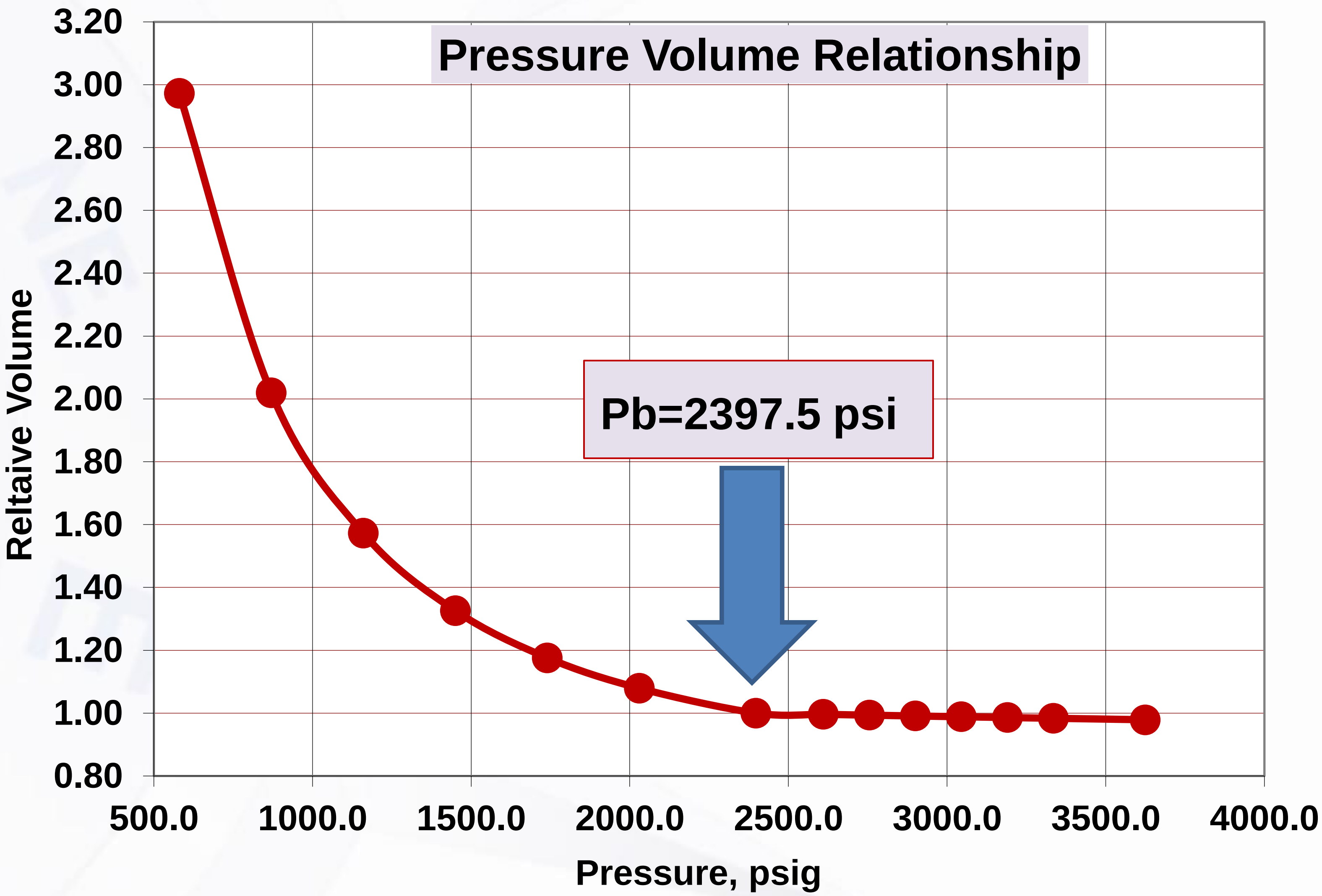
Production

	Black Oil	Volatile Oil	Retrograde Gas	Wet Gas	Dry Gas
Initial Producing GOR, scf/STB	<1750	1750 to 3200	> 3200	> 15,000*	100,000*
Initial ST Liquid Gravity, °API	< 45	> 40	> 40	Up to 70	No Liquid
Color of ST Liquid	Dark	Colored Brown	Lightly Colored	Water White	No Liquid

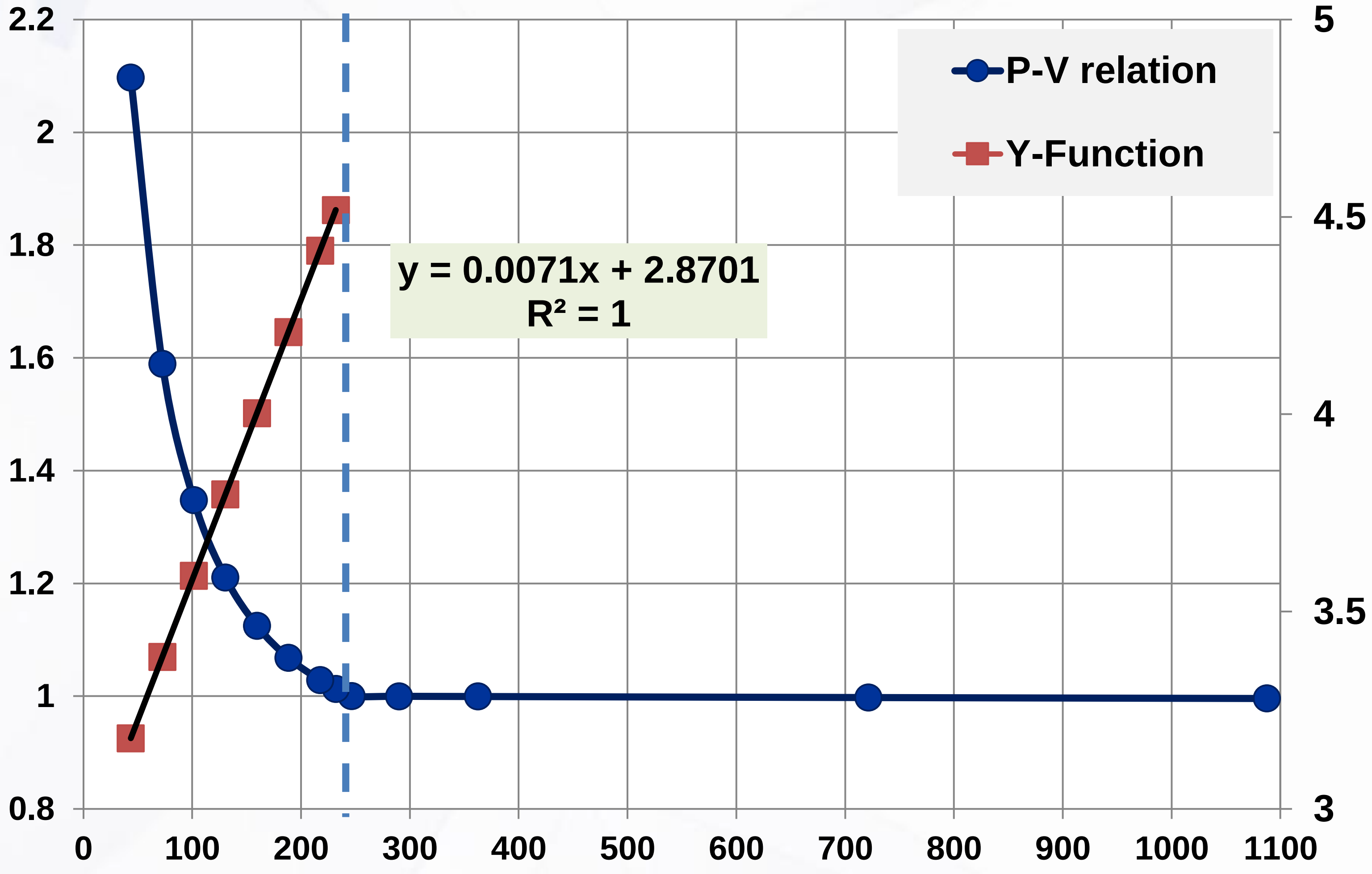
Laboratory

Phase Change in Reservoir	@ Pb	@ Pb	@ Pd	No Phase Change	No Phase Change
C7+, Mole %	> 20%	20 to 12.5	< 12.5	< 4*	< 0.8*
B_{ob} ,rb/STB	< 2.0	> 2.0	-	-	-

Actual Black Oil CCE Data



Actual Heavy Oil CCE Data



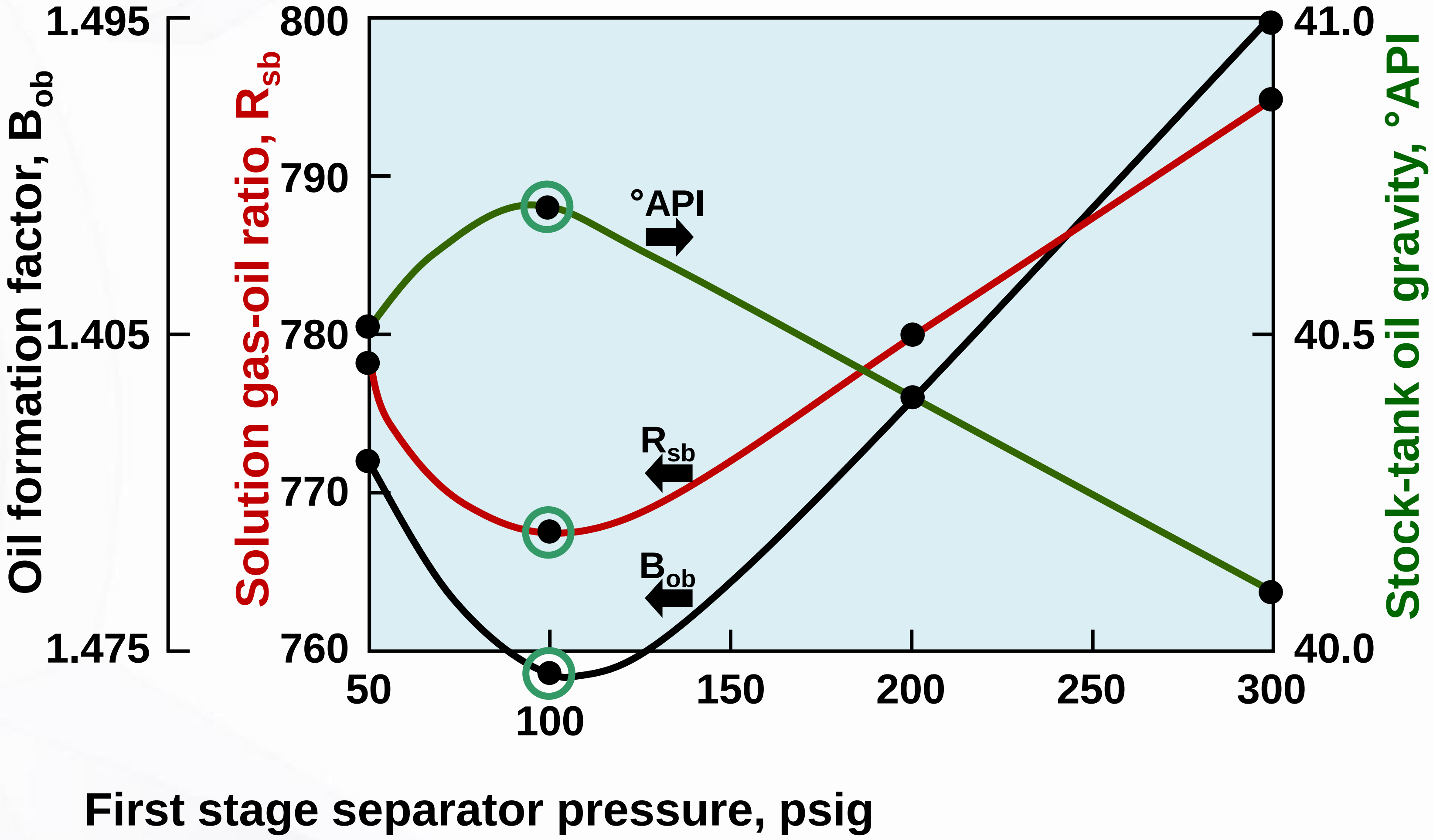
Flash GOR, SCF/STB	51.13
Bubble Point Pressure, psi	246.50
Reservoir Pressure, psi	721.52
Reservoir Temperature, ºF	136.56
Differential GOR, SCF/STB	59.82
Density, g/cc	0.94571
F.V.F, bbl/STB (at Pb)	1.04944
API for ST Oil	13.23

C1=5.034 Mole % & C7+=84.31 Mole %

Results of Separator Tests

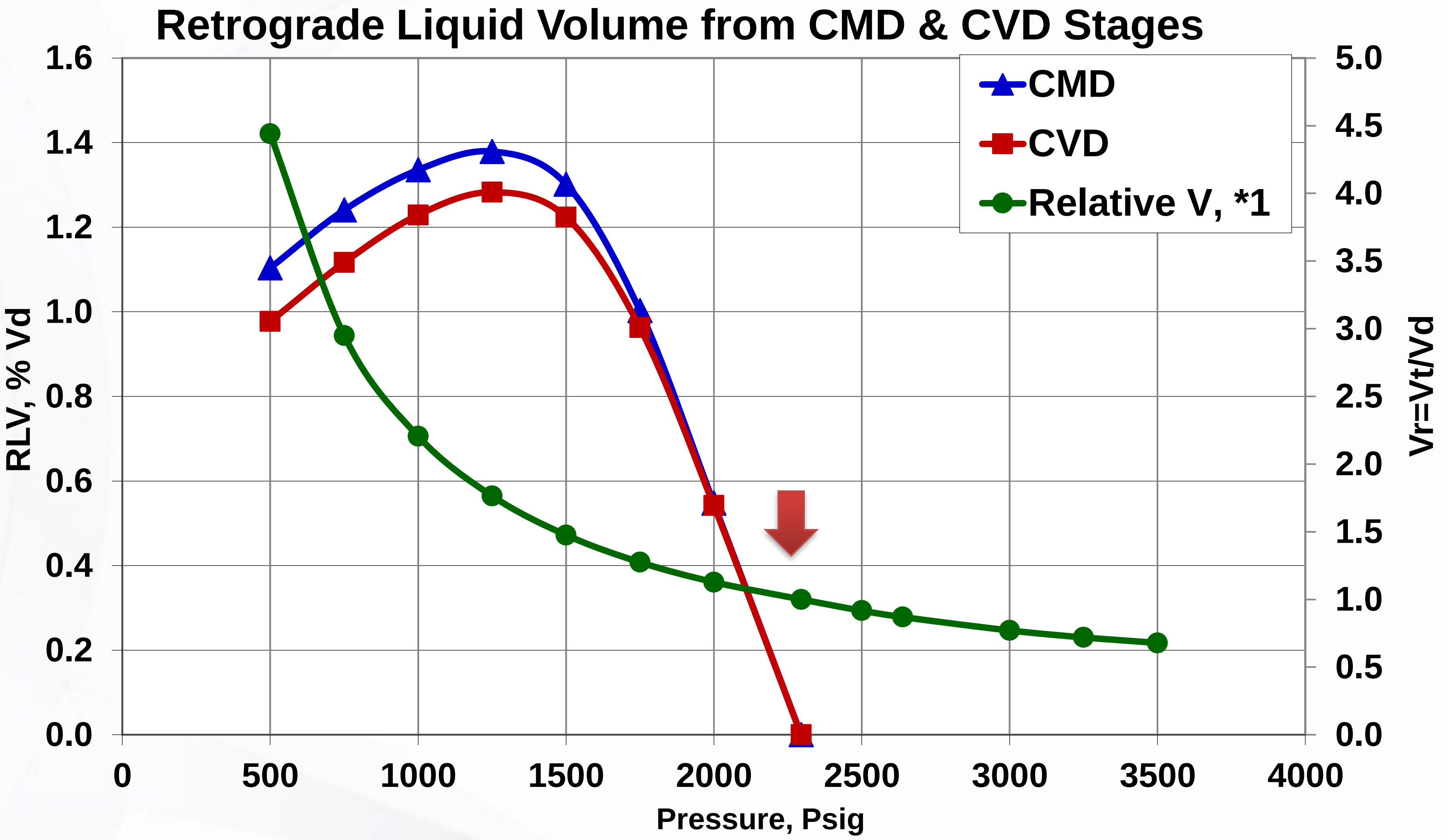
- The objective of SEP is to determine the effect of separator **P & T** **on Bo & Rso, API, to introduce the optimum SEP conditions that give the maximum Liquid recovery & max. API at Stock-tank.**

- Separator tests are used are in **combination with FV & DL** tests to provide the **adjusted Bo & Rso** over a full pressure range above and below Pb.



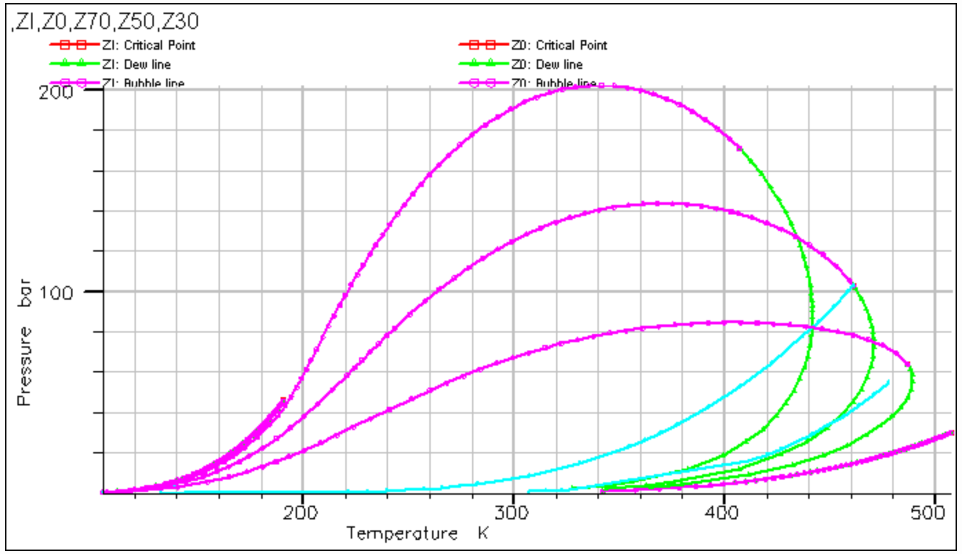
Retrograde Liquid Volume from CMD & CVD

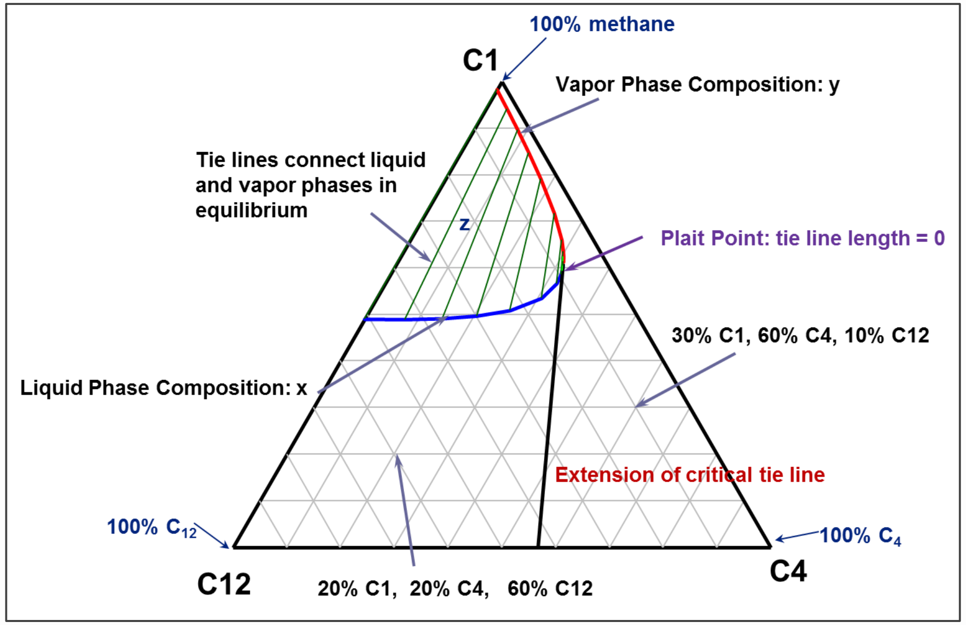
- For gas condensates, No distinct change in slope occurs at the dew point.
- The dew point is obtained by observation of the condensation on the window of the PVT cell.



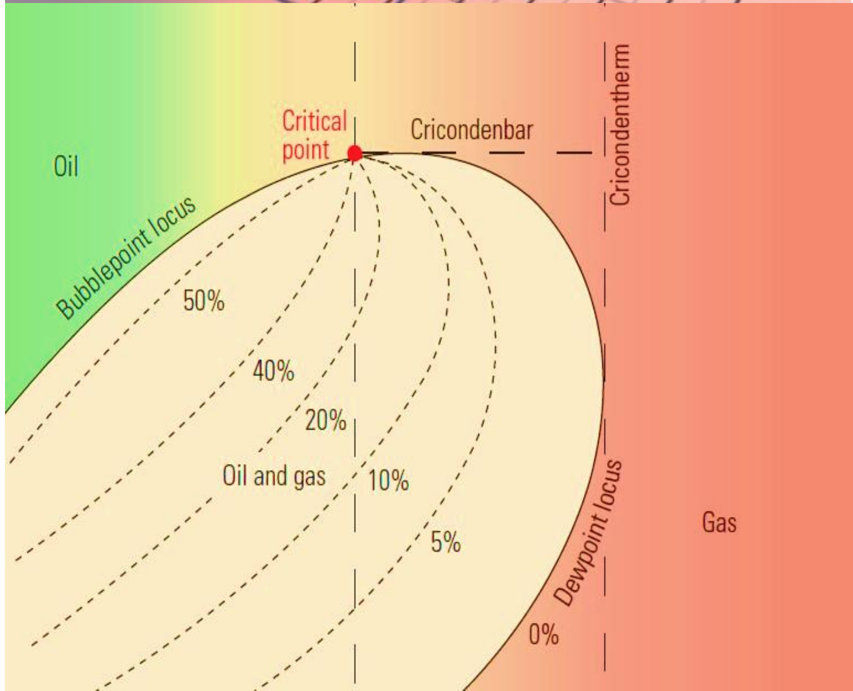
Phase vs. Ternary Diagram

- Both phase and ternary diagrams shows **shape** and **size of two-phase region.**
- **Phase Plot:**
  - ❑ **Fixed composition** and is a function of pressure & temperature
- Ternary Plot:
  - ❑ **Fixed pressure & temperature** and is a function of composition.
  - ❑ Ternary Diagram - graphical display of 3 component groupings: light, intermediate and heavy component mixtures
  - ❑ Mainly used for analysis of **MISCIBILITY**.



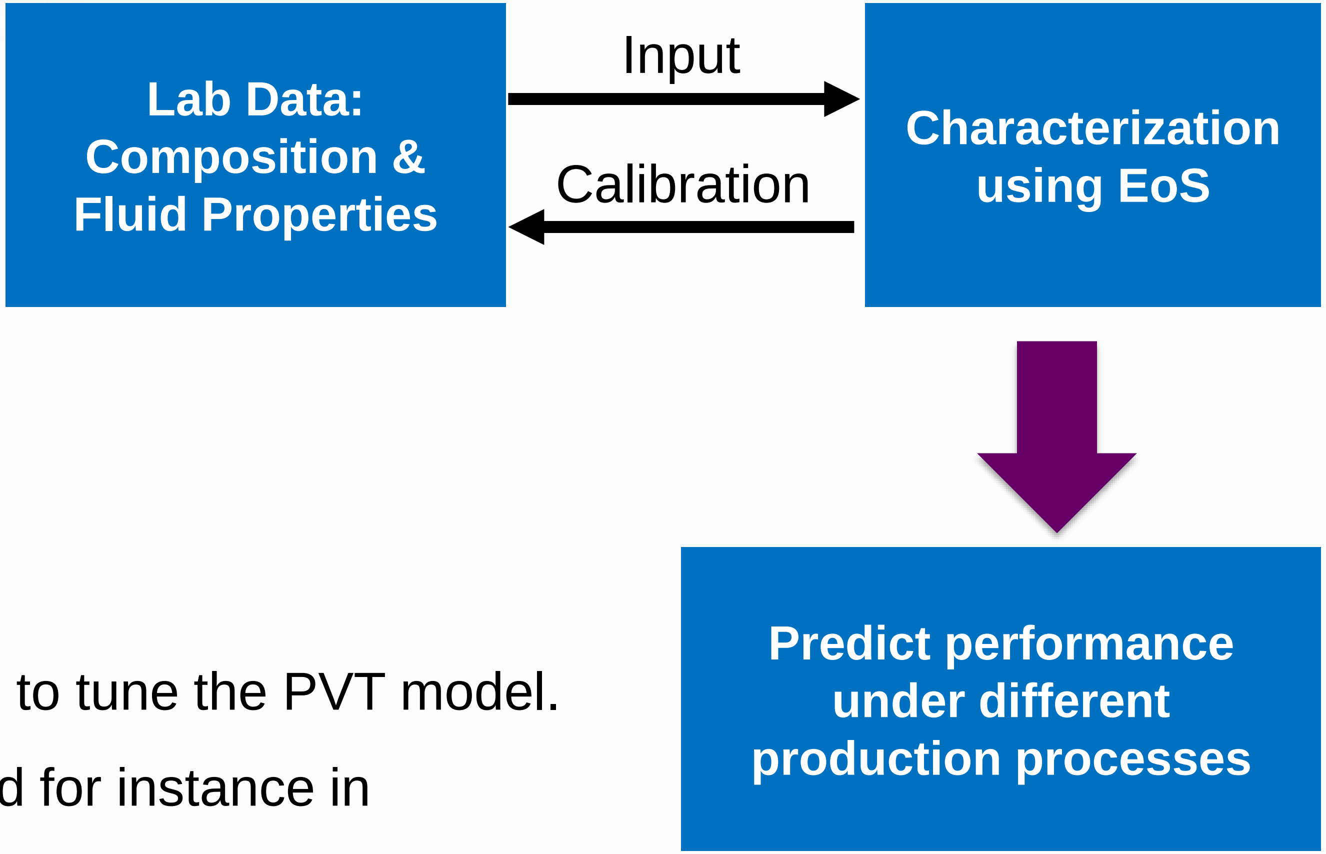


Phase Behavior Simulation



Phase Behavior Simulation

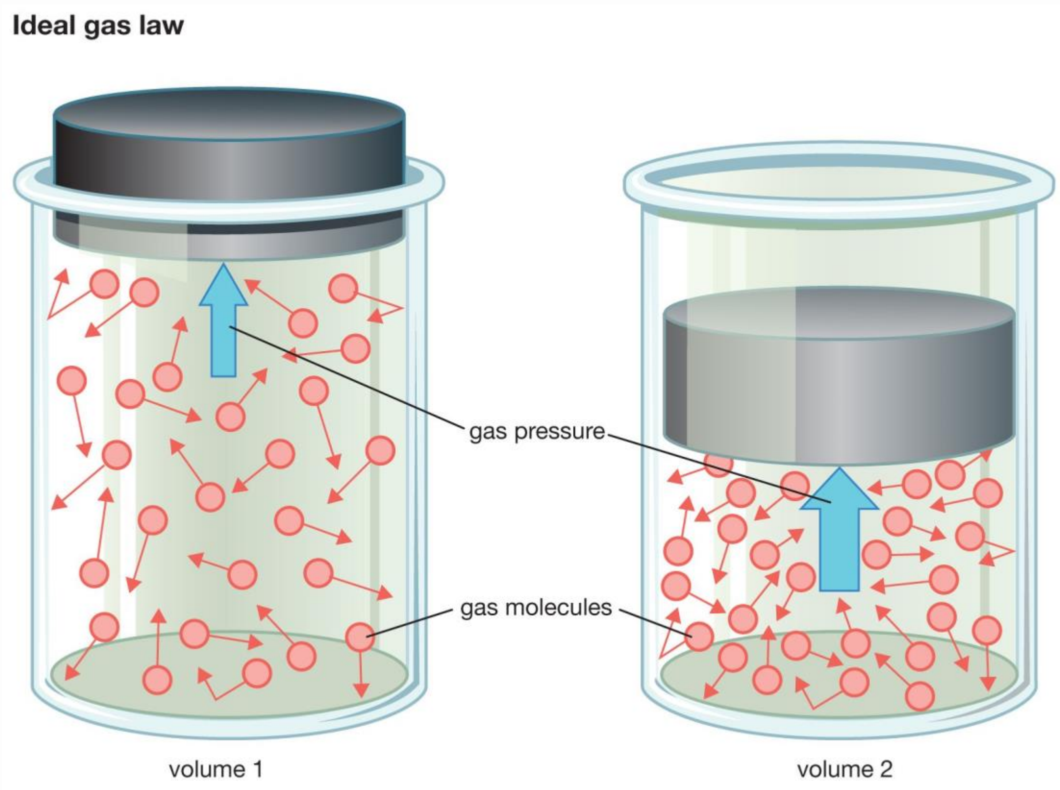
- From the compositional data, a PVT model can be initially defined.
- **Hydrocarbon fractions up to C6 are modeled EXACTLY with known properties.**
- However, a characterization of C7+ fraction is necessary as **NO** exact data are available.



- Lab measurements (FVF, Rs, etc.) must be used to tune the PVT model.
- After a satisfactory match, the model can be used for instance in **optimization of the facilities design (optimum separator pressure).**
- The PVT model can be used for what-if questions and this is obviously cheaper than redoing the experiments.

Ideal Gas Law

- **Boyle's Law: fixed mass of gas at constant T**
  - PV = constant
- **Charles' Law: fixed mass of gas at constant P**
  - V/T = constant
- **Combining gives the Ideal Gas Law**
  - PV = nRT n = number of moles
    - R = 10.372 psia /ft^3/lbmole
    - R = 0.0821 Barsa/m^3/kgmole
- **Assumptions:**
  - Molecules are point-like, i.e. zero volume
  - No inter-molecular forces
- **Limitations:**
  - Gases are not infinitely compressible
  - No account of change of phase
  - Adequate only for low pressure gases



EOS of a Hydrocarbon Fluid

$$PV = ZnRT$$

- The EOS takes a ‘**cubic**’ form:

$$Z^3 + Z^2 + (A - B - B^2)\,Z - A.B = 0$$

Where; A & B = f(T & P)

- Physical solutions of the EOS are Z_{min} (liquid phase) and Z_{max} (vapor phase).
- One of the most important solutions of the EOS is the phase envelope in the P-T

Equations of State

- Working with cubic EOS, more convenient to work in terms of the Z -factor rather than V.
- Replacing V in equation by:

V = ZRT/p

- Rearranging:

$$p = \frac{RT}{(V-b)} - \frac{a}{V^2}$$

$$Z^3 - Z^2 + (A - B - B^2)Z - AB = 0$$

Where

$$A = \frac{ap}{R^2T^2} \qquad B = \frac{bP}{RT}$$

- This Equation yields 1 or 3 Real Roots depending on the no. of phases in the system.

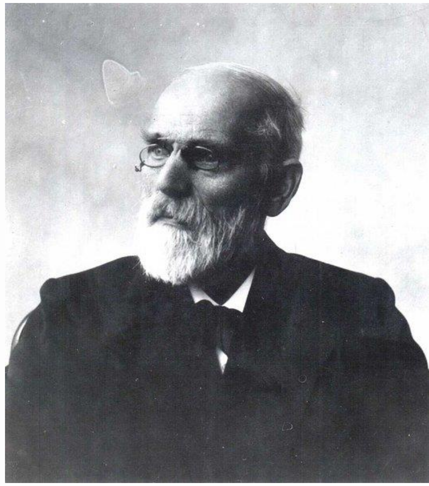
Equation of State

- **Van der Waals (1873):**

$$\left(p + \frac{a}{V^2}\right)(V - b) = RT$$

a: attractive force **b: co-volume**

Johannes Diderik
van der Waals
(1837 – 1923)



- **To find values of "a" and "b", Rewrite the equation as a cubic:**

$$p = \frac{RT}{(V-b)} - \frac{a}{V^2} \quad \Rightarrow \quad V^3 - \left(b - \frac{RT}{p}\right)V^2 + \frac{a}{p}V - \frac{ab}{p} = 0$$

$$a = \frac{27 R^2 T_c^2}{64 p_c} \qquad b = \frac{RT_c}{8 p_c}$$

Equation Of State (EOS)

- **EOS is an analytic expression relating P to V and T.**
- Best method for handling large amounts of P-V-T data.
- Efficient and versatile means of expressing thermodynamic functions in terms of P-V-T data
- **PV=ZRT** is an equation of state
- **Van der Waals EOS:** a cubic in volume (or Z), three roots.

$$V^3 - \left(b - \frac{RT}{p}\right)V^2 + \frac{a}{p}V - \frac{ab}{p} = 0$$

- a is a measure of the attractive forces between the molecules
- b is related to the size of the molecules.

- The two corrective terms to overcome the limiting assumptions of the ideal gas equation are:
  - **a/V^2** : The internal pressure or cohesion term , which accounts for the cohesion forces.
  - b: co-volume, which represents the volume occupied by 1 mole at infinite pressure and results from the repulsion forces which occur when the molecules move close together.

Summary: Equations of State

- The EoS is an analytic expression relating P, V, and T.
- PV=ZRT is an equation of state
- Common EoS are PR, SRK
  - These are cubic in Z
- None completely satisfactory for all engineering applications

$$PV = nRT \quad \text{Ideal Gas}$$

$$PV = ZnRT \quad \text{Real Gas}$$

$$P = \frac{RT}{V-b} - \frac{a}{V(V)} \quad \text{Van der Waals}$$

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)} \quad \text{Soave - Redlich - Kwong}$$

$$P = \frac{RT}{V-b} - \frac{a(T)}{V(V+b)+b(V-b)} \quad \text{Peng - Robinson}$$

Acentric Factor

- Pitzer (1955): introduce ω as a correlating parameter to characterize **the centricity or non-sphericity of a molecule**.
- Corresponding State Theory States:
  - All the fluids behave similarly if their conditions are close or far (with the same amount) from critical point.
  - Or At the same reduced temperature and pressure, all hydrocarbons have the same value of Z

$$\omega = -\log\left(\frac{p_v}{p_c}\right)_{T=0.7T_c} - 1$$

EOS Characterization

- **EOS Characterization Involves:**
  - **Splitting** of the plus fraction (**C7+**)
  - **Characterization** of plus fraction pseudo-components (assigning properties)
  - **Grouping or lumping** to reduce the number of pseudo-components
  - **Tuning** (modifying) properties to match laboratory data

Identifying Components - Plus Fraction

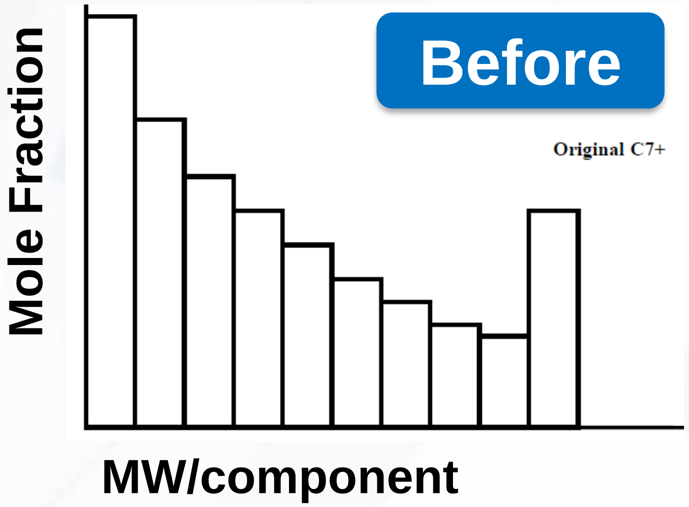
- All PVT reports have a component analysis up to some upper carbon number to be specified by the owner of the fluid, say 6, 11, 19 or 29.
- Residual hydrocarbon fluid is usually referred to as the plus fraction, i.e., **C_{7+}, C_{12+} C_{20+} or C_{30+}**.
- Detailed component analysis is made of pure component and SCN fractions up to a PLUS fraction
  - C_{7+} - old/cheap
  - C_{12+}
  - C_{20+}
  - C_{30+} - expensive
- Mole Weight of C_+ fraction made by freezing point depression or boiling point elevation.

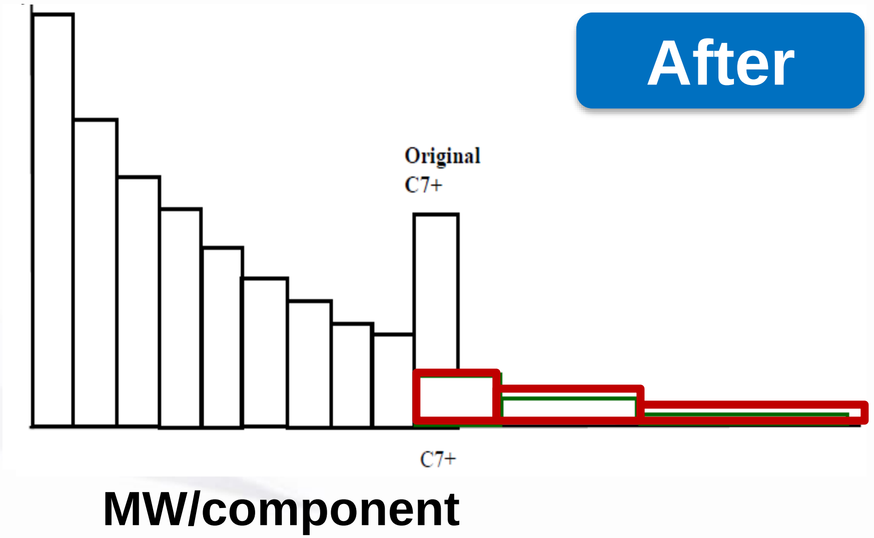
Identifying Components - Plus Fraction

- For C_{7+}, C_{12+} C_{20+} or C_{30+} only a limited set of information available, usually the molecular weight M_{N+} and sometimes the specific gravity γ_{N+}
- **For use in an EOS model, we need the EOS parameters such as T_c, P_c, ω, etc.,**
- These are obtained from correlations depending on M_{N+} and γ_{N+}, for example the Kesler-Lee Correlation.
- **This is called "Characterization of the Plus fraction".**

Splitting Plus Fraction

- **Why Splitting the Plus Fraction?**
  - Insufficient description of heavier hydrocarbons reduces the accuracy of PVT predictions*
  - **Plus Fraction Characterization:**
    - Divide the C7+ pseudo-component into a number of fractions with known compositions.
    - Define the molecular weight ,specific gravity ,and boiling point of each C7+ fraction.
- For compositional simulation, we want to match all the available observations with the **MINIMUM** number of components.





Grouping or Pseudoization

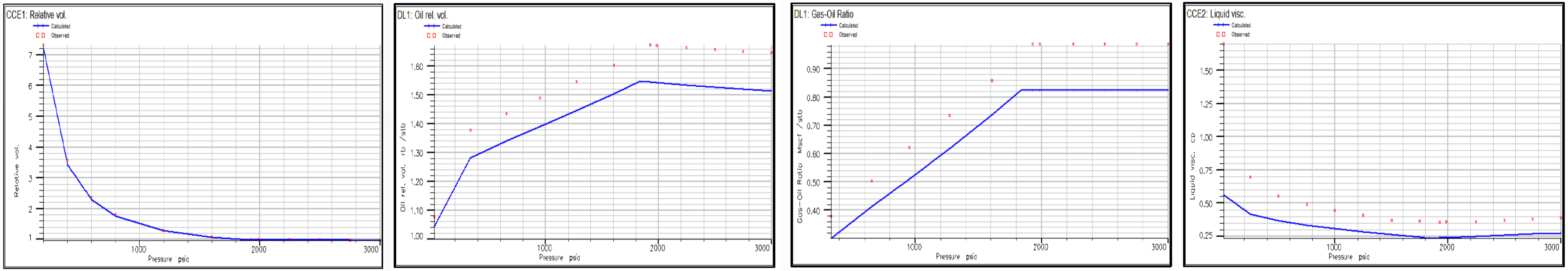
- Compositional simulator uses EOS models
  - **Flash calculations can take ~ 50% of simulation time**
- Need to reduce number of components $\Rightarrow$ to reduce number of equations
- The number of grouped 'pseudo-components' needed in a compositional simulation depends on the process that is modelled:
  - For depletion, 2 pseudo-components may be enough (Black-oil model)
  - For miscibility, more than 10 components may sometimes be needed.
- In general, 4 to 10 components should be enough to describe the phase behaviour

EOS Tuning

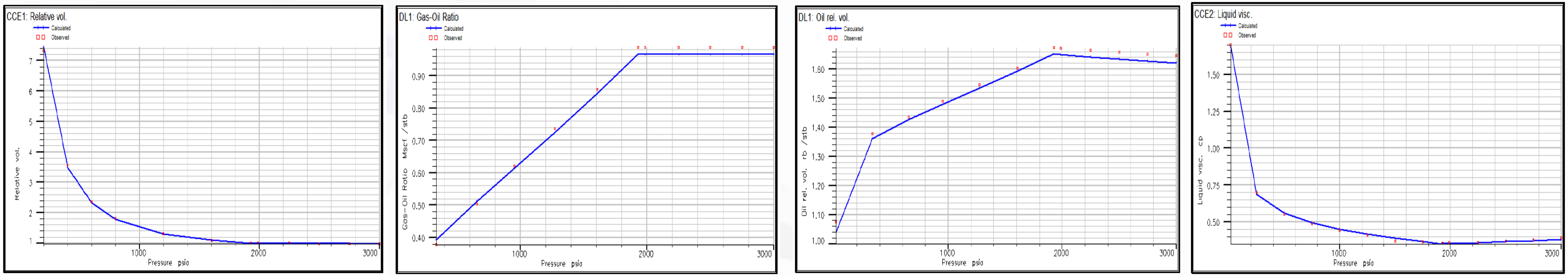
- The parameters of the EOS are often adjusted to honor the available data.
- **Such adjustments to regress on the available data is often referred as "Tuning" in the industry.**
- Modification of the properties of the constituents (C7, C8, …, CNP) of the plus fraction is the common practice.
- In general, the attributes (**Tc, Pc, ω**) of the plus fraction constituents, or the coefficients of the a and b (Ω_A and Ω_B, respectively) are modified during the tuning process.
- For systems containing significant amount of non-HC components (some EOR fluid systems) non-HC-C7+ kij's may also become a key set parameters.

PVT Procedure

- After the splitting the sensitivity analysis was applied on the system “Regression techniques” to predict a best PVT model with very low error between the measured and simulated value.



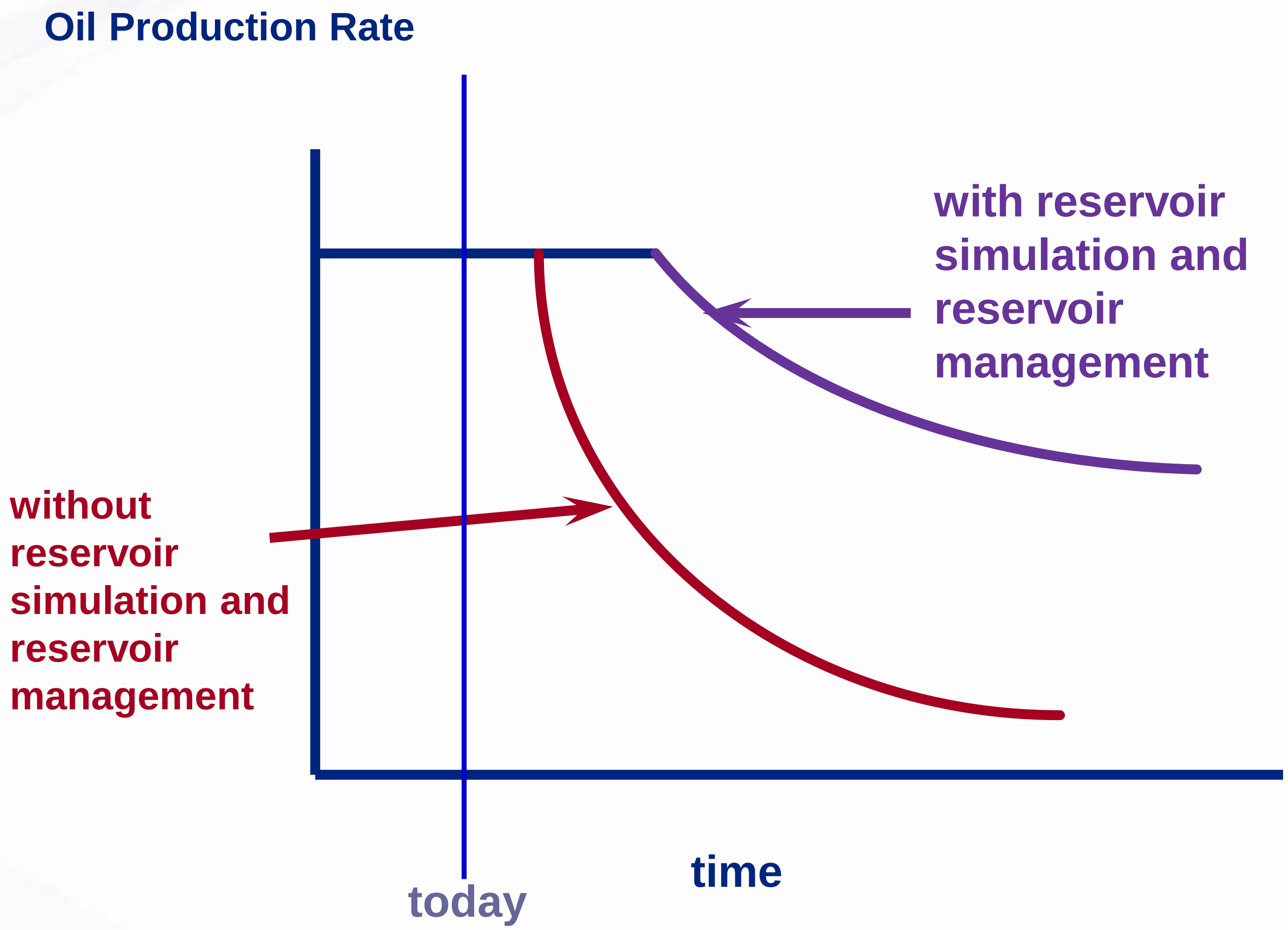
Before Tuning



After Tuning

Uses Of PVT Analysis

- **Predict:**
  - Composition of well stream vs. time
  - Completion design (wellbore liquids)
  - Gas injection or re-injection
    - Specification of injected gas - how much C3, 4, 5's to leave in
    - separator configuration and stage for injection gas
  - Miscibility effects
  - Amounts and composition of liquids left behind and their properties: density, surface tension, viscosity.
  - Separator/NGL Plant Specifications
  - H_2S and N_2 concentration in produced gas
  - Product values vs. time



Uses of Compositional Simulation

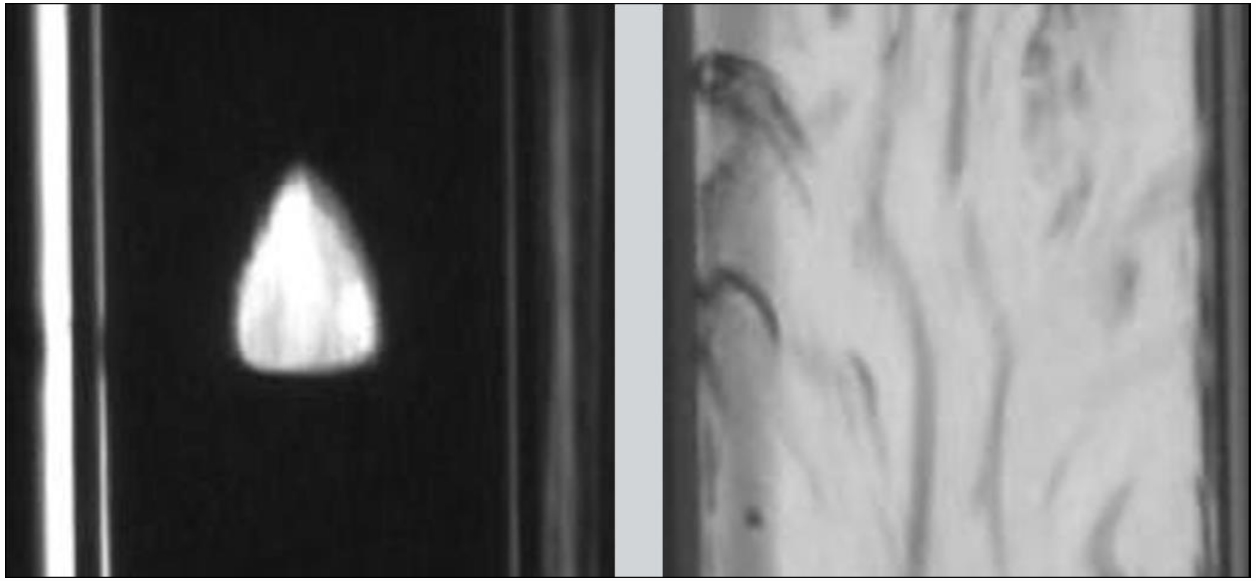
Processes where

- EOR involves a miscible displacement
- Gas injection/re-injection into an oil produces large compositional changes in the fluids
- Condensates are recovered using gas cycling
- Surface facilities department needs detailed compositions of the production stream

Miscible Processes

- **Under normal conditions, oil & gas reservoir fluids form distinct, immiscible phases**
- Immiscible phases are separated by an interface
  - Associated with inter-facial tension (IFT)
  - When IFT=0, fluids mix => **Miscibility**
- Residual oil saturation to gas (and water) directly proportional to IFT
- Miscible displacement characterized by low/zero residual oil saturations
- **Establishment of miscibility depends on:**
  - Pressure (MMP)
  - Fluid system compositions

Rising bubble experiment to determine miscibility



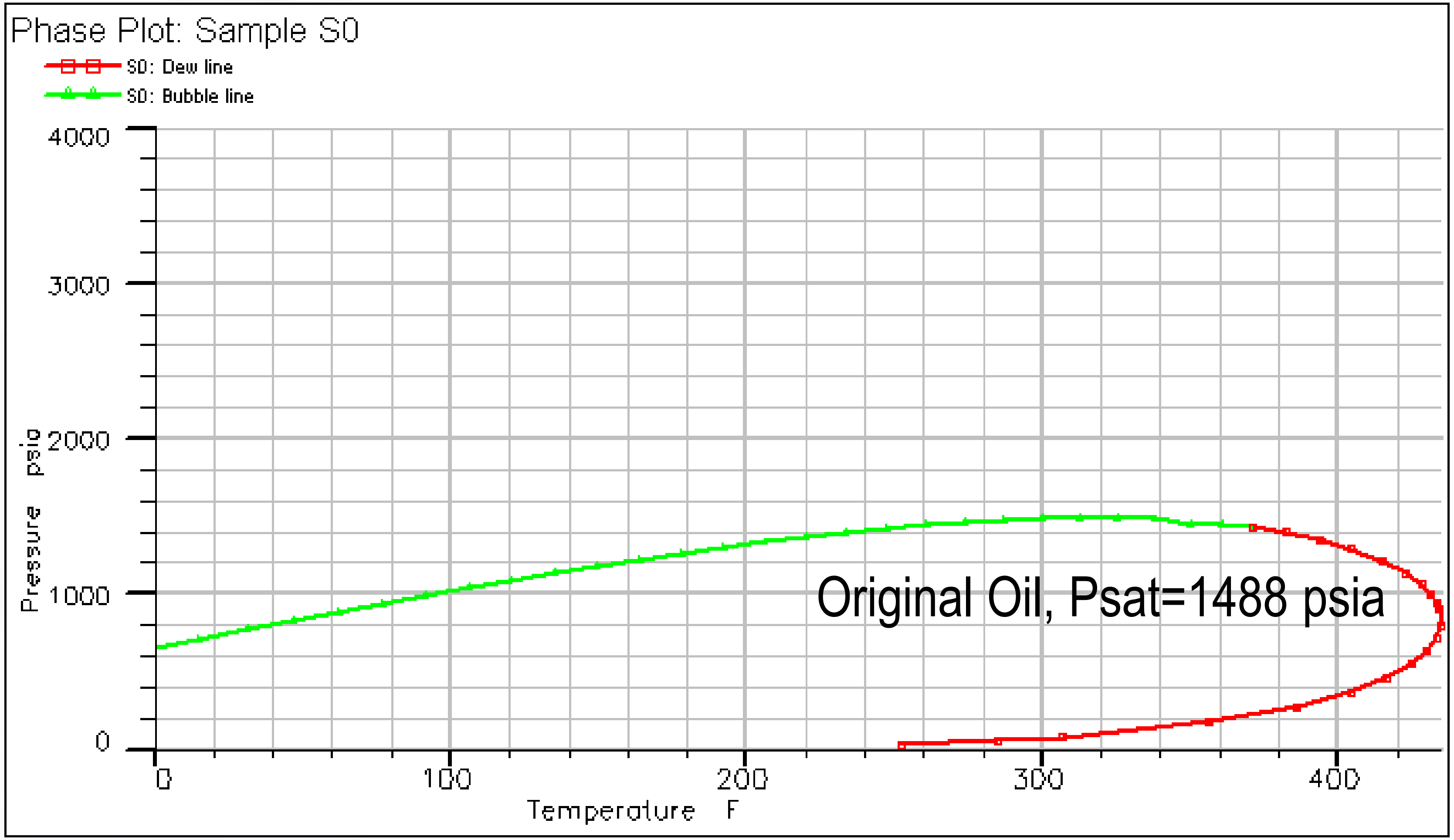
Non-miscible **Miscible**

- Basic types of miscible process
  - First-contact miscibility
  - Multi-contact miscibility

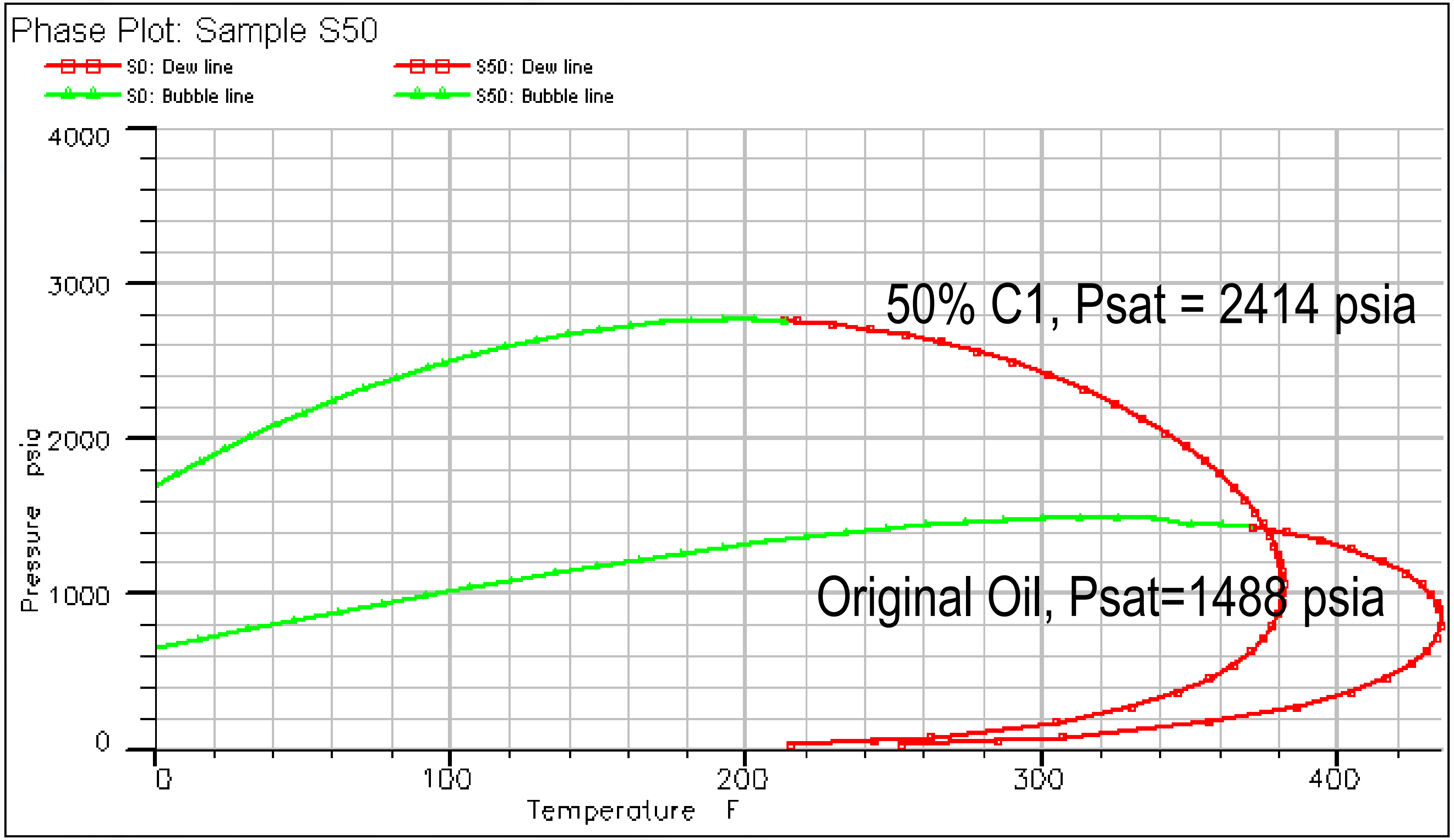
Miscible Processes

- Consider an oil made up of 31% C_1, 55% iC_4 and 14% C_{10}.
- Reservoir temperature = 302 F
- Psat = 1488 psia.

- Inject methane into this oil - perform a swelling test.
- As the oil gets lighter, Psat starts to increase.



Miscible Processes



THANK YOU

Hesham Mokhtar