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PVT in whitson+

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½ Virtual Course

14 February 2024

support@whitson.com

General Information

REPETITION!

General Information

- 1/2-day course
- Session 1: 8 am – 12 pm Central Time
- Interactive class
- Ask questions – drive the course emphasis
  - In chat
  - … or unmute to ask question (mute when not talking☺)
- Will send out all digital material after class
  (class recording, presentations etc.)
- Some content in this slide deck is meant for presentation purposes, while some parts are meant for reference.

Disclaimer

The course is tailored for practitioners, i.e., folks that need PVT properties, or to understand fundamental PVT, in their day-to-day work for different reasons (*reservoir, production, processing, facility, exploitation, completion, geologists, petrophysics, managers, sales, marketing*).

The course will be of a more pragmatic character, i.e., we will focus on items that you can go out an apply immediately with readily available data and industry standard tools.

It is not tailored for "PVT experts" → we have a 5-day course for that
(even though they are more than welcome as well 🙂).

Hence, “advanced topics” that

- require a lot of detail (PVT lab QC, PVT lab reports, EOS development)
- or lack industry consensus (e.g. “nano pore” PVT)

will not be prioritized

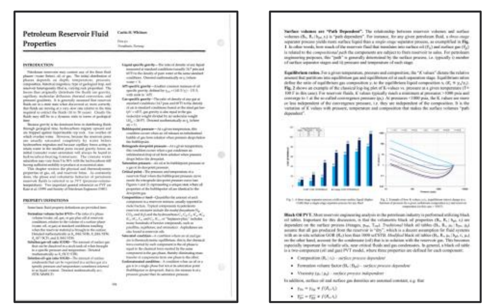
Digital Handouts

Digital Handouts

- All slides

- **whitson+** software (courses.whitson.com)

- Preparation Material



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Software

Access to whitson+

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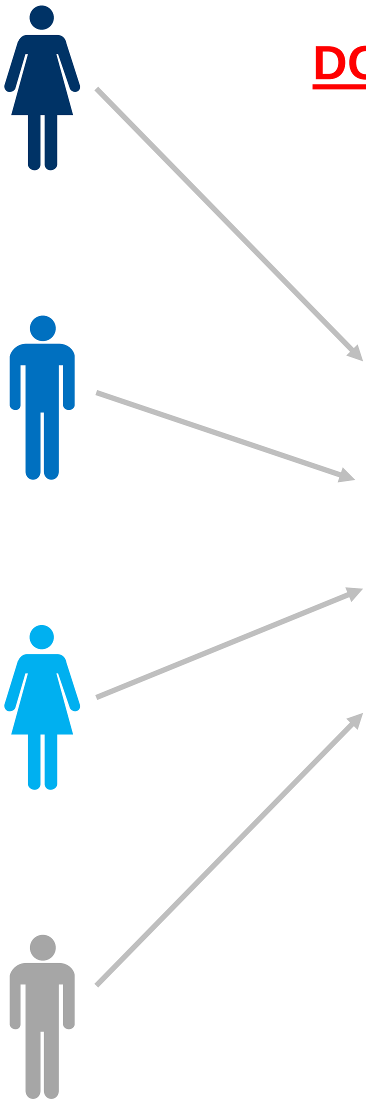

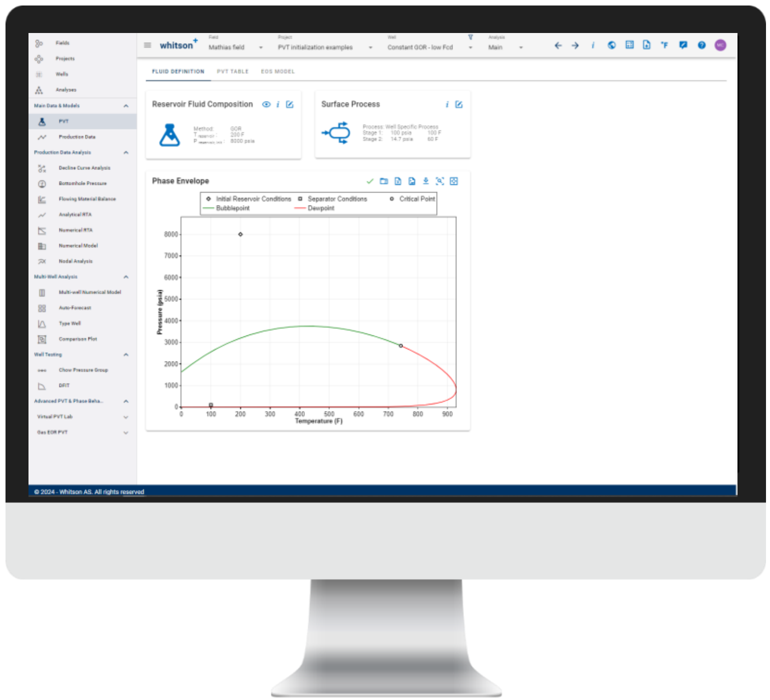

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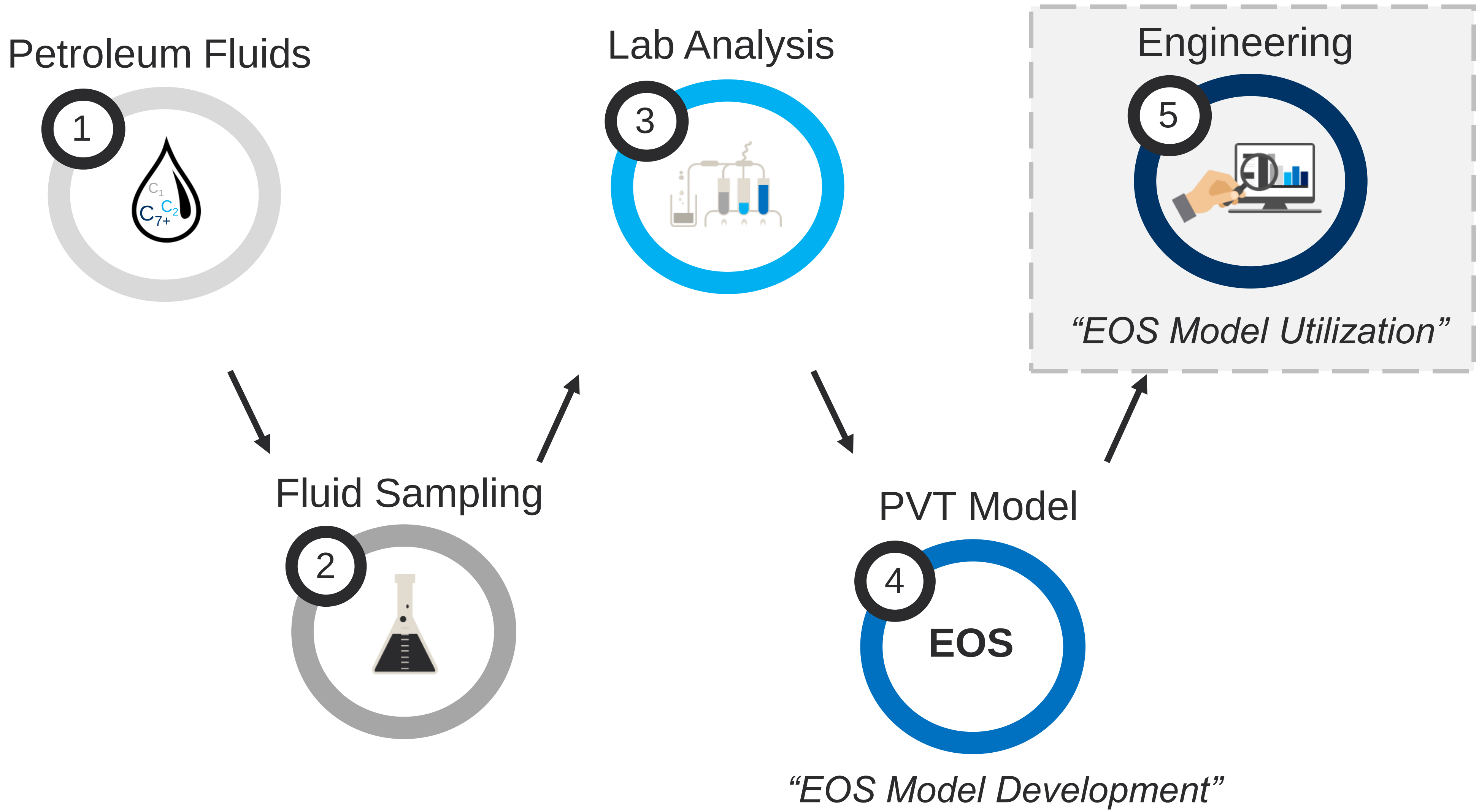
*Send an e-mail to support@whitson.com if you need help to login. Use Google Chrome, Firefox or Microsoft Edge. Internet Explorer won't work.

Course Contents

Course Progress “Logic”



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Course Goals

Course Goals

- Classify reservoirs into black oils, volatile oils, near-critical fluids, gas condensates, wet gases & dry gases
- Understand the difference between "in-situ" and "reservoir" representative samples
- Conceptionally understand what an EOS model is and what the inputs are
- Predict PVT data (composition) from readily available data and EOS model
- Perform fluid initialization on a "shale well" using readily available data
- Estimate PVT properties at initial reservoir conditions from EOS model
- Calculate OOIP | OGIP for **OIL**, **GAS** and **TWO-PHASE** systems
- Generate PVT tables (B_o, R_s, μ_o, p_{bub} | B_{gd}, r_s, μ_g, p_{dew}) from EOS model
- Understand the most important parts of a PVT report

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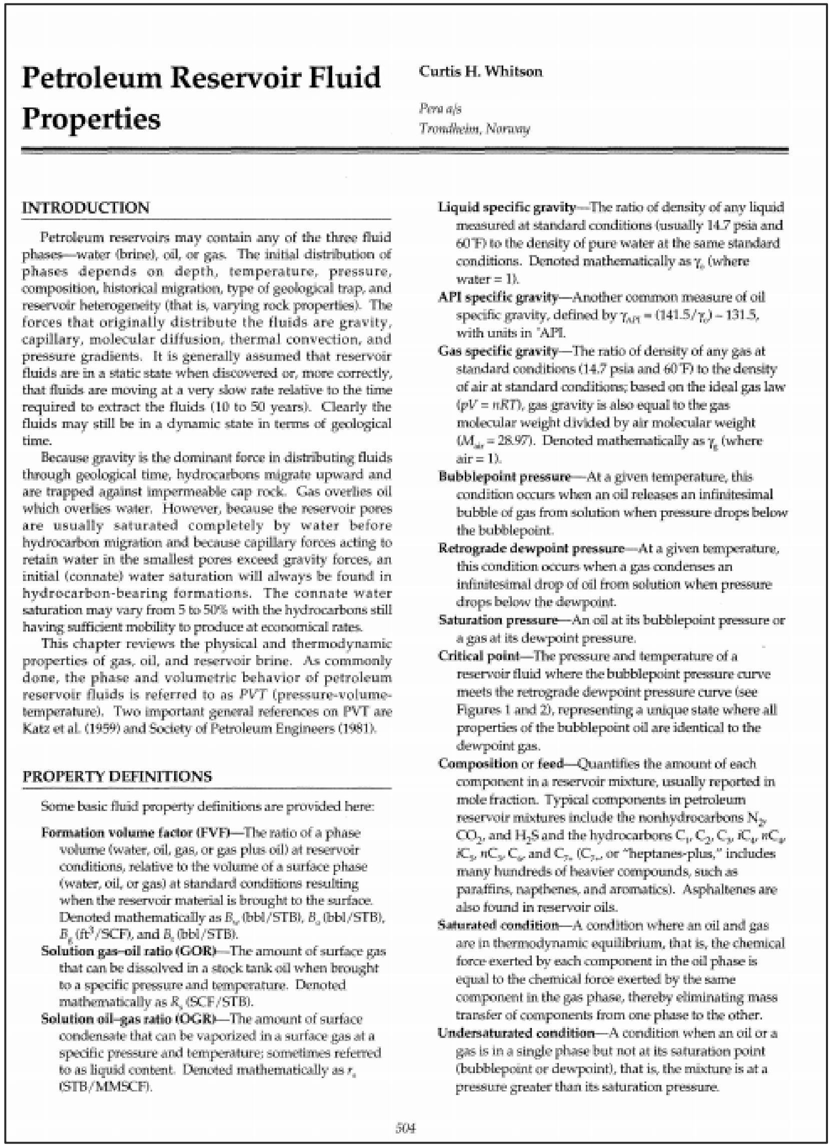
PVT for the first time?

Exposed to PVT First Time?



Petroleum Reservoir Fluid Properties

Curtis H. Whitson

Pera a/s
Trondheim, Norway

INTRODUCTION

Petroleum reservoirs may contain any of the three fluid phases—water (brine), oil, or gas. The initial distribution of phases depends on depth, temperature, pressure, composition, historical migration, type of geological trap, and reservoir heterogeneity (that is, varying rock properties). The forces that originally distribute the fluids are gravity, capillary, molecular diffusion, thermal convection, and pressure gradients. It is generally assumed that reservoir fluids are in a static state when discovered or, more correctly, that fluids are moving at a very slow rate relative to the time required to extract the fluids (10 to 50 years). Clearly the fluids may still be in a dynamic state in terms of geological time.

Because gravity is the dominant force in distributing fluids through geological time, hydrocarbons migrate upward and are trapped against impermeable cap rock. Gas overlies oil which overlies water. However, because the reservoir pores are usually saturated completely by water before hydrocarbon migration and because capillary forces acting to retain water in the smallest pores exceed gravity forces, an initial (connate) water saturation will always be found in hydrocarbon-bearing formations. The connate water saturation may vary from 5 to 50% with the hydrocarbons still having sufficient mobility to produce at economical rates.

This chapter reviews the physical and thermodynamic properties of gas, oil, and reservoir brine. As commonly done, the phase and volumetric behavior of petroleum reservoir fluids is referred to as *PVT* (pressure-volume-temperature). Two important general references on PVT are Katz et al. (1959) and Society of Petroleum Engineers (1981).

PROPERTY DEFINITIONS

Some basic fluid property definitions are provided here:

Formation volume factor (FVF)—The ratio of a phase volume (water, oil, gas, or gas plus oil) at reservoir conditions, relative to the volume of a surface phase (water, oil, or gas) at standard conditions resulting when the reservoir material is brought to the surface. Denoted mathematically as B_w (bbl/STB), B_o (bbl/STB), B_g (ft^3/SCF), and B_t (bbl/STB).

Solution gas–oil ratio (GOR)—The amount of surface gas that can be dissolved in a stock tank oil when brought to a specific pressure and temperature. Denoted mathematically as R_s (SCF/STB).

Solution oil–gas ratio (OGR)—The amount of surface condensate that can be vaporized in a surface gas at a specific pressure and temperature; sometimes referred to as liquid content. Denoted mathematically as r_s (STB/MMSCF).

Liquid specific gravity—The ratio of density of any liquid measured at standard conditions (usually 14.7 psia and 60°F) to the density of pure water at the same standard conditions. Denoted mathematically as γ_o (where water = 1).

API specific gravity—Another common measure of oil specific gravity, defined by $\gamma_{API} = (141.5/\gamma_o) - 131.5$, with units in °API.

Gas specific gravity—The ratio of density of any gas at standard conditions (14.7 psia and 60°F) to the density of air at standard conditions; based on the ideal gas law ($pV = nRT$), gas gravity is also equal to the gas molecular weight divided by air molecular weight ($M_{air} = 28.97$). Denoted mathematically as γ_g (where air = 1).

Bubblepoint pressure—At a given temperature, this condition occurs when an oil releases an infinitesimal bubble of gas from solution when pressure drops below the bubblepoint.

Retrograde dewpoint pressure—At a given temperature, this condition occurs when a gas condenses an infinitesimal drop of oil from solution when pressure drops below the dewpoint.

Saturation pressure—An oil at its bubblepoint pressure or a gas at its dewpoint pressure.

Critical point—The pressure and temperature of a reservoir fluid where the bubblepoint pressure curve meets the retrograde dewpoint pressure curve (see Figures 1 and 2), representing a unique state where all properties of the bubblepoint oil are identical to the dewpoint gas.

Composition or **feed**—Quantifies the amount of each component in a reservoir mixture, usually reported in mole fraction. Typical components in petroleum reservoir mixtures include the nonhydrocarbons N_2, CO_2, and H_2S and the hydrocarbons C_1, C_2, C_3, iC_4, nC_4, iC_5, nC_5, C_6, and C_{7+} (C_{7+}, or "heptanes-plus," includes many hundreds of heavier compounds, such as paraffins, napthenes, and aromatics). Asphaltenes are also found in reservoir oils.

Saturated condition—A condition where an oil and gas are in thermodynamic equilibrium, that is, the chemical force exerted by each component in the oil phase is equal to the chemical force exerted by the same component in the gas phase, thereby eliminating mass transfer of components from one phase to the other.

Undersaturated condition—A condition when an oil or a gas is in a single phase but not at its saturation point (bubblepoint or dewpoint), that is, the mixture is at a pressure greater than its saturation pressure.

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Recommendation

Read *Petroleum Reservoir Fluid Properties* in digital handouts

PVT – What is This?

- In this course, we'll review the physical and thermodynamic properties of gas and oil

- As commonly done, the phase and volumetric behavior of petroleum reservoir fluids is referred to as *PVT* (pressure-volume-temperature)

- What about water?

$$pV = nRT$$

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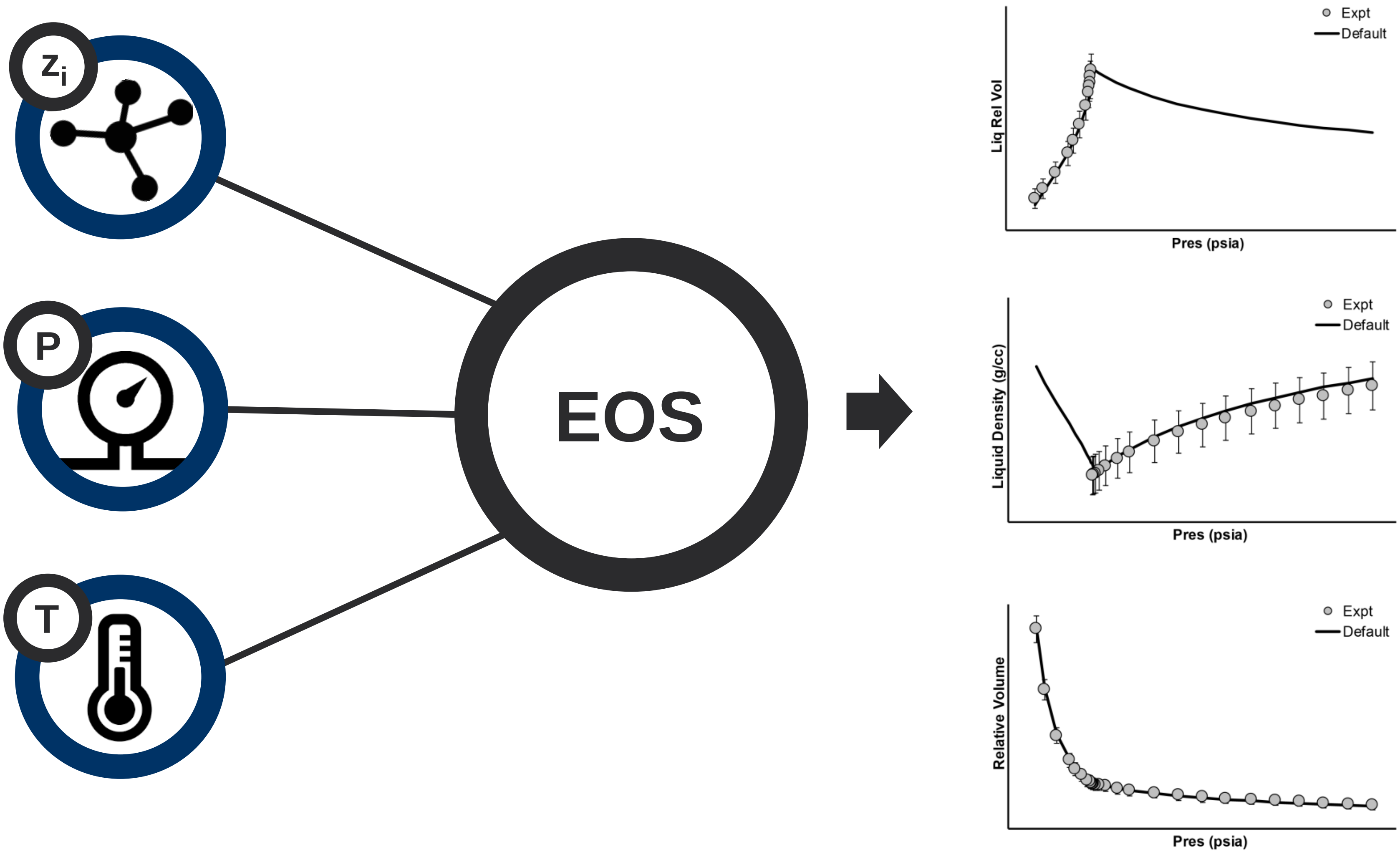
Vocabulary

Vocabulary

1. EOS Model
2. Compositions
3. Flash
4. K-Values
5. “Representative” Samples
6. Solution CGR (r_s) aka Vaporized Oil Ratio (R_v)

What is an EOS Model?



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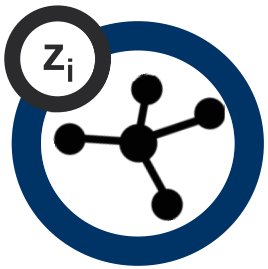
What is a Composition?



“The amount of different components”

usually expressed in mol%.

$$z_i = n_i \;/ \textstyle\sum_j n_j \quad | \quad y_i = n_{Vi} \;/ \textstyle\sum_j n_{vj} \quad | \quad x_i = n_{Li} \;/ \textstyle\sum_j n_{Lj}$$

Total *Vapor* *Liquid*

2

What is a Composition?

Air	Sparkling Water	Petroleum Fluids
z_i	z_i	z_i
N_2 = 78%	H_2O = 99%	C_1
O_2 = 21%	CO_2 = 1%	C_2
...	...	...
		C_{7+}
Total = 100%	**Total = 100%**	**Total = 100%**

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3

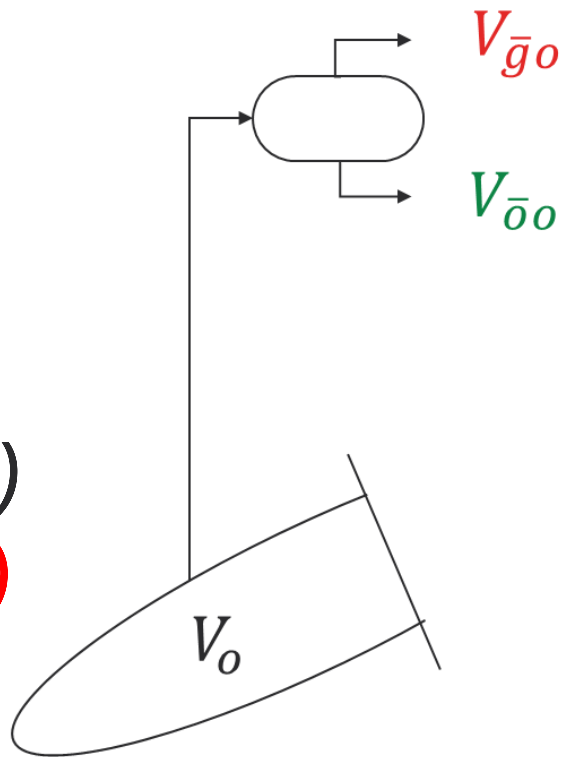
Flash … Neither of These

3

Flash

Two-phase isothermal flash calculations are used for processes with vapor/liquid-equilibrium (VLE).

A flash takes a feed stream (z_i) that separates into a Vapor (y_i) and Liquid (x_i) phases – or remains a single phase.



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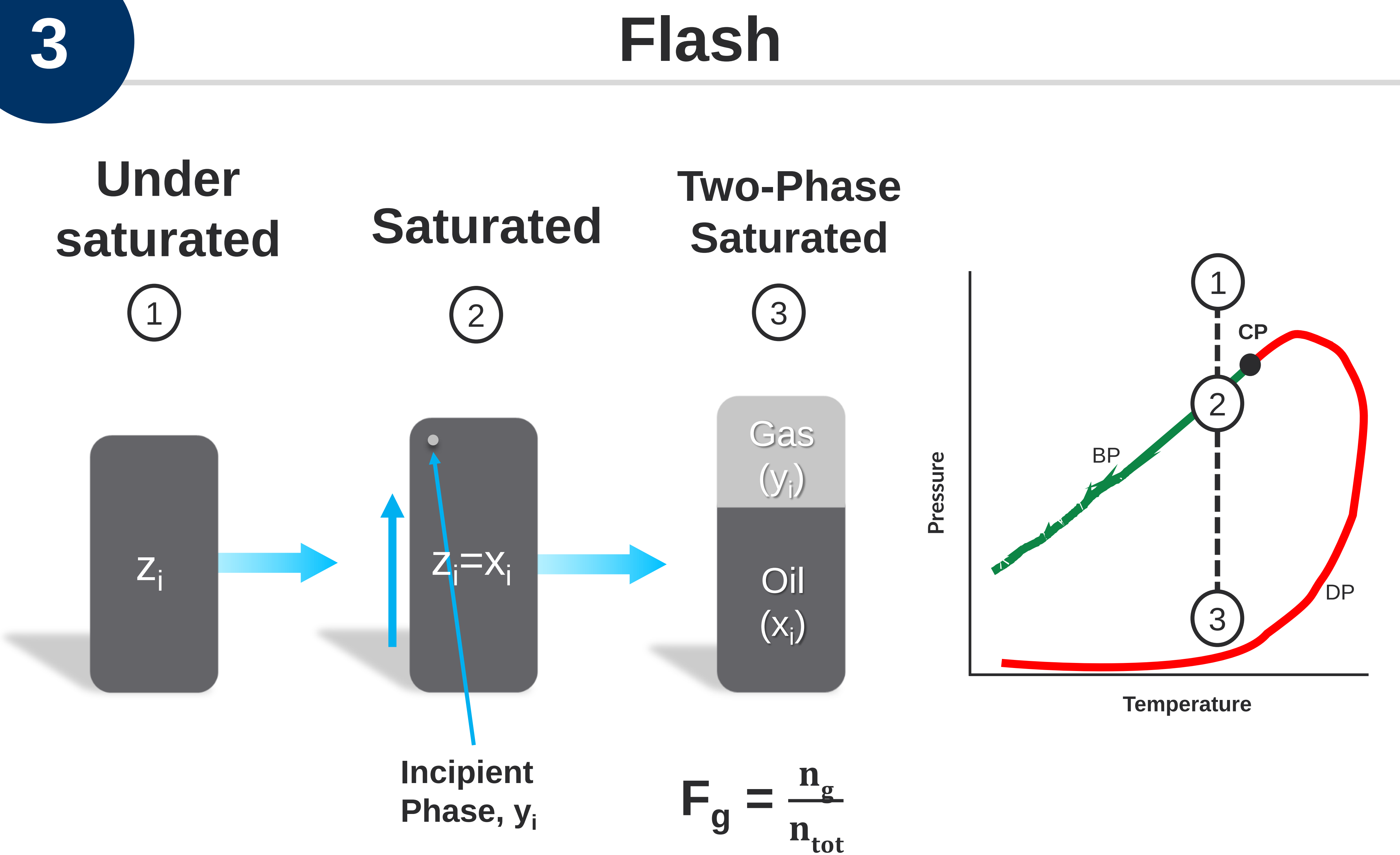
Flash


3
Under saturated
Saturated
Two-Phase Saturated
1
2
3
z_i
$z_i = x_i$
Gas (y_i)
Oil (x_i)
Incipient Phase, y_i
$F_g = \frac{n_g}{n_{tot}}$
Pressure
Temperature
CP
BP
DP

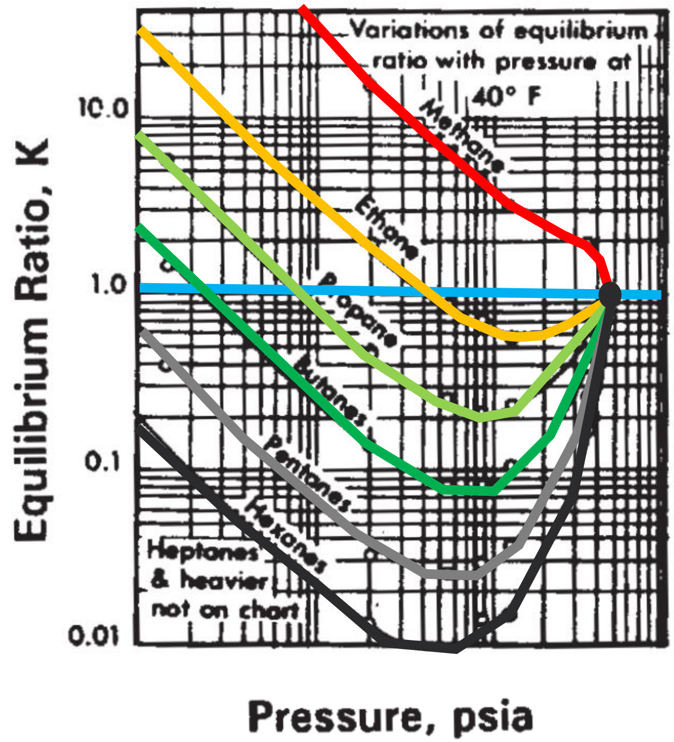
K-Values

$$K_i \equiv y_i / x_i$$

For a given **temperature (T)** and **composition (zi)**

K_i represents the relative preference of a component i to "be" in the gas phase or oil phase:

- *$K_i > 1$ – Relative preference is to be in gas phase*
- *$K_i < 1$ – Relative preference is to be in the oil phase*



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“Representative” Samples

“Reservoir Representative”

Any uncontaminated fluid sample produced from a reservoir is automatically representative of that reservoir

“In-situ Representative”

A sample representative of the original fluid(s) in place

Accuracy of PVT Data ≠ “In-situ Representivity” of Sample

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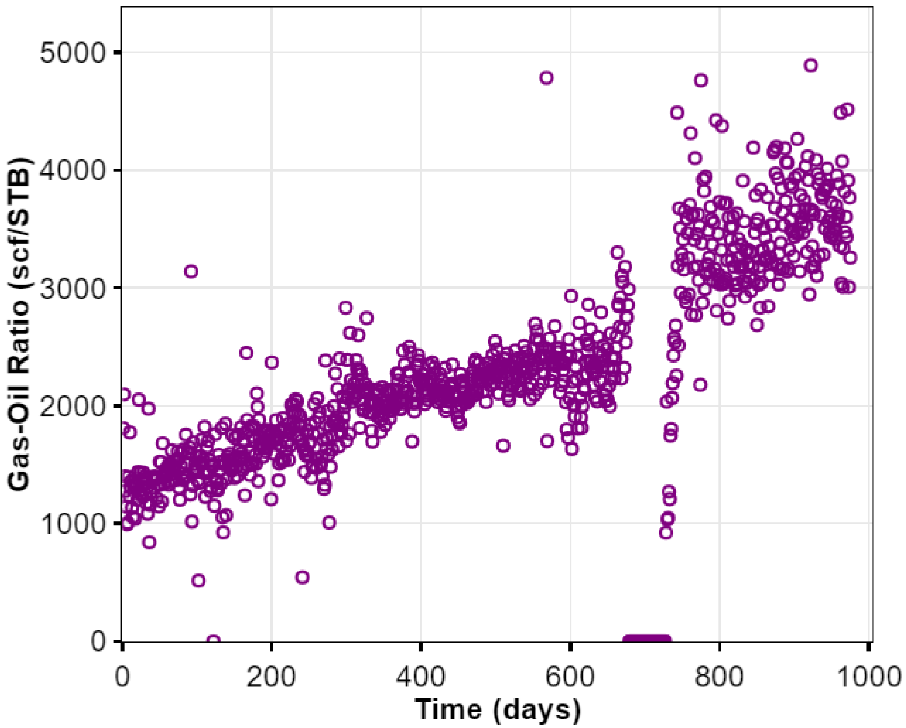
5 Samples to use in PVT model development?



- In PVT / EOS model development one would like to use all **“reservoir representative”** samples.
- **Why?** You want a PVT model that works well for all times, not only time = 0.
- “In-situ” representative samples should be used **together** with a proper EOS model to initialize your reservoir model (called “Fluid Initialization”).

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Example

Classification	Sample while $p_{wf} > p_{sat}$ (not mud contaminated)	Sample while $p_{wf} < p_{sat}$ (not mud contaminated)	Mud Contaminated Sample
"In-situ Representative"	✓	X	X
"Reservoir Representative"	✓	✓	X

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6 Solution CGR/OGR (r_s) aka Vaporized Oil Ratio (R_v)

Quantifies: condensate in **solution** with reservoir gas phase

Hence, relevant for:

- wet gas
- gas condensates
- oil reservoirs below bubblepoint (gas out of solution)

Units: STB/MMscf (most common)

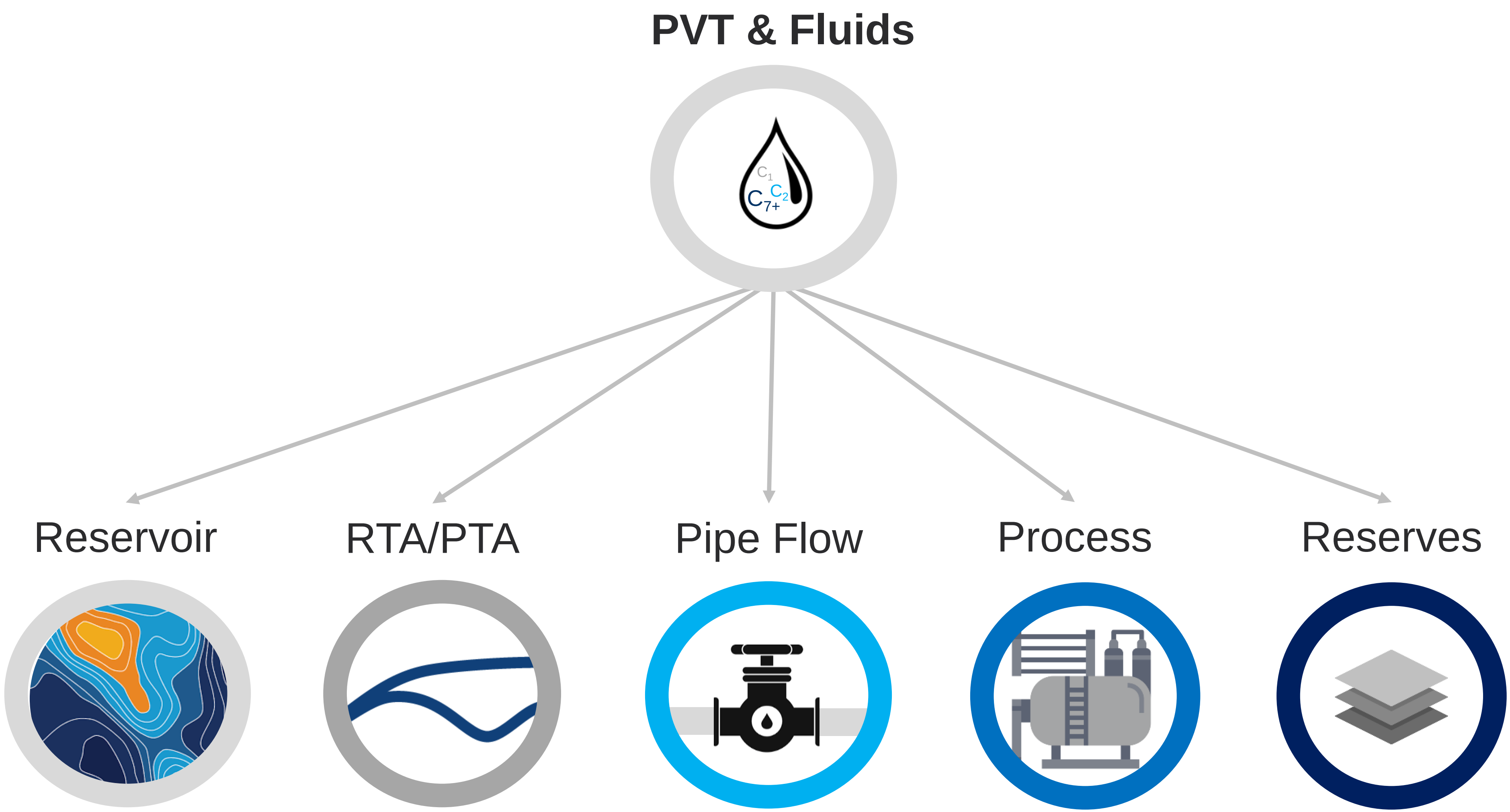
Symbol:

- SPE - r_s ("little rs" or solution CGR / OGR)
- Industry - R_v ("RV" or vaporized oil ratio)

r_s and R_v is used interchangeably throughout the course

PVT Fundamentals

PVT has an Impact on Every Discipline in the Petroleum Domain!



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Key Concept

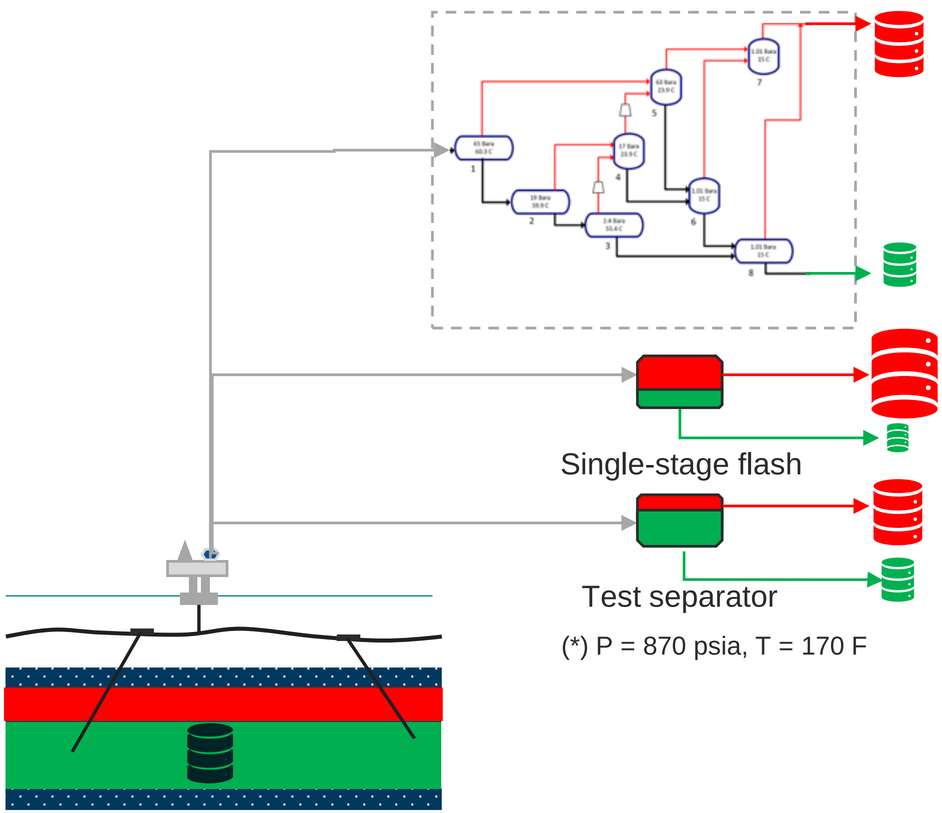
1 m^3 is not always 1 m^3

Courtesy: Knut Uleberg, Equinor

1 reservoir m^3 ≠ 1 separator m^3 ≠ 1 stock tank m^3

What we mean by “not same”: the volume is the same, 1 m^3.
The amount of mass, density, composition, and monetary value are different.

Process dependencies



GOR = 8400 scf/STB

GOR = 9250 scf/STB

GOR = 6700 scf/sep.bbl

- Final product volumes depends on pressure & temperature conditions, and the path to get there…
- GOR and FVF are process dependent.

Courtesy: Knut Uleberg, Equinor

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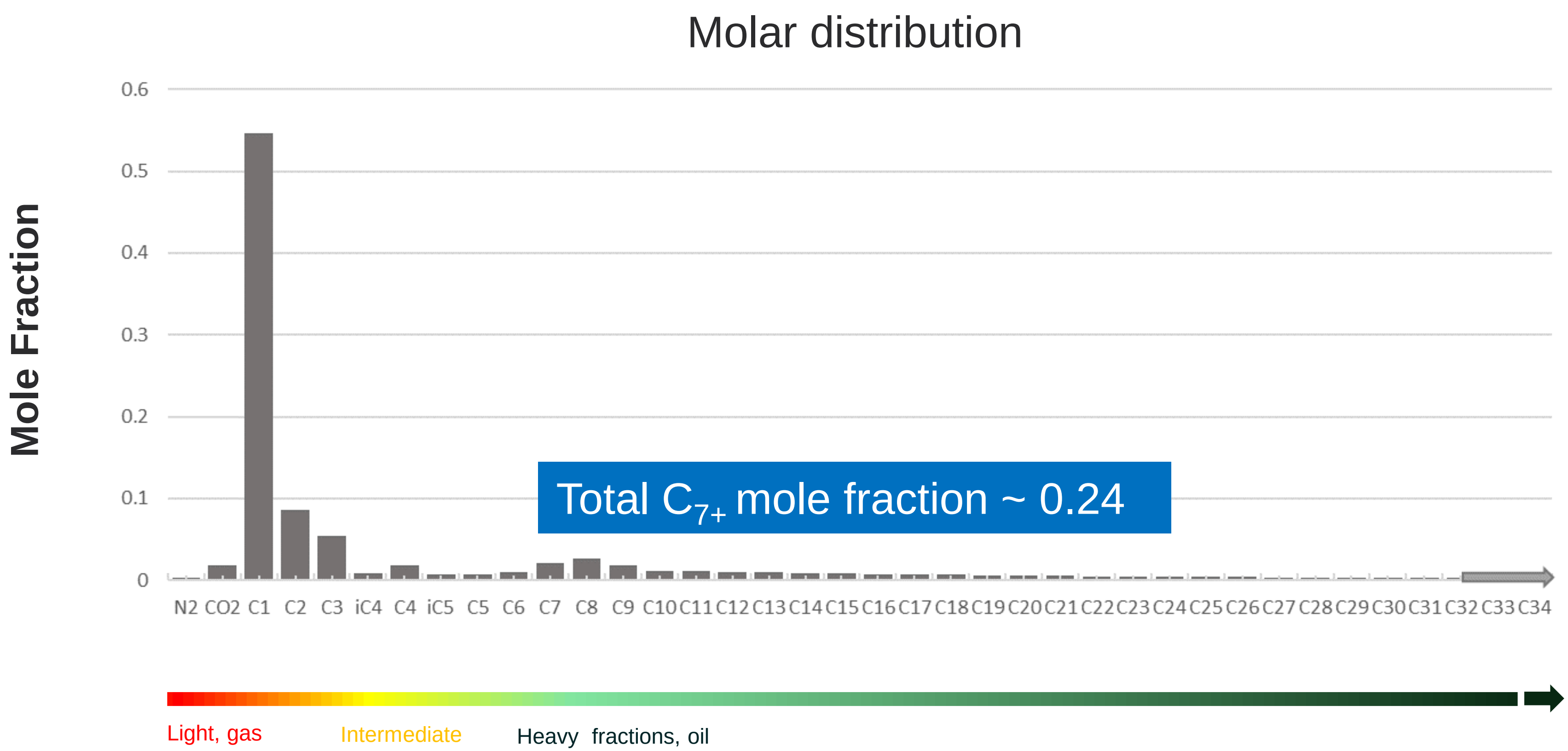
A little quiz | Reservoir Oil or Gas?



Courtesy: Knut Uleberg, Equinor

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A little quiz | Reservoir Oil or Gas?

Courtesy: Knut Uleberg, Equinor

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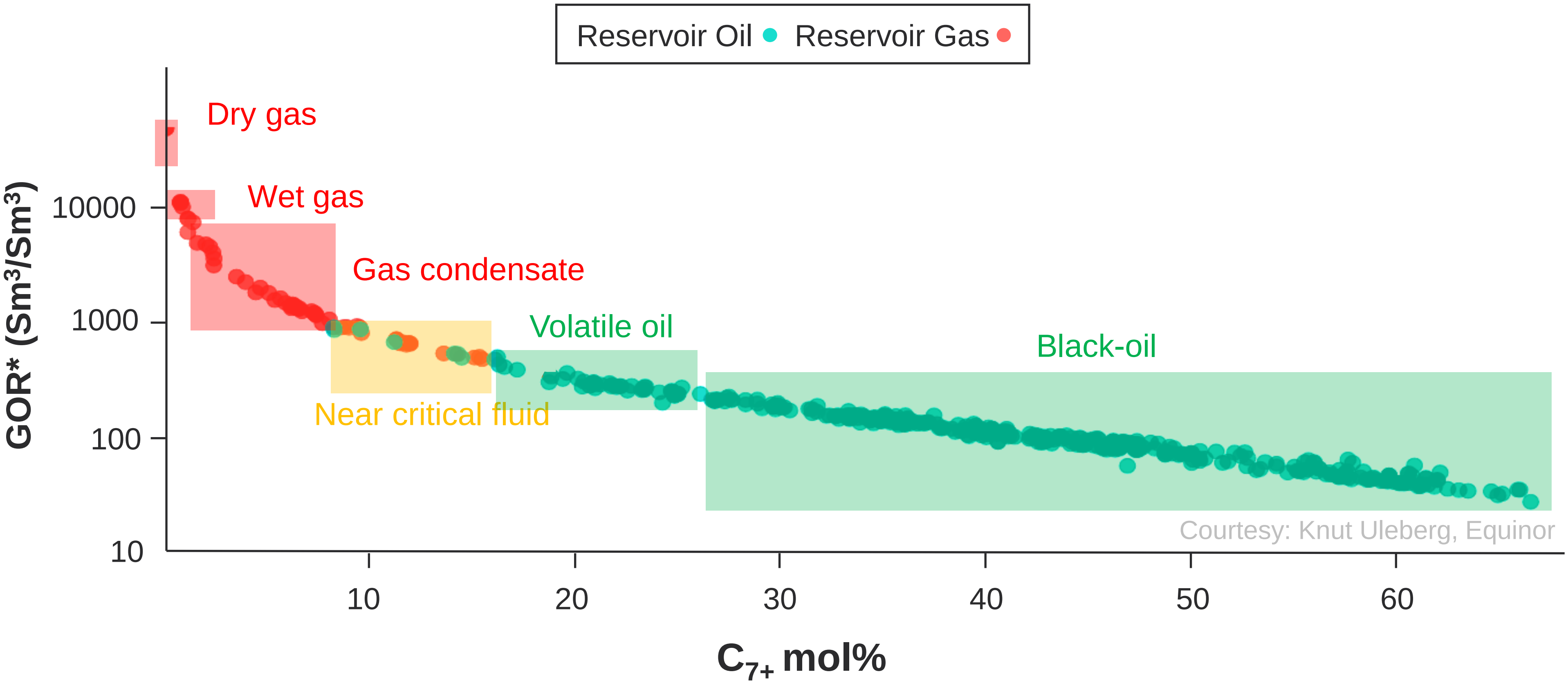
Key to Understand PVT

Heptanes Plus (C_{7+})

Courtesy: Knut Uleberg, Equinor

Classification of fluids | Simulated process GOR vs C7+ content



GOR*: Simulated process GOR, Sm^3/Sm^3

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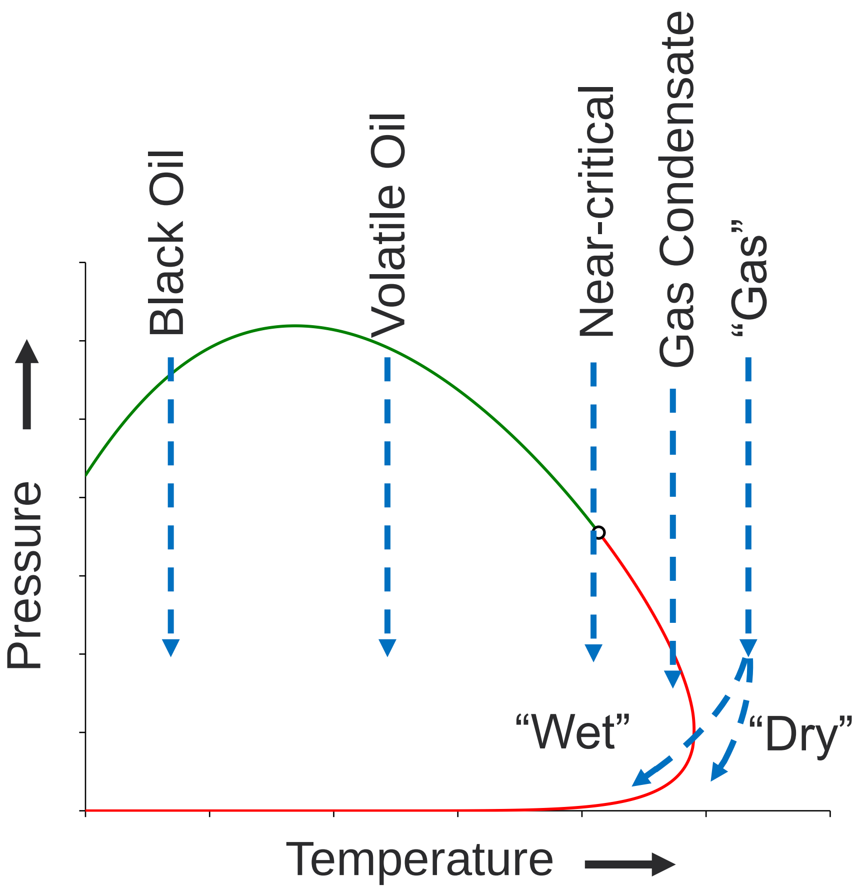
Reservoir Fluid Classification



Fluid type	C_{7+}	GOR
Unit	(mol%)	(scf/STB)
Black Oil	>25	<1,000
Volatile Oil	14-25	1,000-3,000
Near Critical (BP or DP)	11-14	3,000-4,000
Gas Condensate	1-11	4,000-100,000
«Wet» Gas	<1	>100,000
«Dry» Gas	0	∞

** These numbers are rules of thumb and should not be interpreted as absolutes.*

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Reservoir Fluid Classification

Classification of Reservoir Fluid Systems

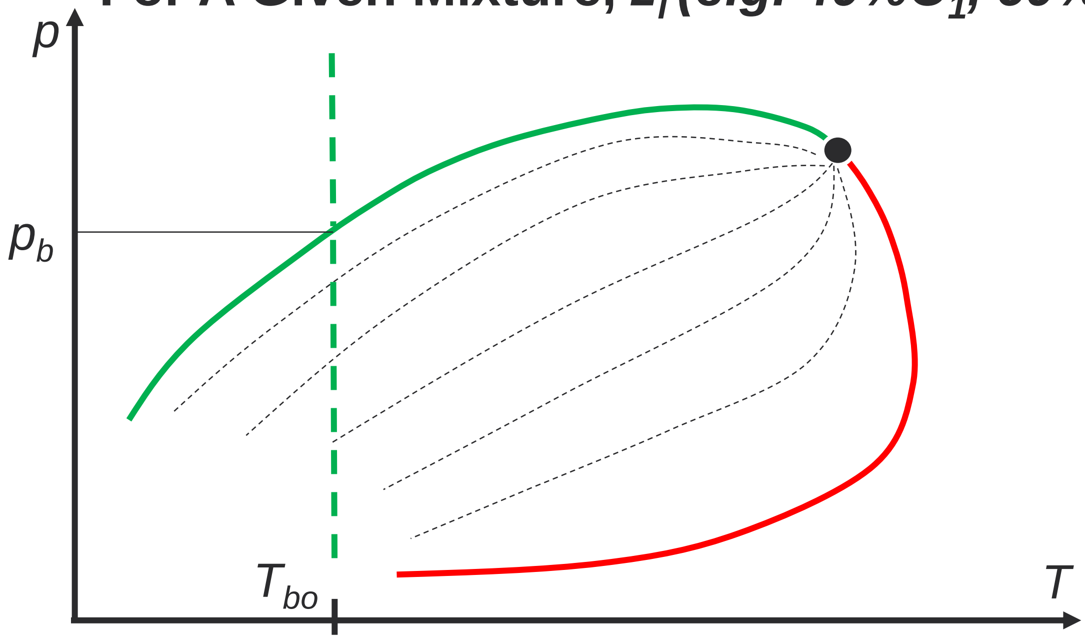
- Dry Gas
- Wet Gas
- Gas Condensate
- Volatile Oil
- Black Oil

The classification of reservoir fluid systems is determined by:

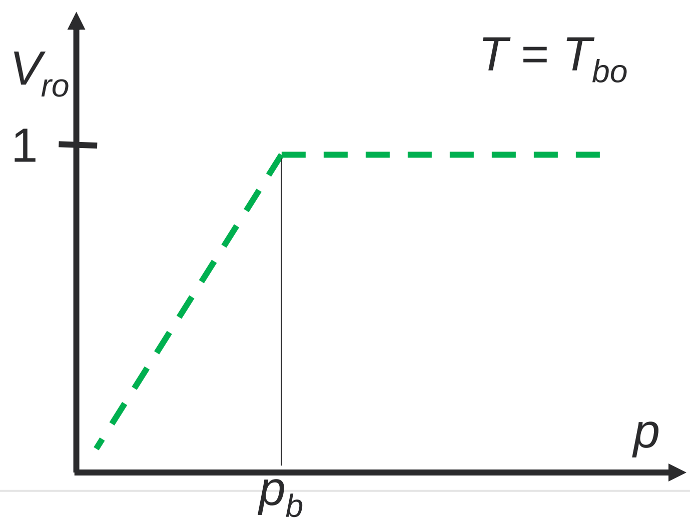
- The location of the reservoir temperature with respect to the critical temperature and cricondentherm.
- Location of the first-stage separator pressure and temperature with respect to the phase diagram of the reservoir fluid.

Black Oil

For A Given Mixture, z_i (e.g. 40%C_1, 60%n-C_{10})



Black Oil

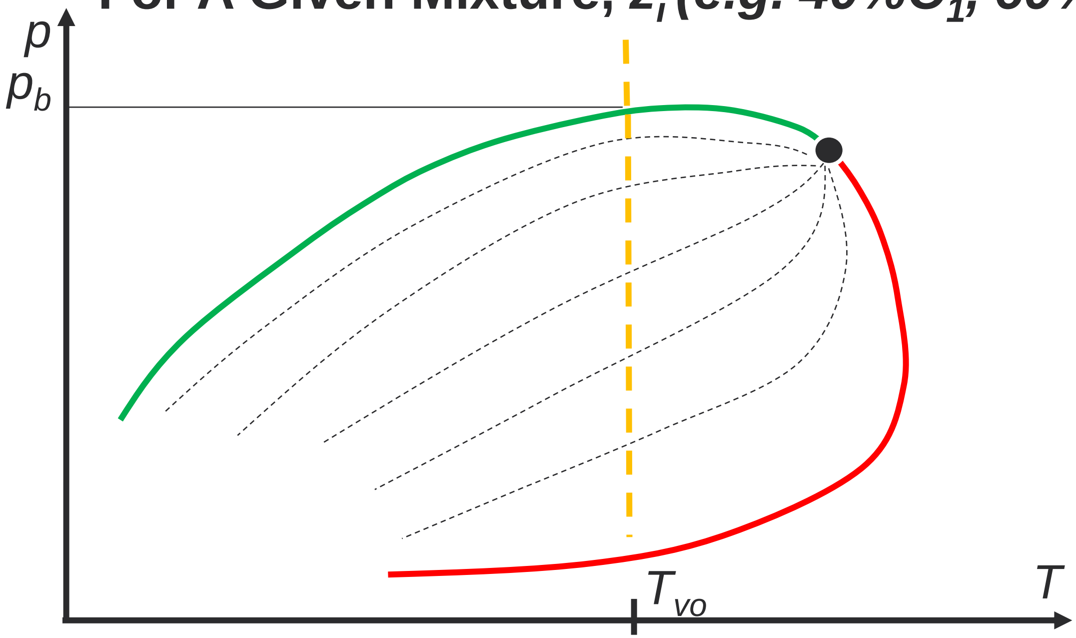


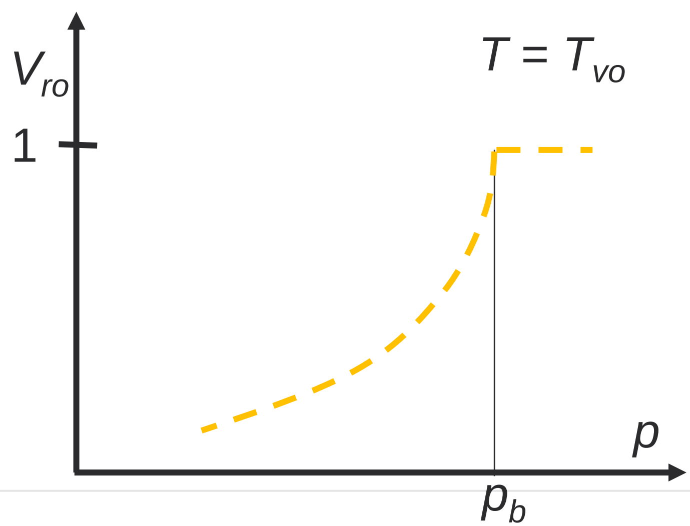
$$V_{ro} = \frac{V_o(p,T)}{V_t(p,T)}$$

V_o = oil phase volume

Volatile Oil

For A Given Mixture, z_i *(e.g. 40%C_1, 60%n-C_{10})*





Volatile Oil

$$V_{ro} = \frac{V_o(p,T)}{V_t(p,T)}$$

V_o = oil phase volume

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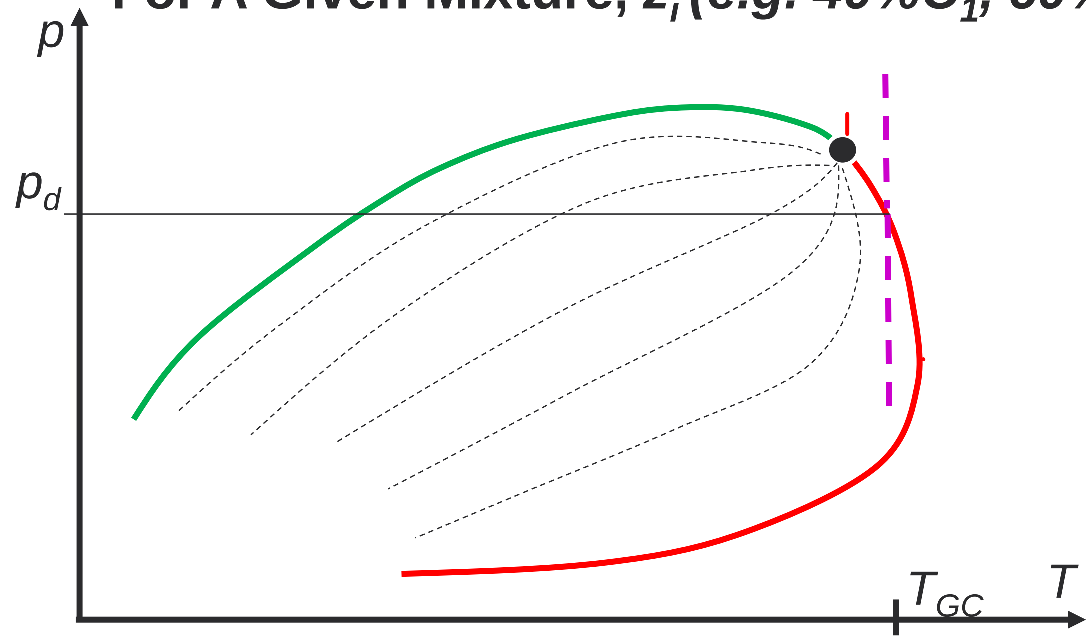
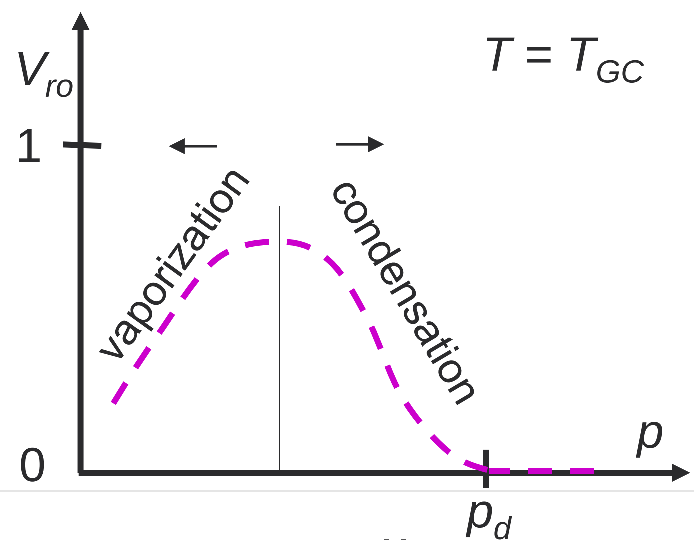
Retrograde Gas Condensate

For A Given Mixture, z_i *(e.g. 40%C_1, 60%n-C_{10})*



Gas Condensate

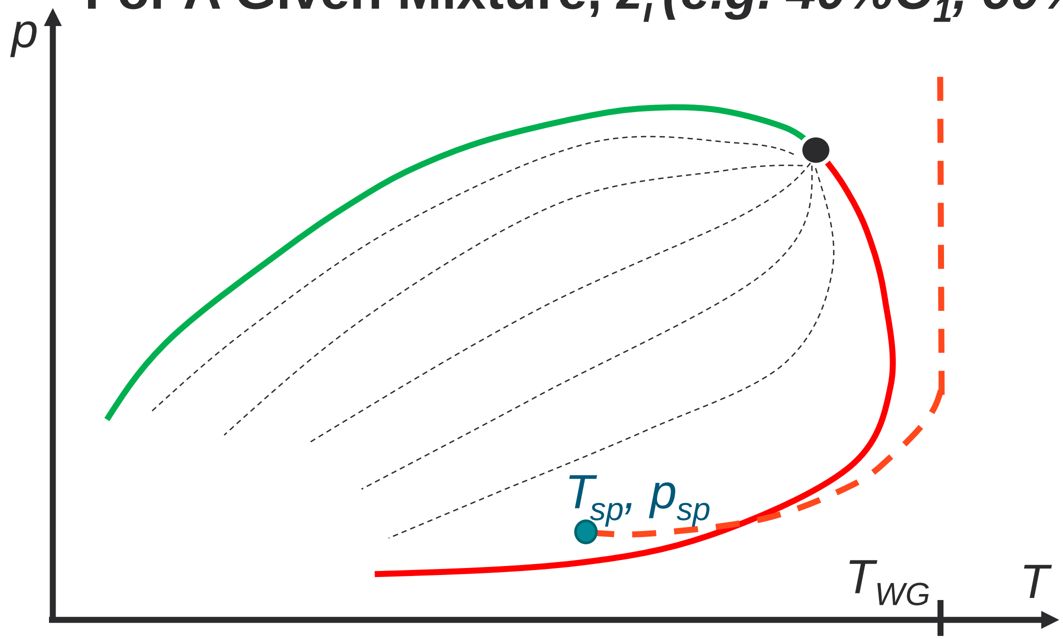


$$V_{ro} = \frac{V_o(p,T)}{V_t(p,T)}$$

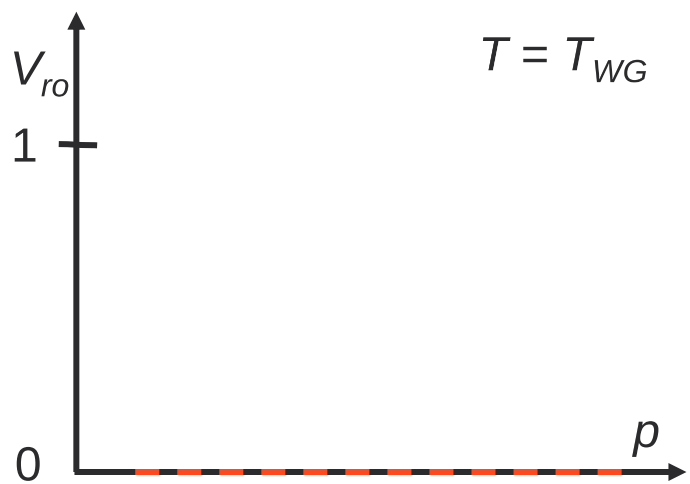
V_o = oil phase volume

Wet Gas

For A Given Mixture, z_i (e.g. 40%C_1, 60%n-C_{10})



Wet Gas

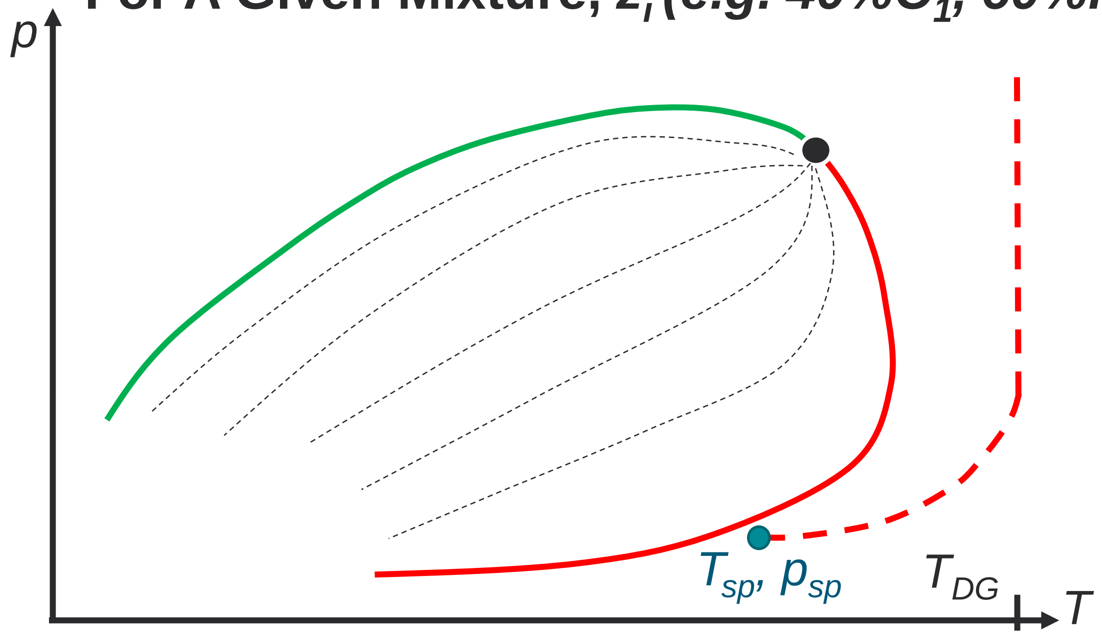


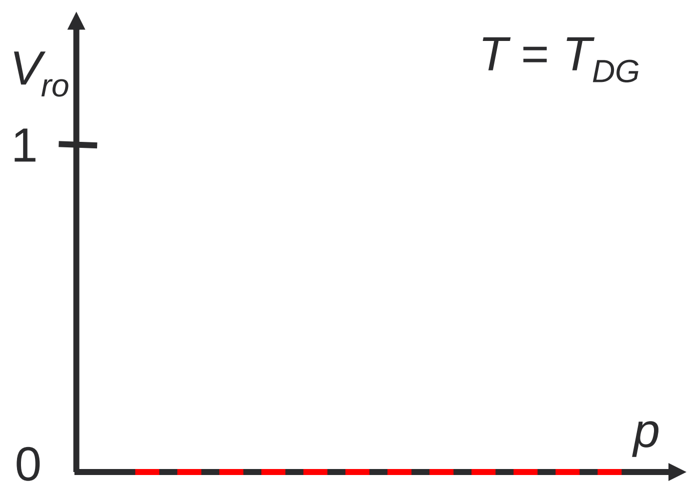
$$V_{ro} = \frac{V_o(p,T)}{V_t(p,T)}$$

V_o = oil phase volume

Dry Gas

For A Given Mixture, z_i (e.g. 40%C_1, 60%n-C_{10})



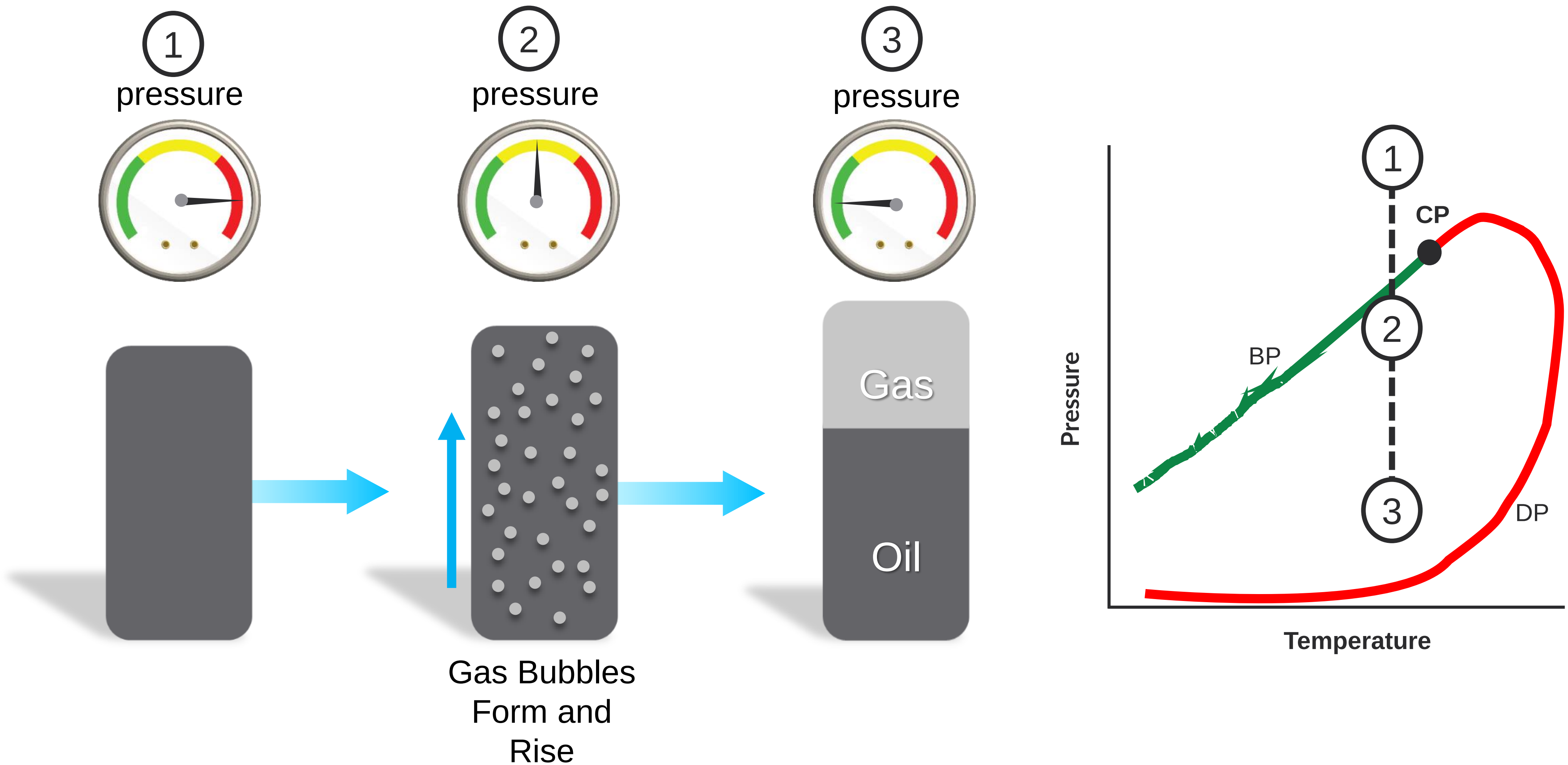


Dry Gas

$$V_{ro} = \frac{V_o(p,T)}{V_t(p,T)}$$

V_o = oil phase volume

Volatile Oil Reservoir Fluid Example



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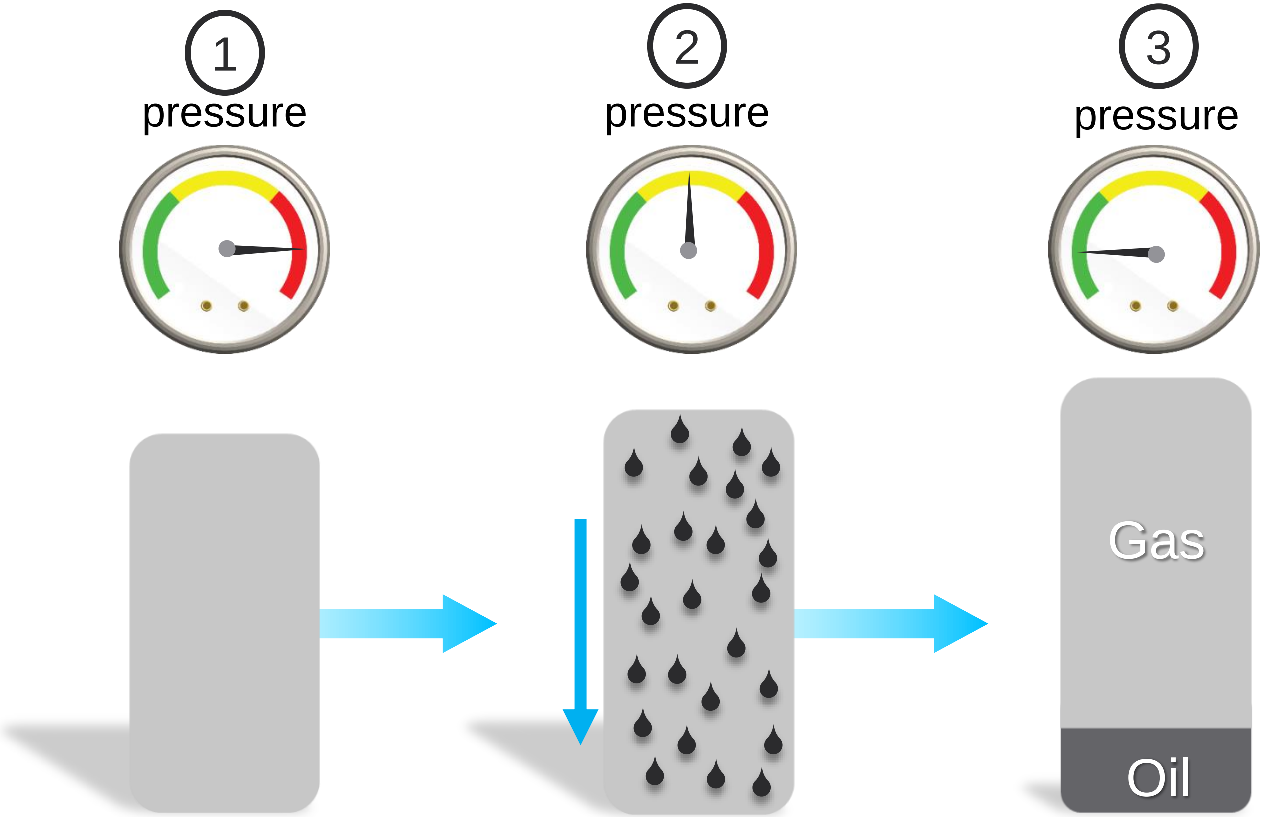
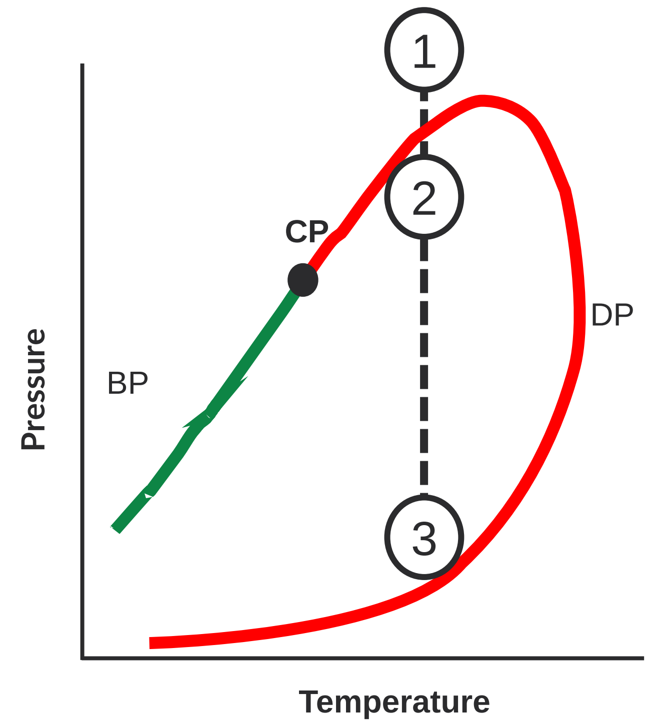
Gas Condensate Reservoir Fluid Example



Oil Droplets Form and Fall



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Petroleum Fluids – Example Compositions

Component	Dry Gas	Wet Gas	Gas Condensate	Near-Critical Oil	Volatile Oil	Black Oil
CO_2	0.10	1.41	2.37	1.30	0.93	0.02
N_2	2.07	0.25	0.31	0.56	0.21	0.34
C_1	86.12	92.46	73.19	69.44	58.77	34.62
C_2	5.91	3.18	7.80	7.88	7.57	4.11
C_3	3.58	1.01	3.55	4.26	4.09	1.01
i-C_4	1.72	0.28	0.71	0.89	0.91	0.76
n-C_4		0.24	1.45	2.14	2.09	0.49
i-C_5	0.50	0.13	0.64	0.90	0.77	0.43
n-C_5		0.08	0.68	1.13	1.15	0.21
$C_{6(s)}$		0.14	1.09	1.46	1.75	1.61
C_{7+}		0.82	8.21	10.04	21.76	56.40
Properties						
$M_{C_{7+}}$		130	184	219	228	274
$\gamma_{C_{7+}}$		0.763	0.816	0.839	0.858	0.920
K_{wC_7}		12.00	11.95	11.98	11.83	11.47
GOR, scf/STB	∞	105,000	5,450	3,650	1,490	300
OGR, STB/MMscf	0	10	180	275		
γ_{API}		57	49	45	38	24
γ_g		0.61	0.70	0.71	0.70	0.63
p_{sat}, psia		3,430	6.560	7,015	5,420	2,810

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Question: What's Wrong with this Table?

Component	Dry Gas	Wet Gas	Gas Condensate	Near-Critical Oil	Volatile Oil	Black Oil
CO_2	0.10	1.41	2.37	1.30	0.93	0.02
N_2	2.07	0.25	0.31	0.56	0.21	0.34
C_1	86.12	92.46	73.19	69.44	58.77	34.62
C_2	5.91	3.18	7.80	7.88	7.57	4.11
C_3	3.58	1.01	3.55	4.26	4.09	1.01
$i\text{-}C_4$	1.72	0.28	0.71	0.89	0.91	0.76
$n\text{-}C_4$		0.24	1.45	2.14	2.09	0.49
$i\text{-}C_5$	0.50	0.13	0.64	0.90	0.77	0.43
$n\text{-}C_5$		0.08	0.68	1.13	1.15	0.21
$C_{6(s)}$		0.14	1.09	1.46	1.75	1.61
C_{7+}		0.82	8.21	10.04	21.76	56.40
Properties						
p_{sat}, psia		3,430	6.560	7,015	5,420	2,810

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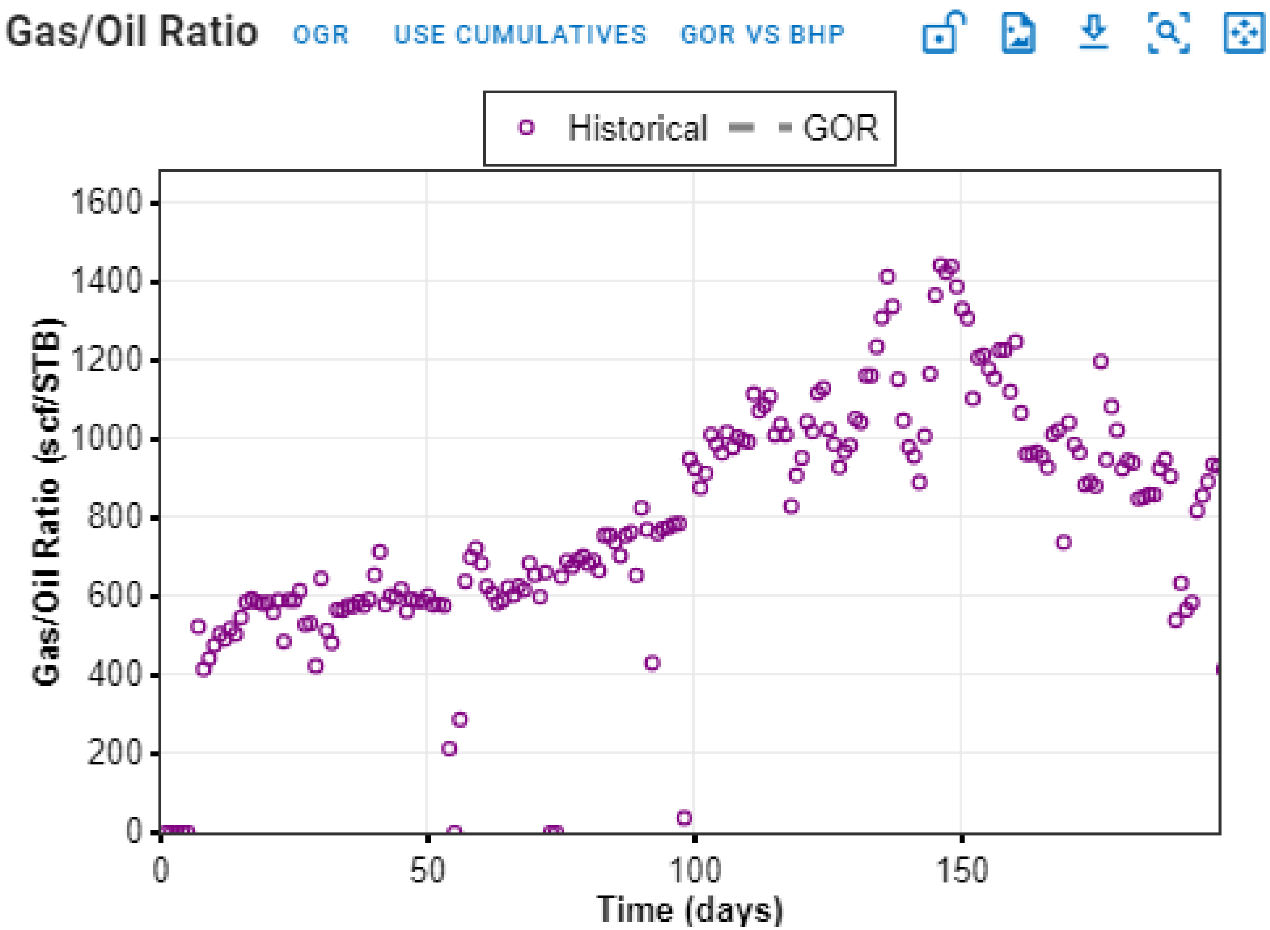
Question: What's Wrong with this Table?

Fluid Initialization

Fluid Initialization 1.01

Goal: Be able to use readily available data, specially producing GOR (or CGR), to initialize a reservoir fluid for an unconventional well



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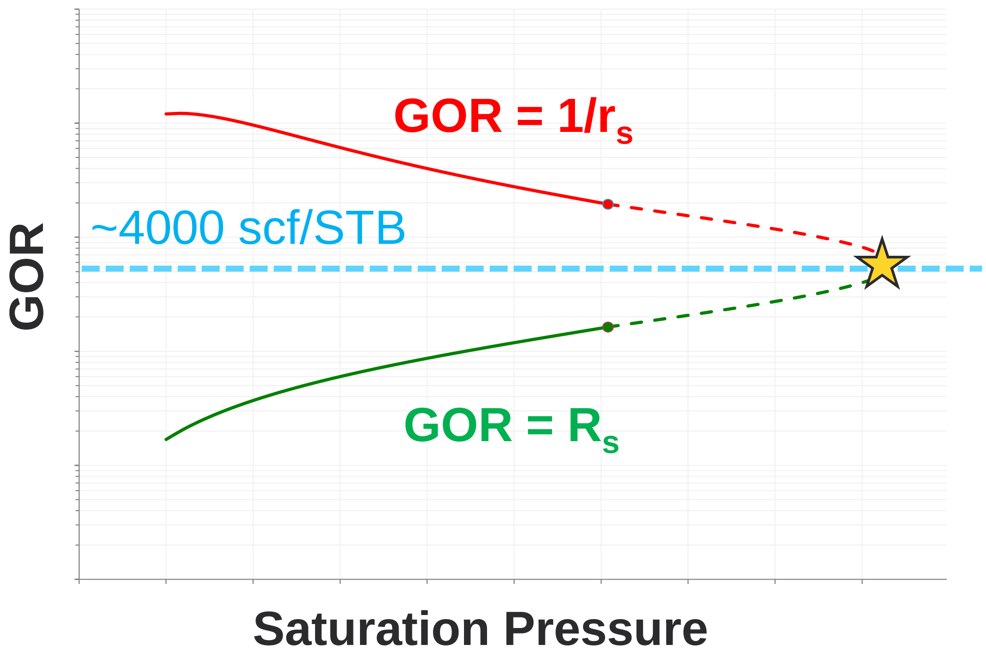
We’ll do the same as Steph Curry – Practice!

PVT: Practical Wisdom



- The producing GOR (CGR) will tell you a lot about the well.
- In general, below p_{sat}, producing GORs are expected to increase.
- Wet gases: CGR (GOR) is constant over time (no p_{sat}).
- Dry gas: doesn't produce hydrocarbon liquids.
- Rule of thumb:
  Critical point ~4000 scf/STB
  (or ~ 250 STB/MMscf).

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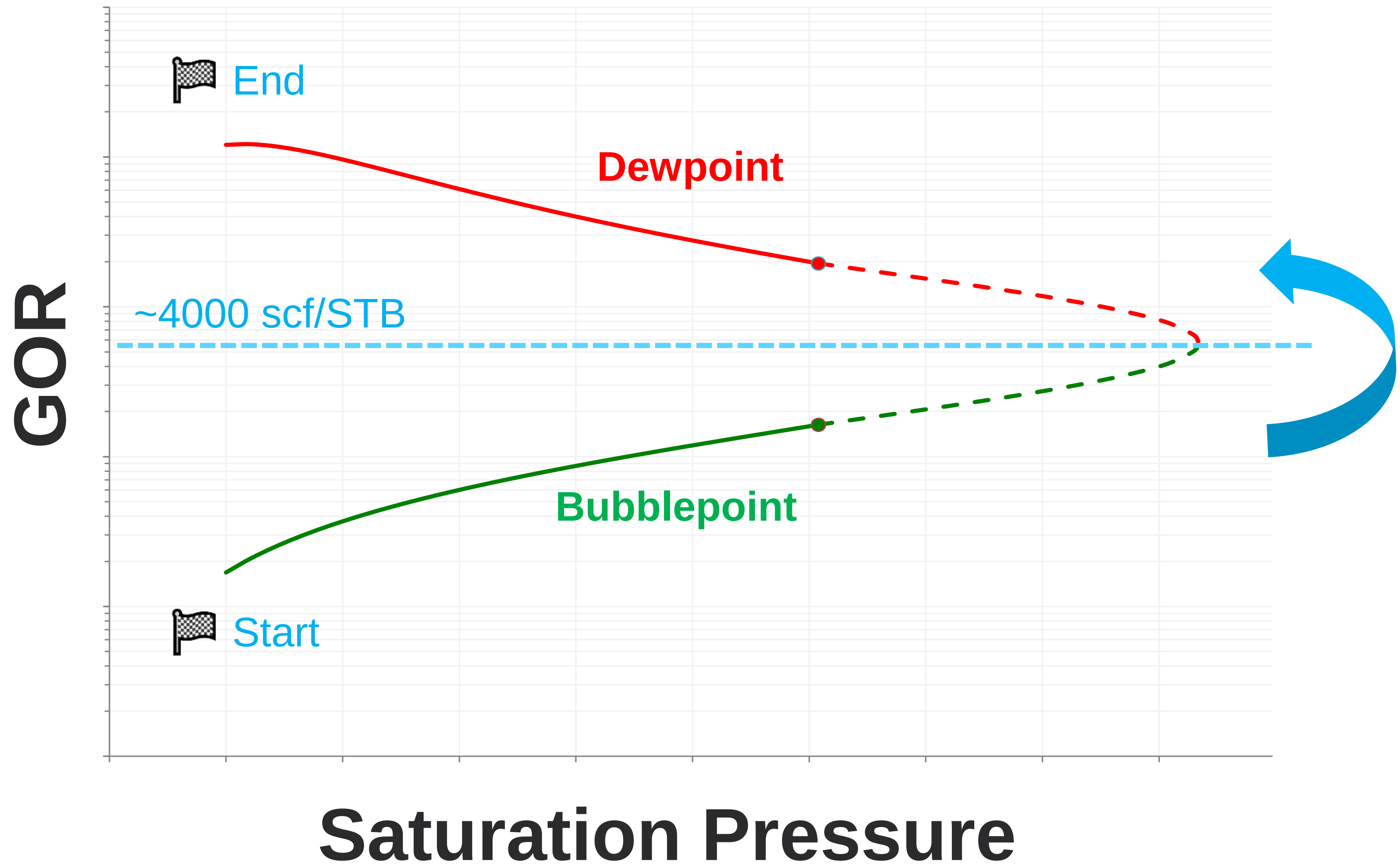
PVT: Practical Wisdom



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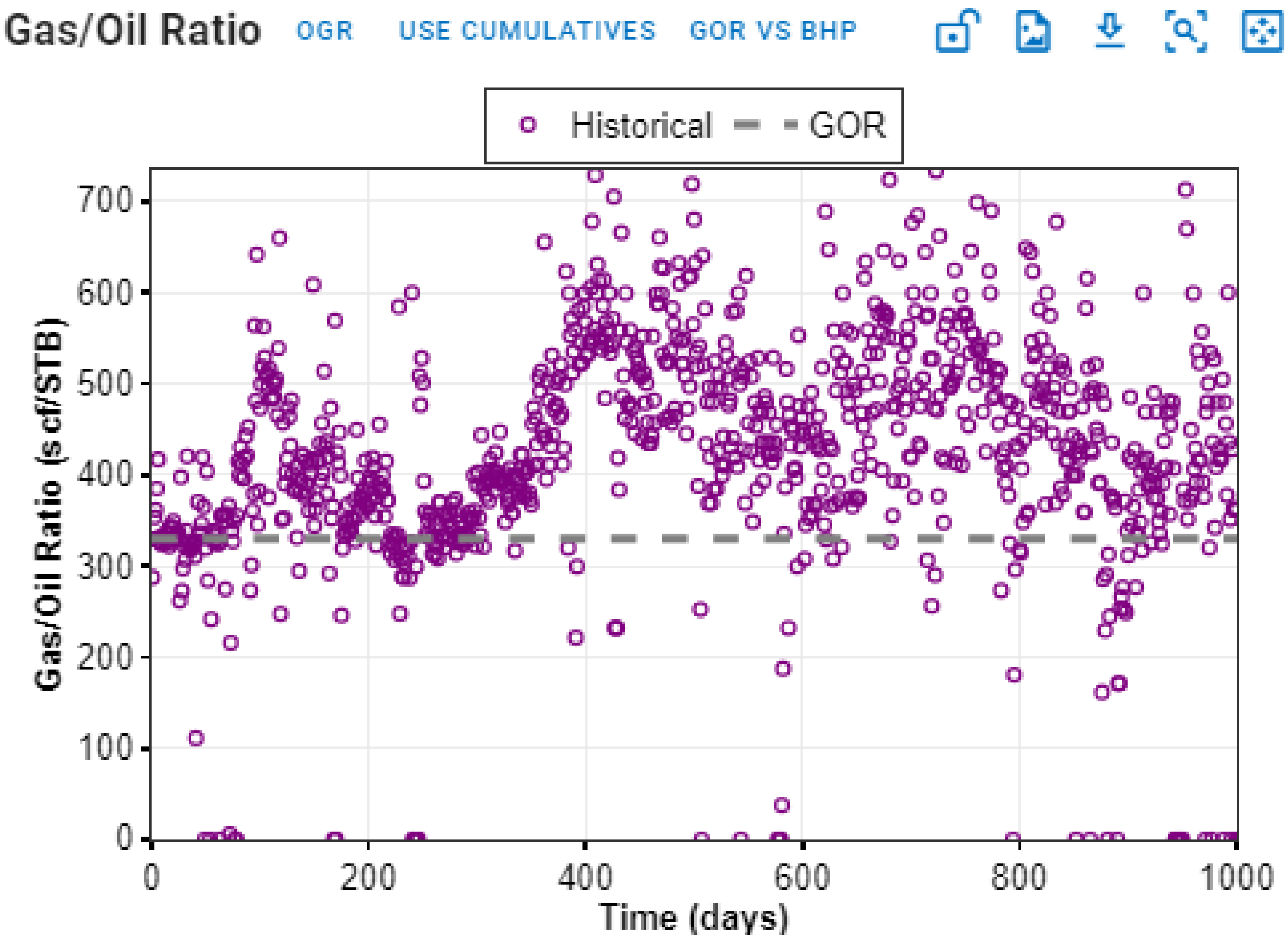
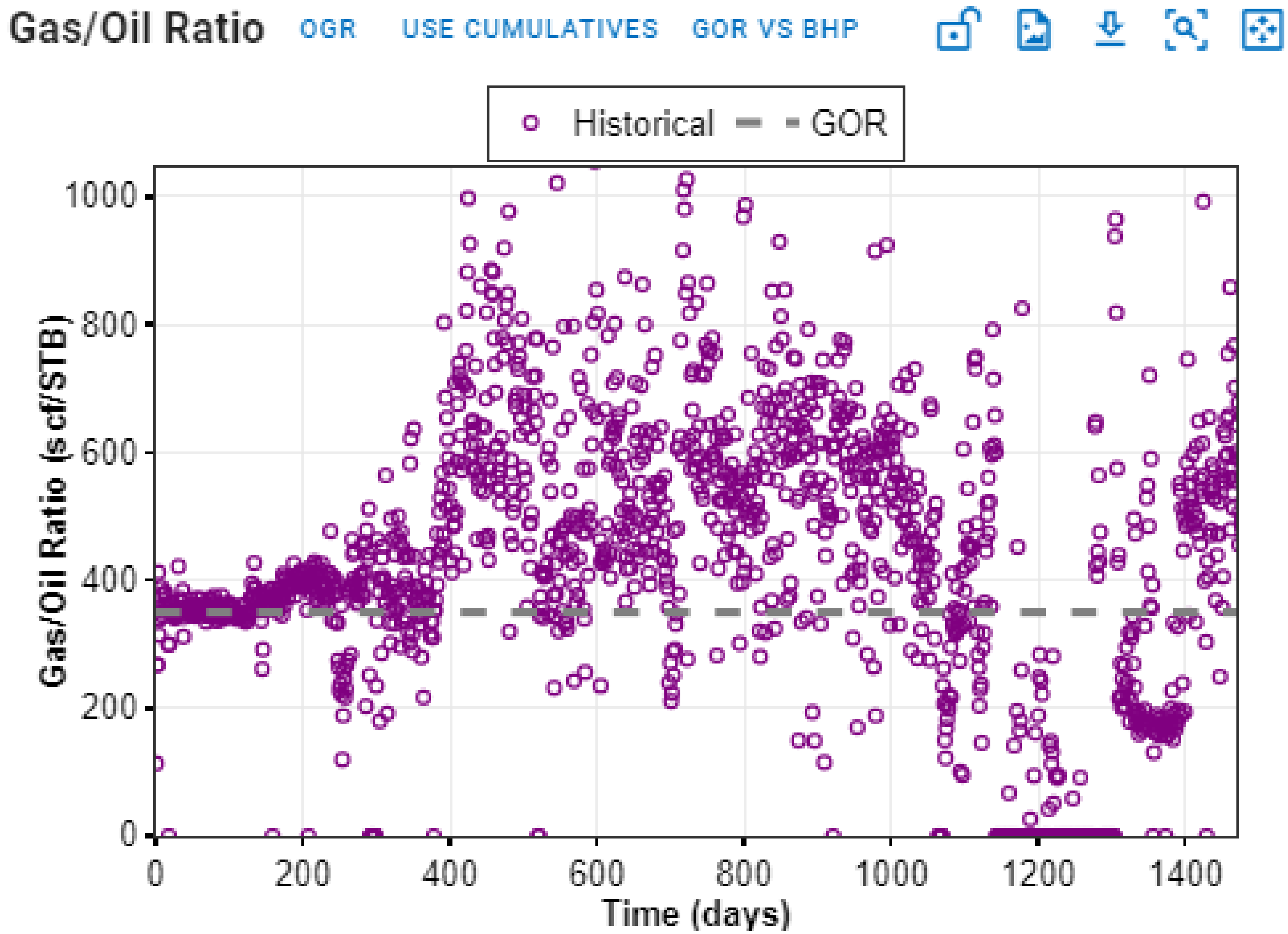
Case Study 1



Gas/Oil Ratio
OGR
USE CUMULATIVES
GOR VS BHP
Historical
GOR
Gas/Oil Ratio (scf/STB)
0
100
200
300
400
500
600
700
0
200
400
600
800
1000
Time (days)

Case Study 2



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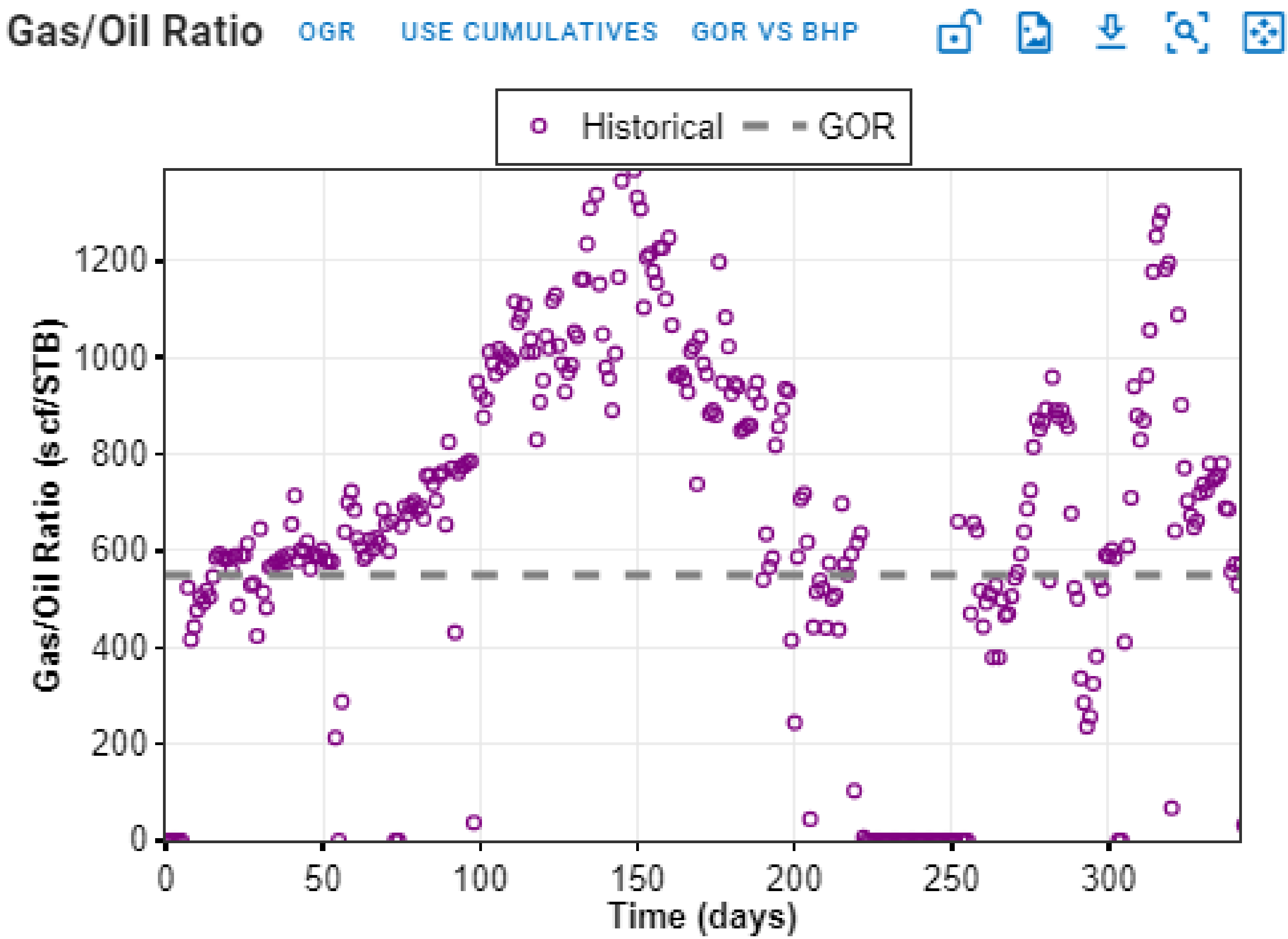
Case Study 3



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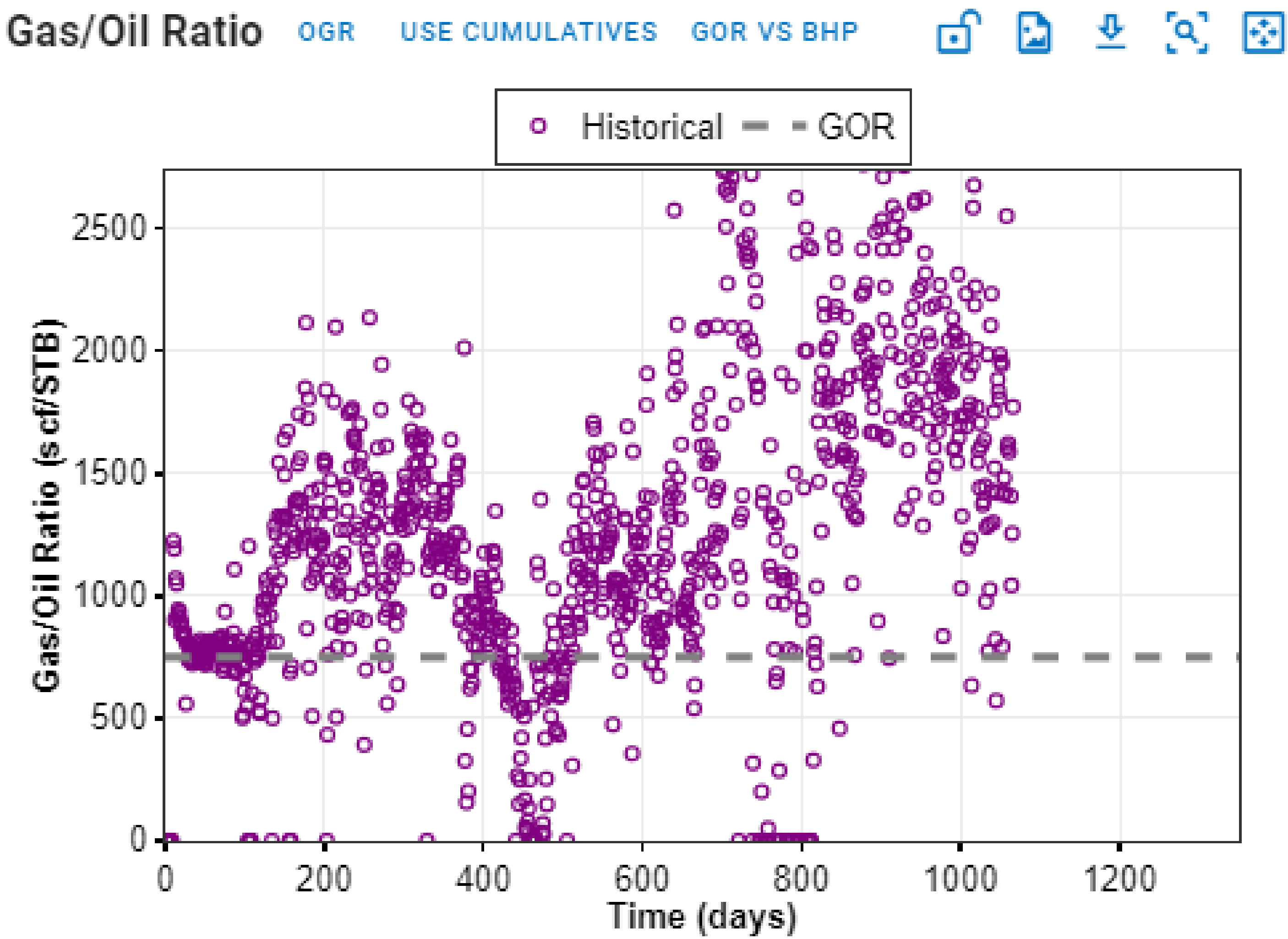
Case Study 4



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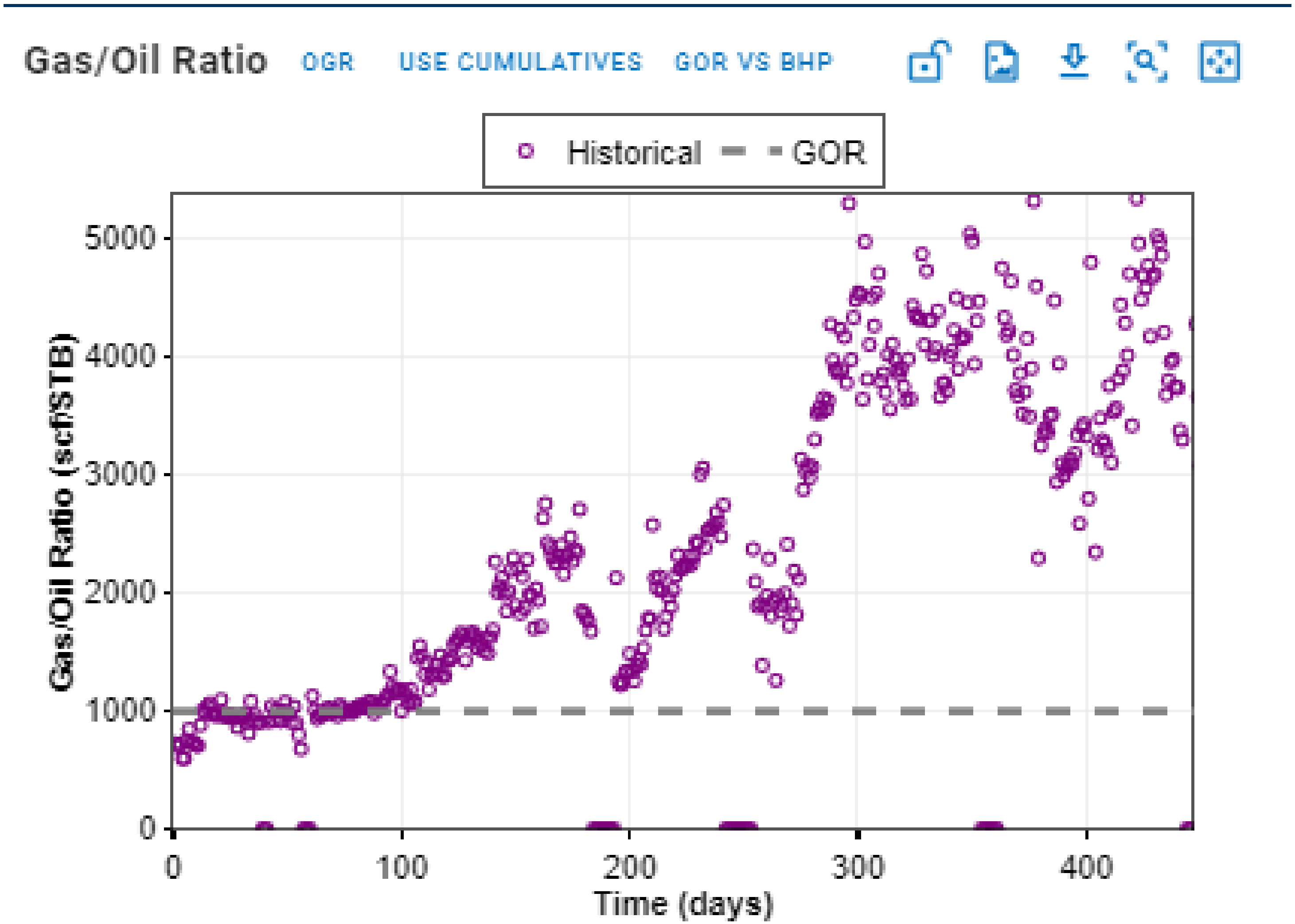
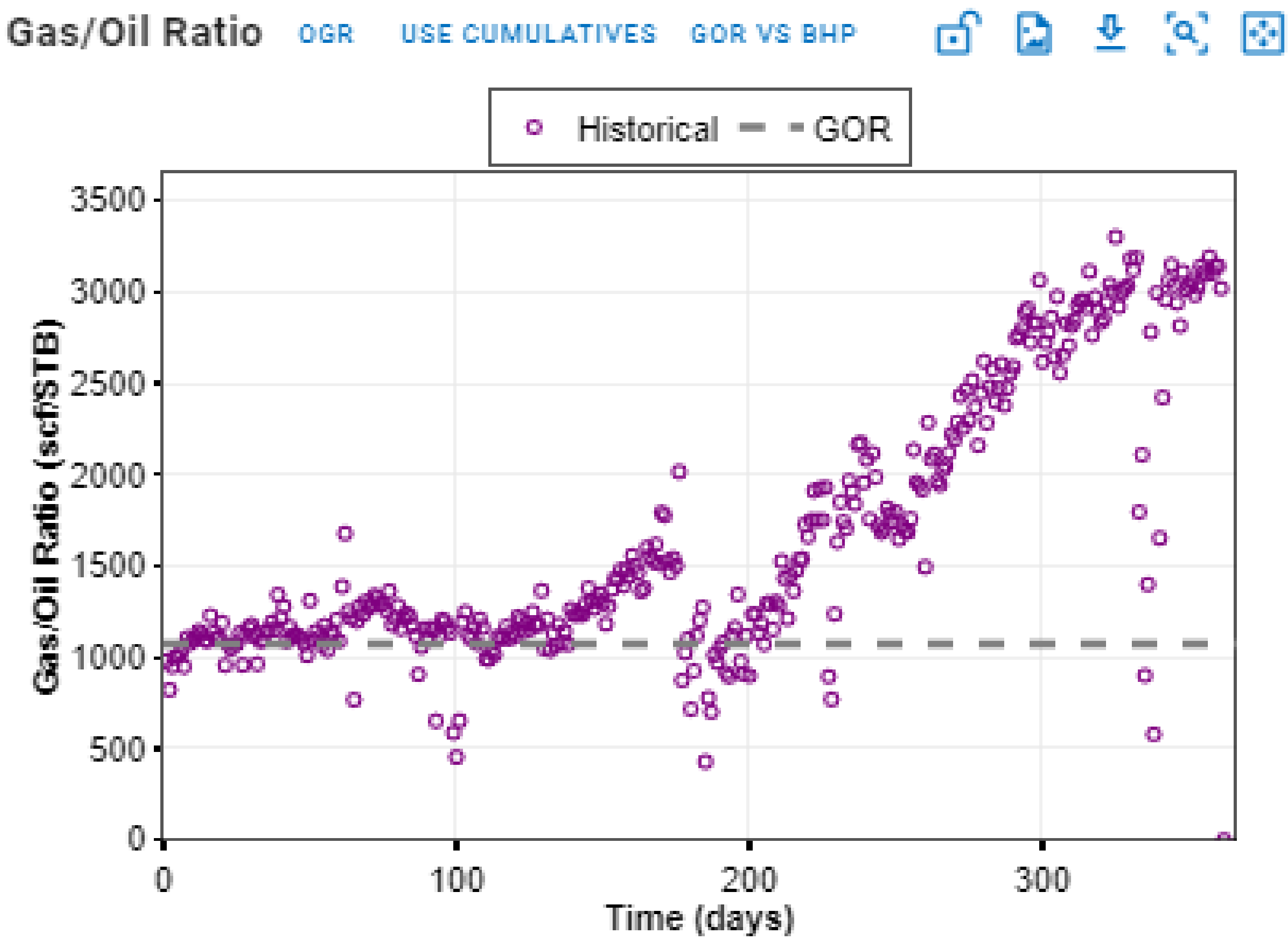
Case Study 5



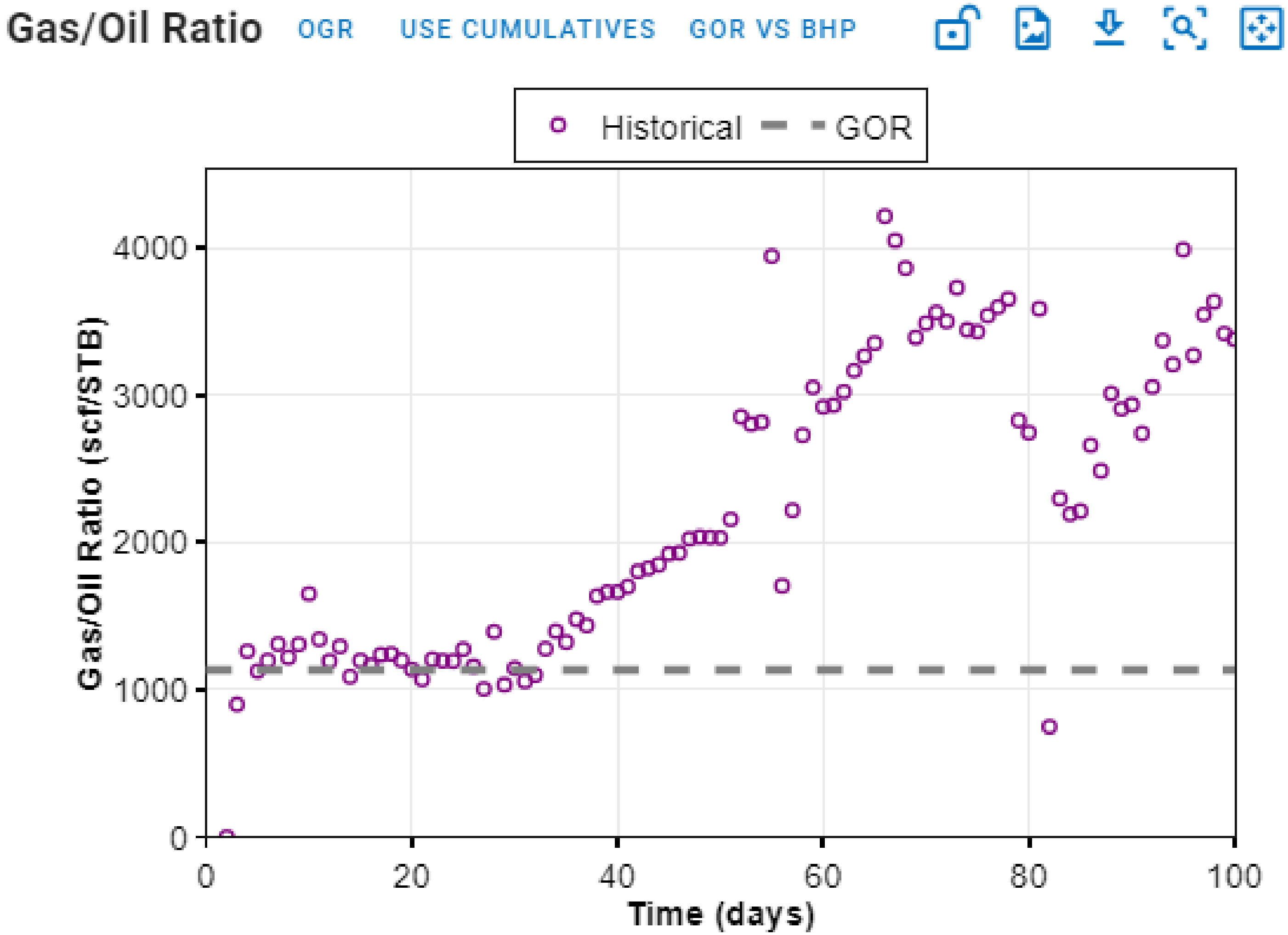
Gas/Oil Ratio
OGR
USE CUMULATIVES
GOR VS BHP
Historical
GOR
Gas/Oil Ratio (scf/STB)
0
1000
2000
3000
4000
5000
0
100
200
300
400
Time (days)

Case Study 6

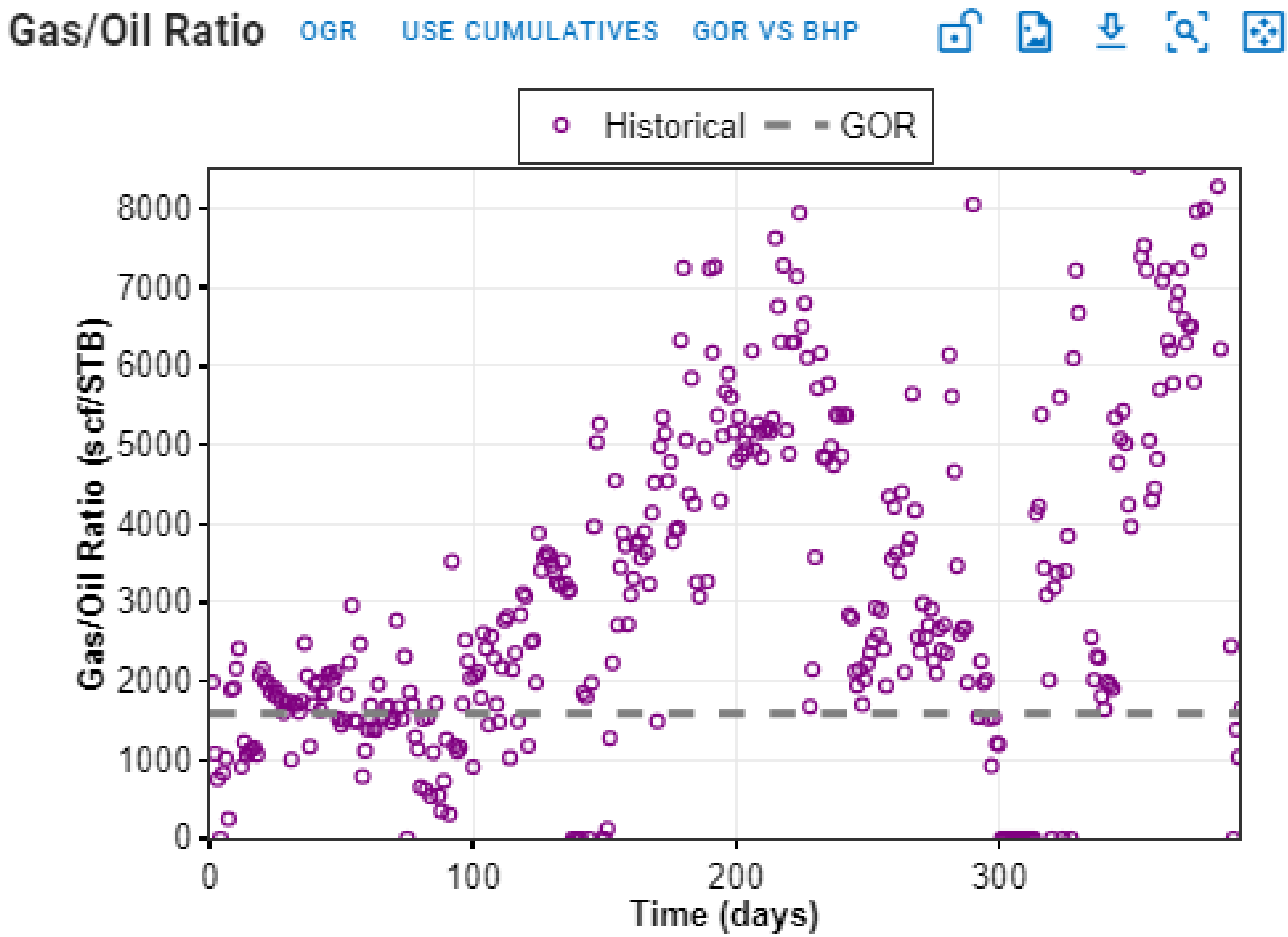


Gas/Oil Ratio
OGR
USE CUMULATIVES
GOR VS BHP
Historical
GOR
Gas/Oil Ratio (scf/STB)
0
500
1000
1500
2000
2500
3000
3500
0
100
200
300
Time (days)

Case Study 7


Gas/Oil Ratio
OGR
USE CUMULATIVES
GOR VS BHP
Historical
GOR
Gas/Oil Ratio (scf/STB)
Time (days)
0
1000
2000
3000
4000
0
20
40
60
80
100

Case Study 8



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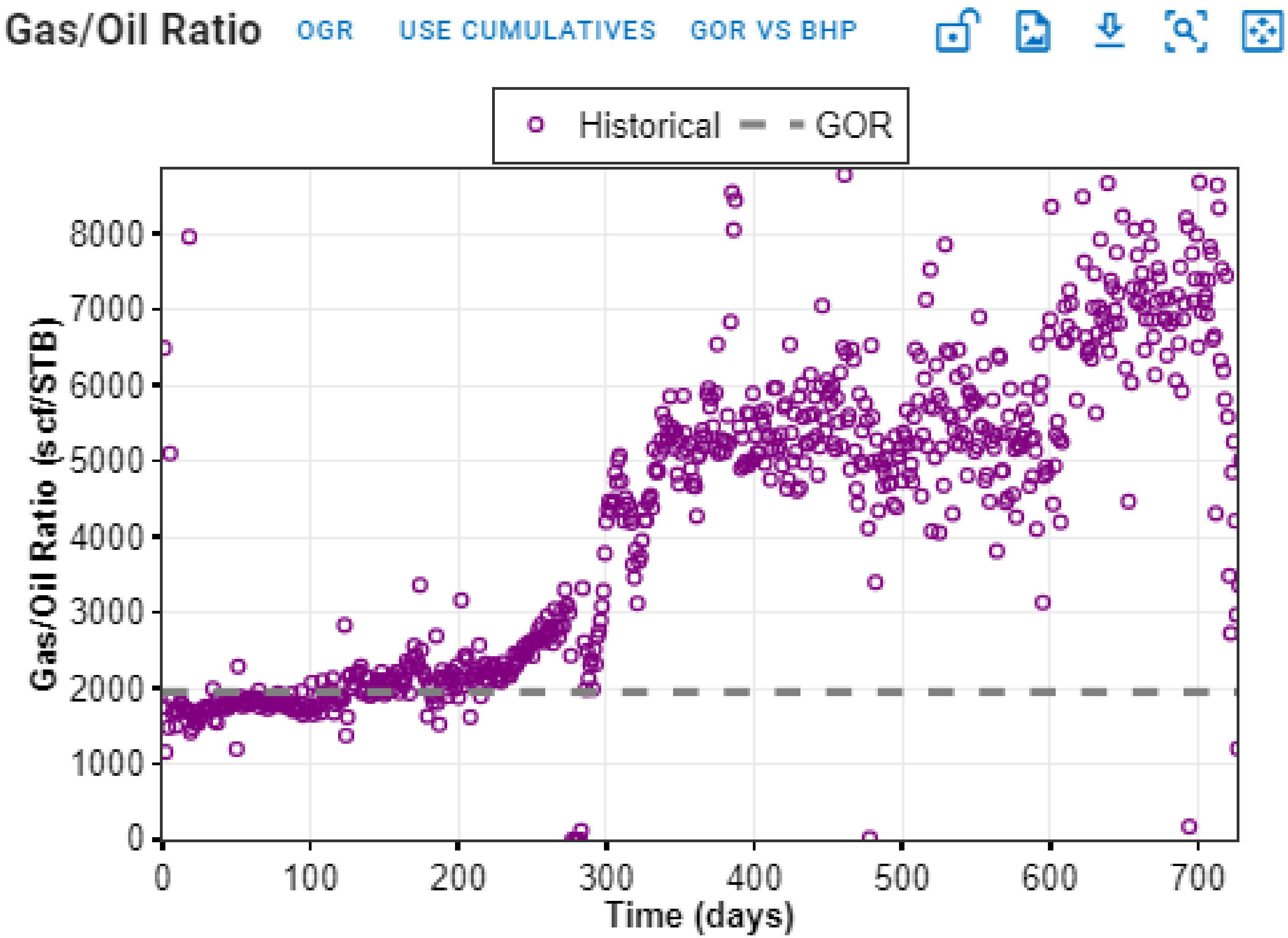
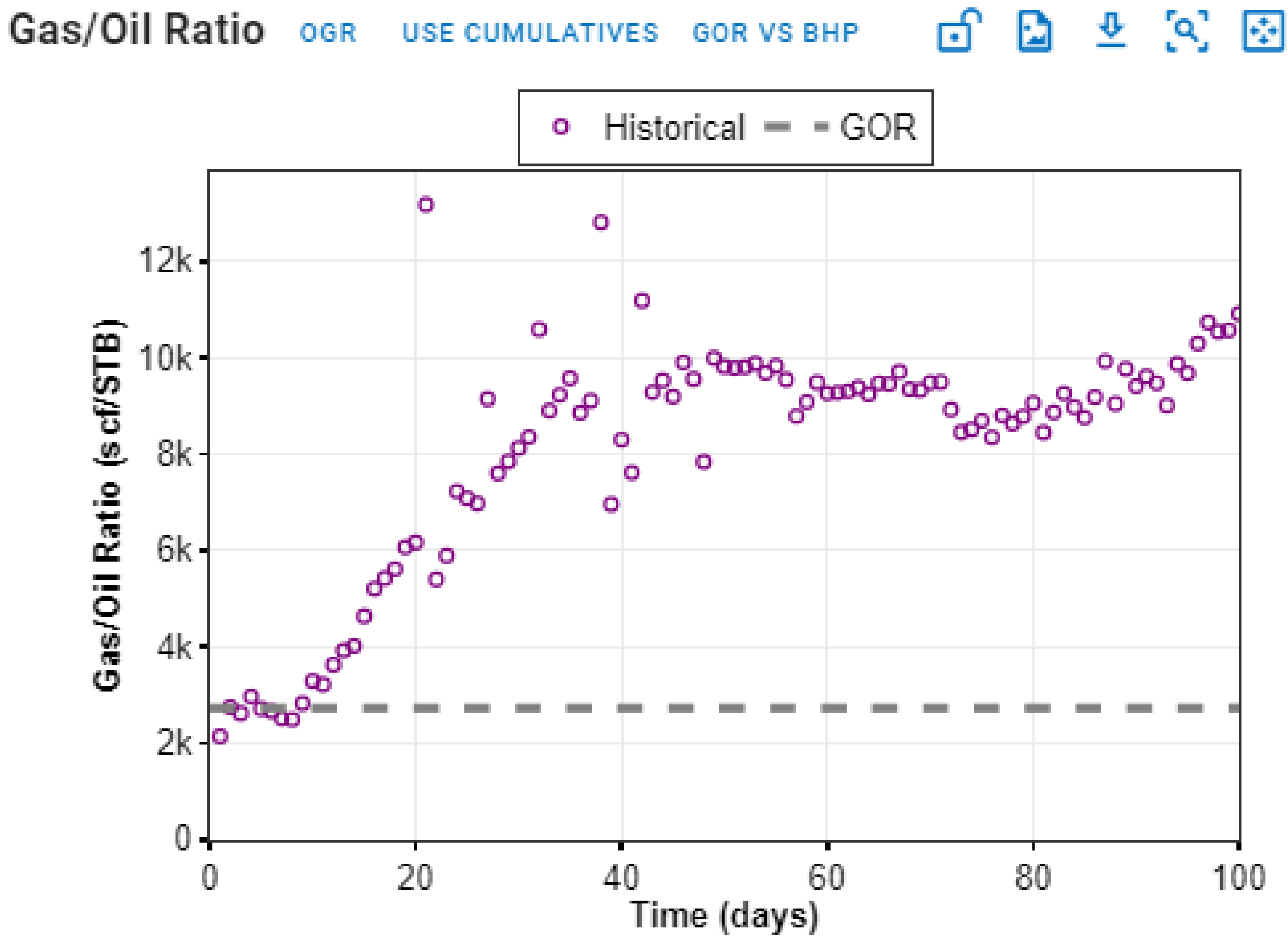
Case Study 9

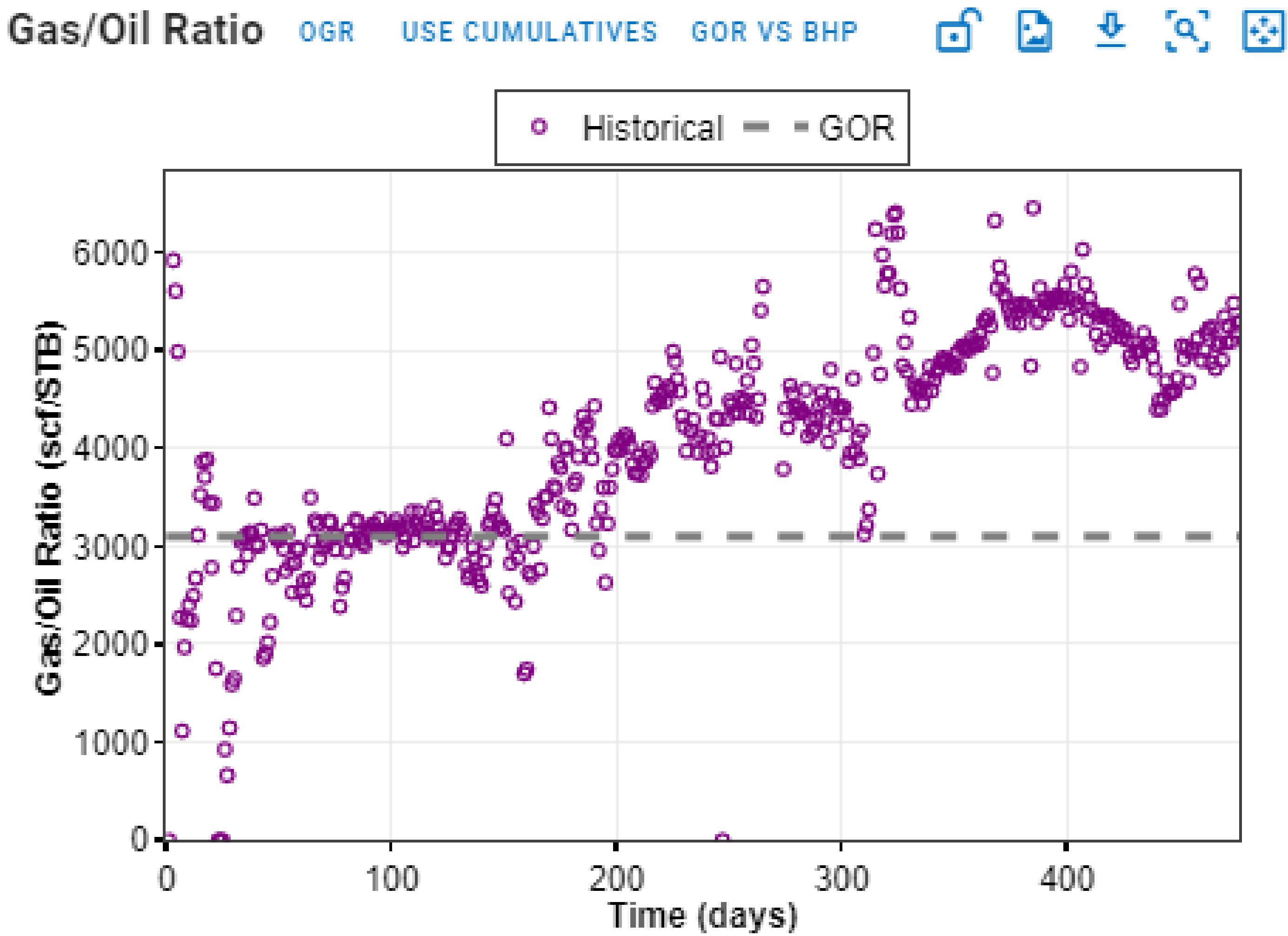


Gas/Oil Ratio
OGR
USE CUMULATIVES
GOR VS BHP
Historical
GOR
Gas/Oil Ratio (scf/STB)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
600
700
Time (days)

Case Study 10



Case Study 11



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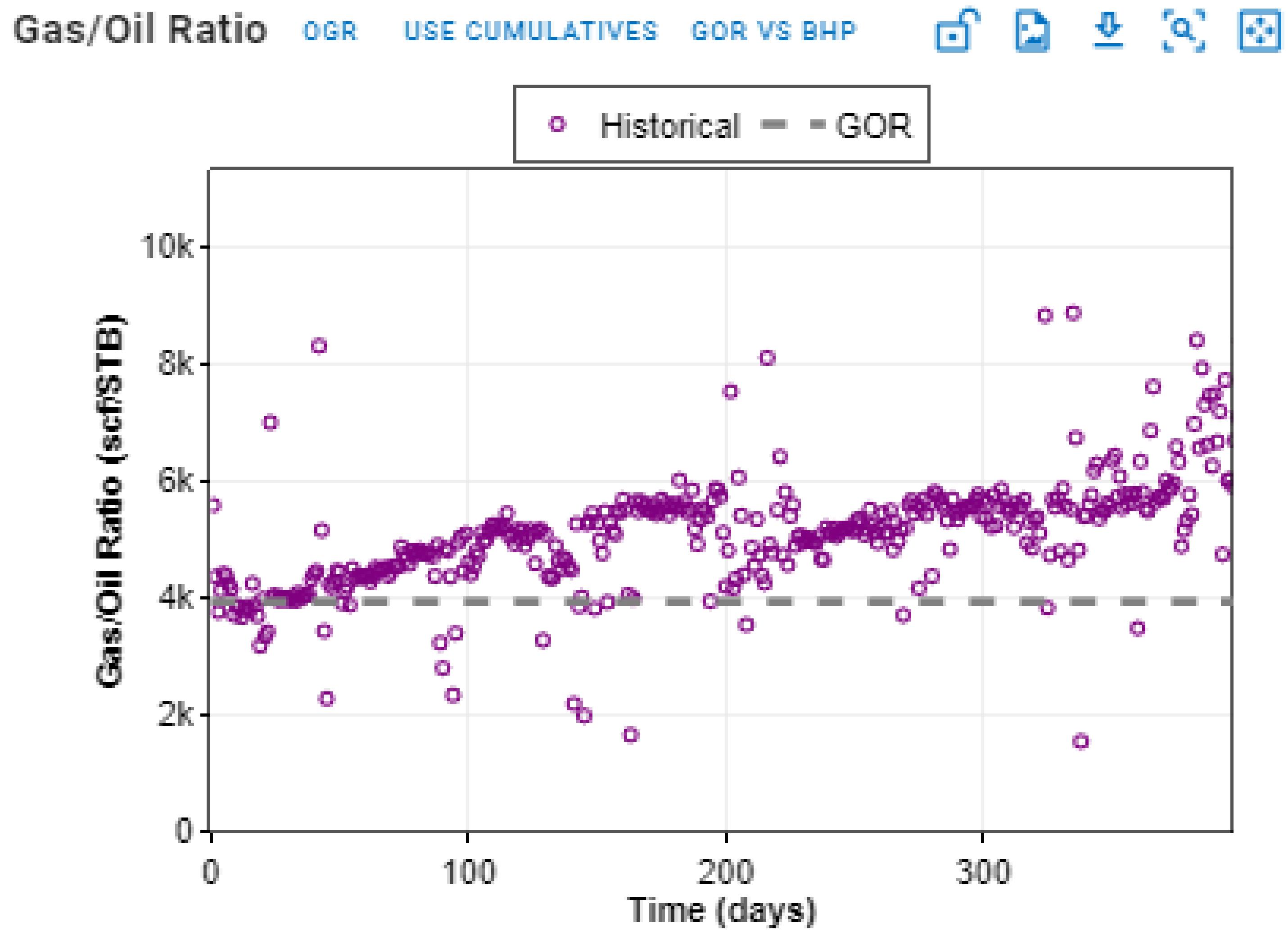
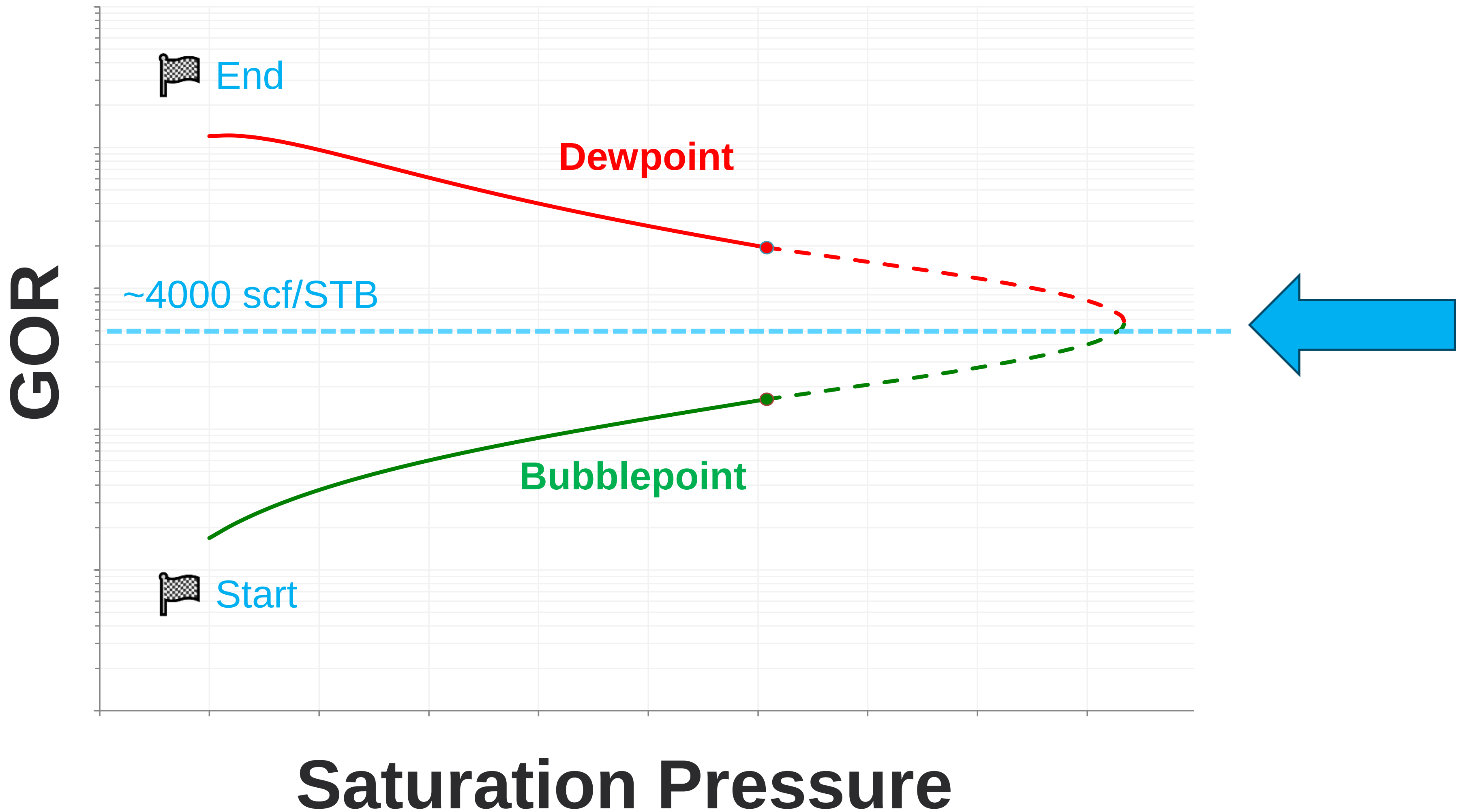
Case Study 12



PVT: Practical Wisdom



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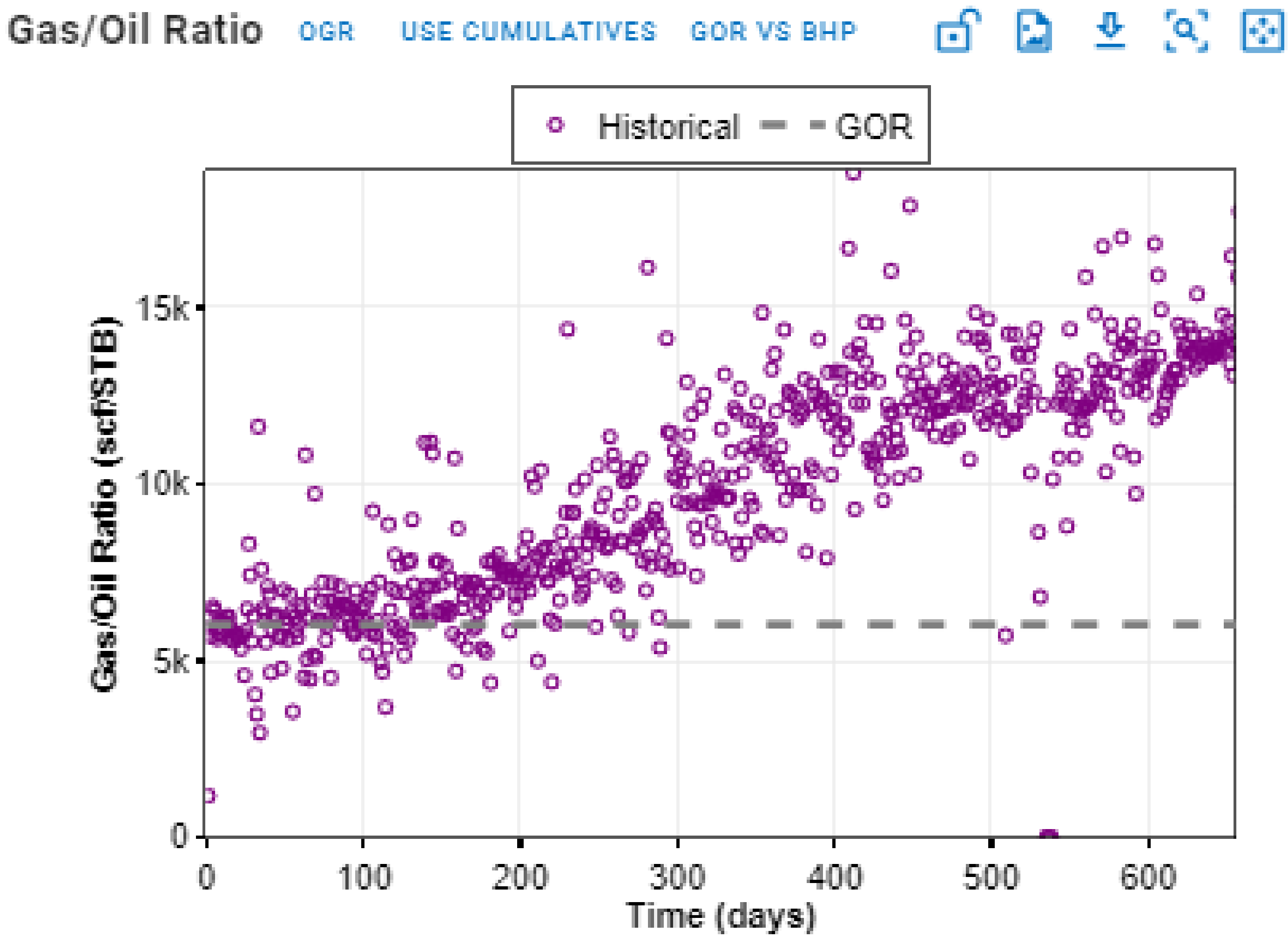
Case Study 13



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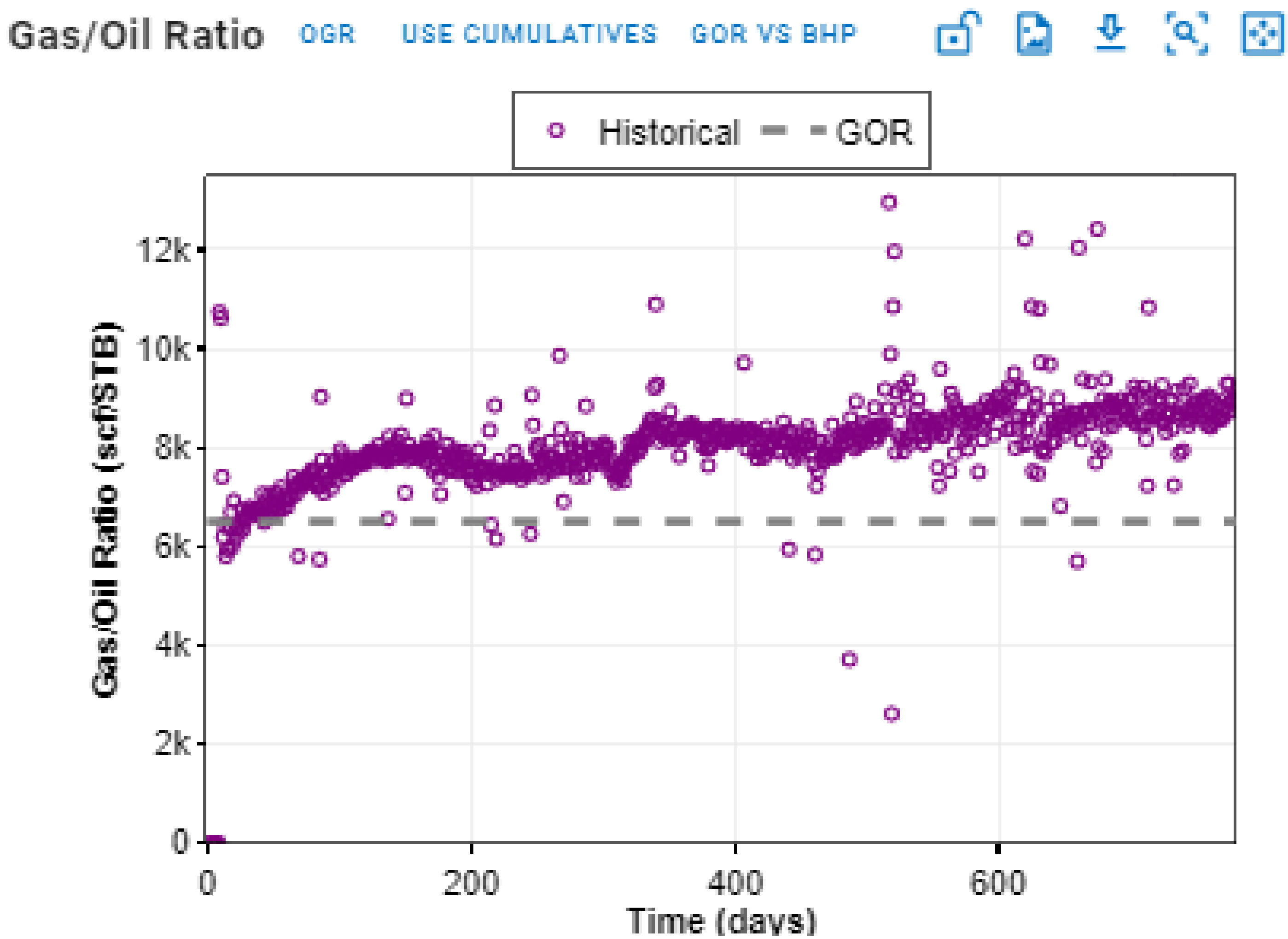
Case Study 14



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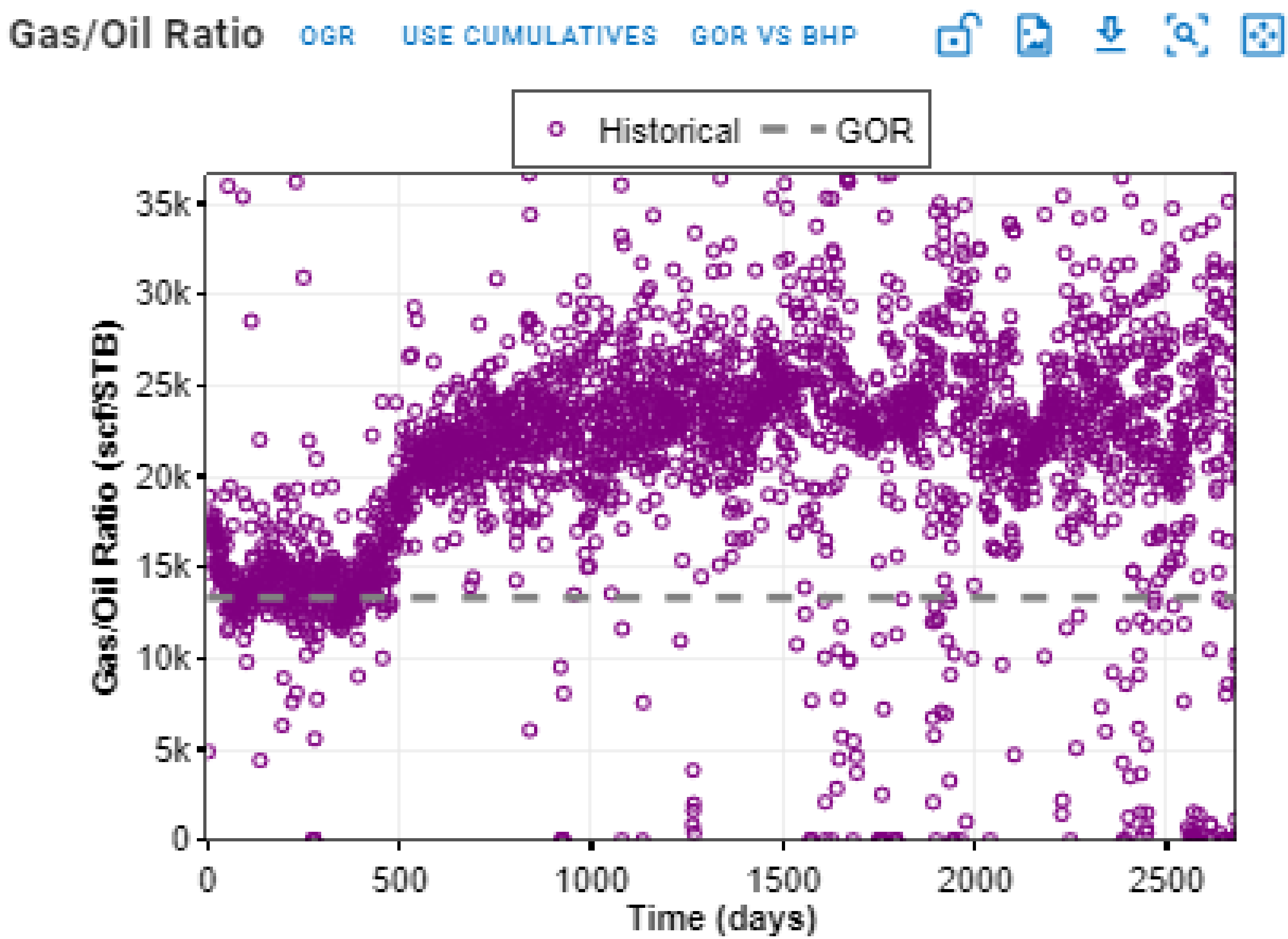
Case Study 15



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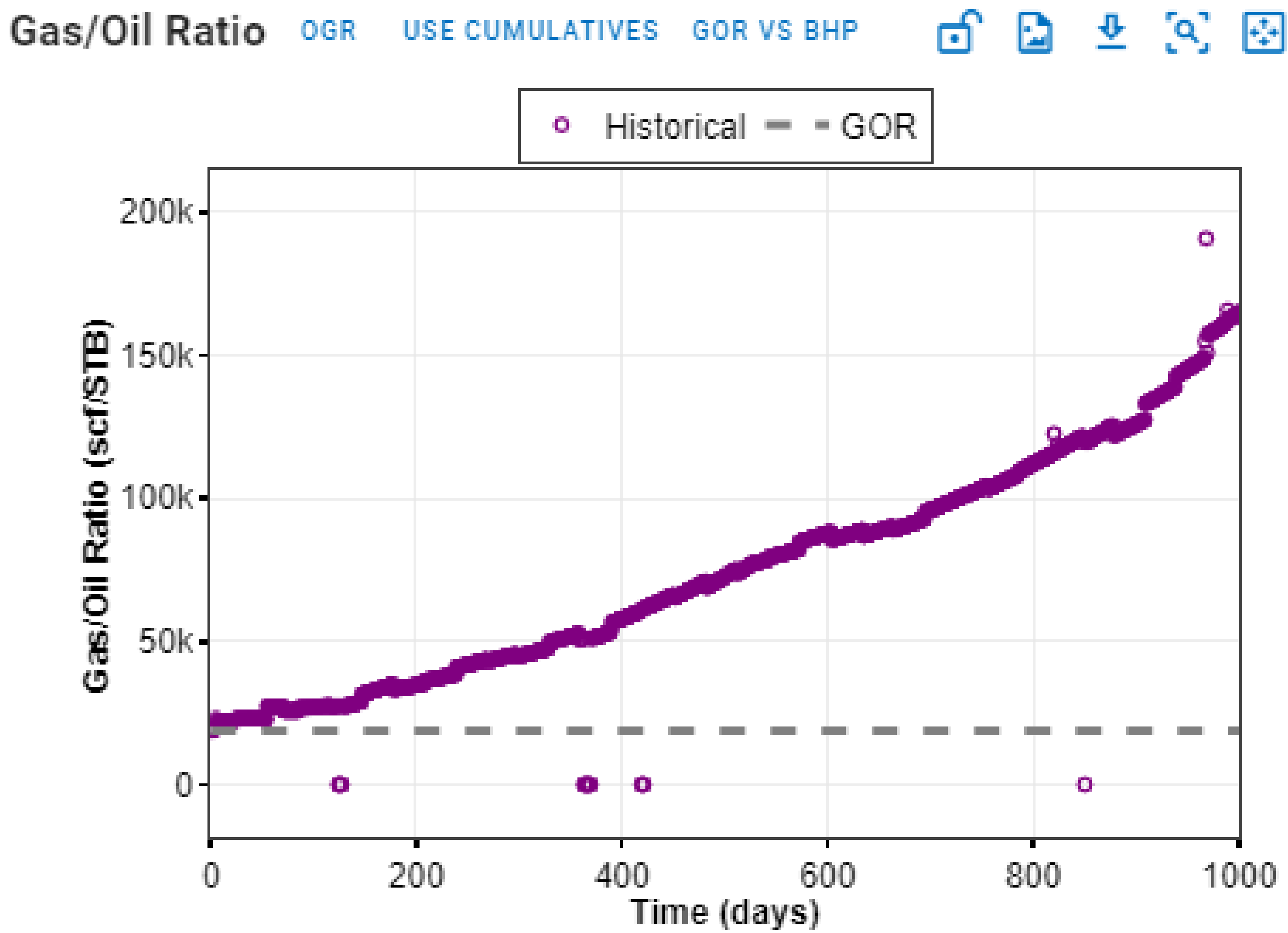
Case Study 16



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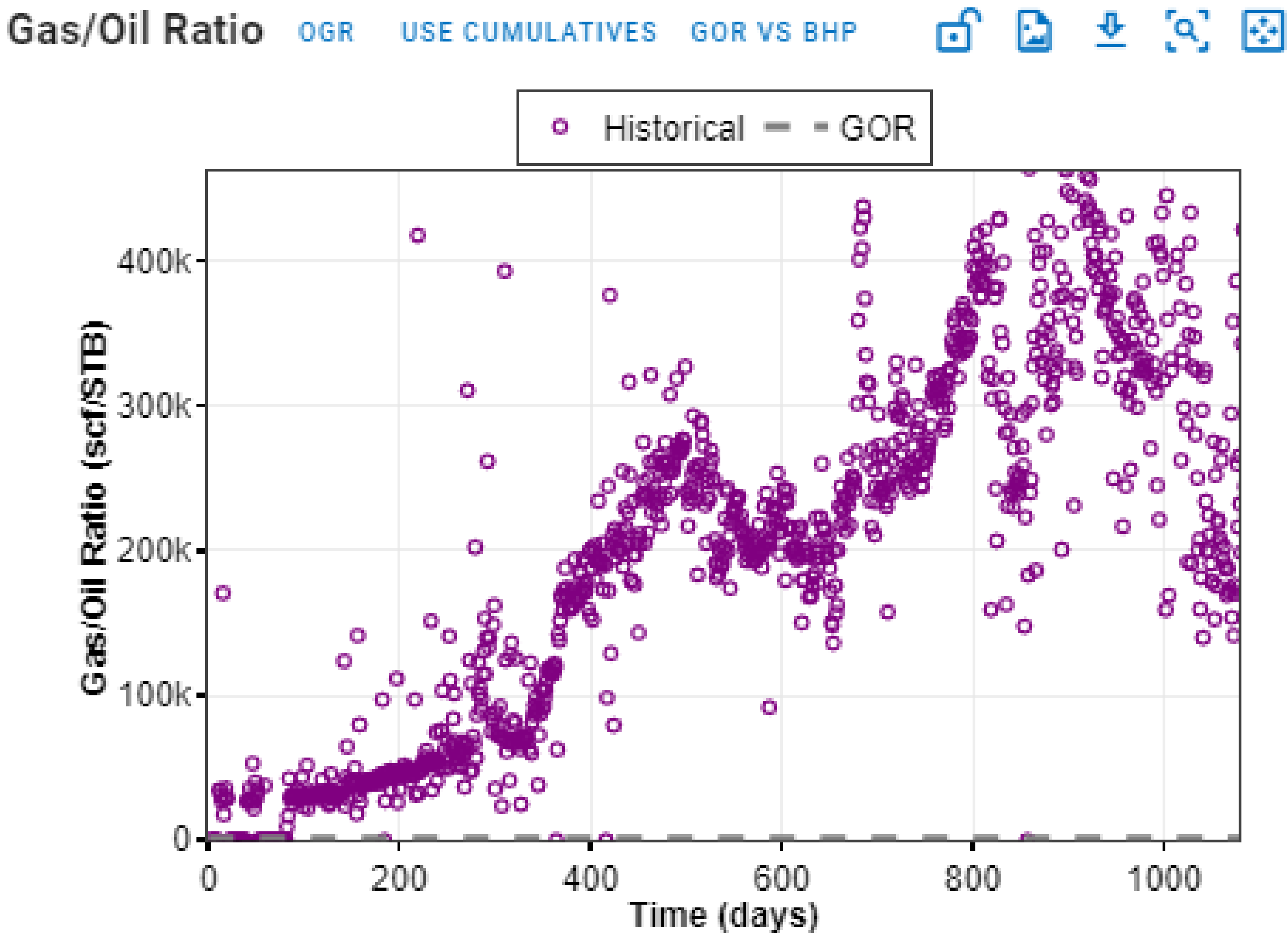
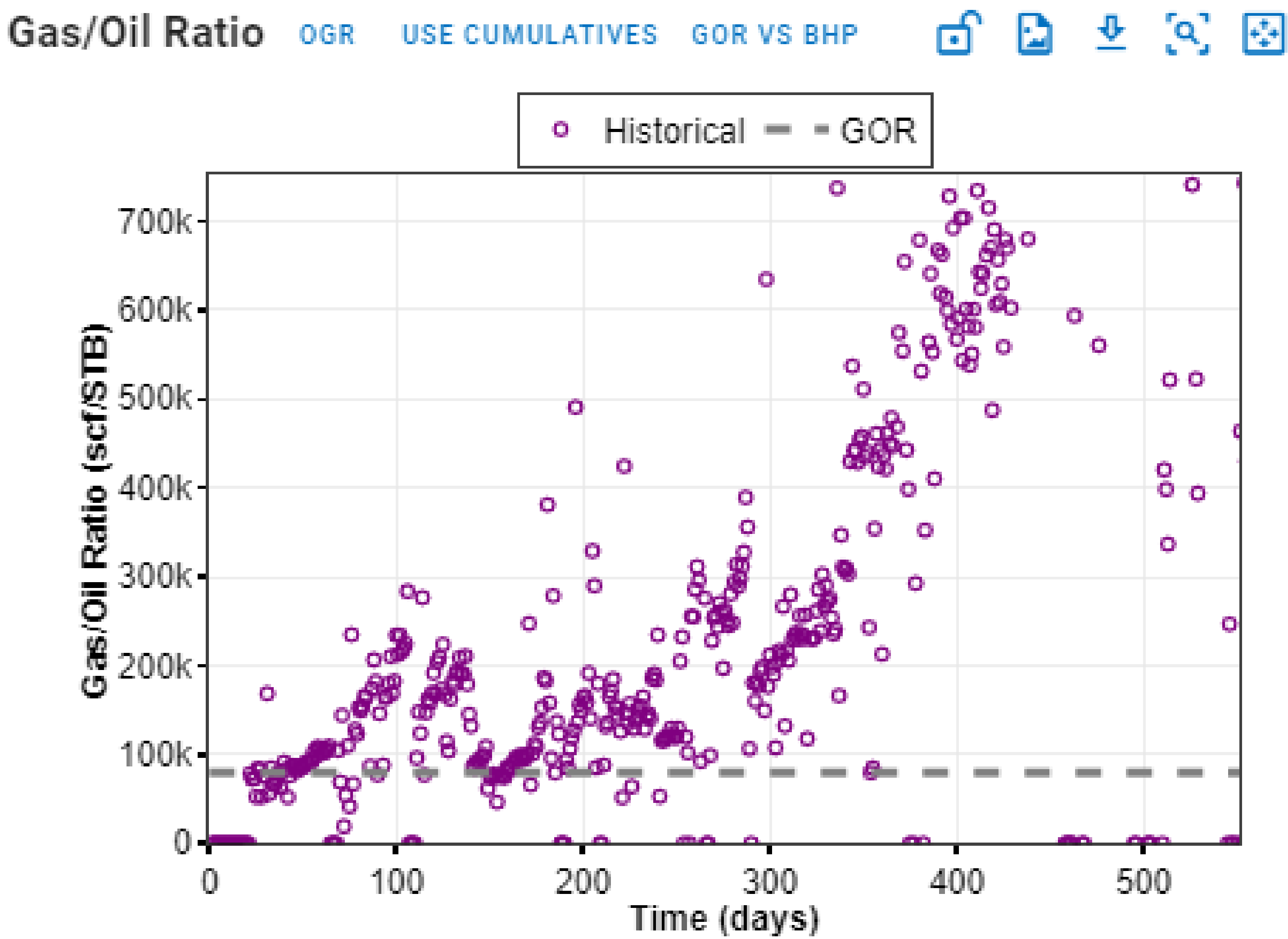
Case Study 17



Case Study 18



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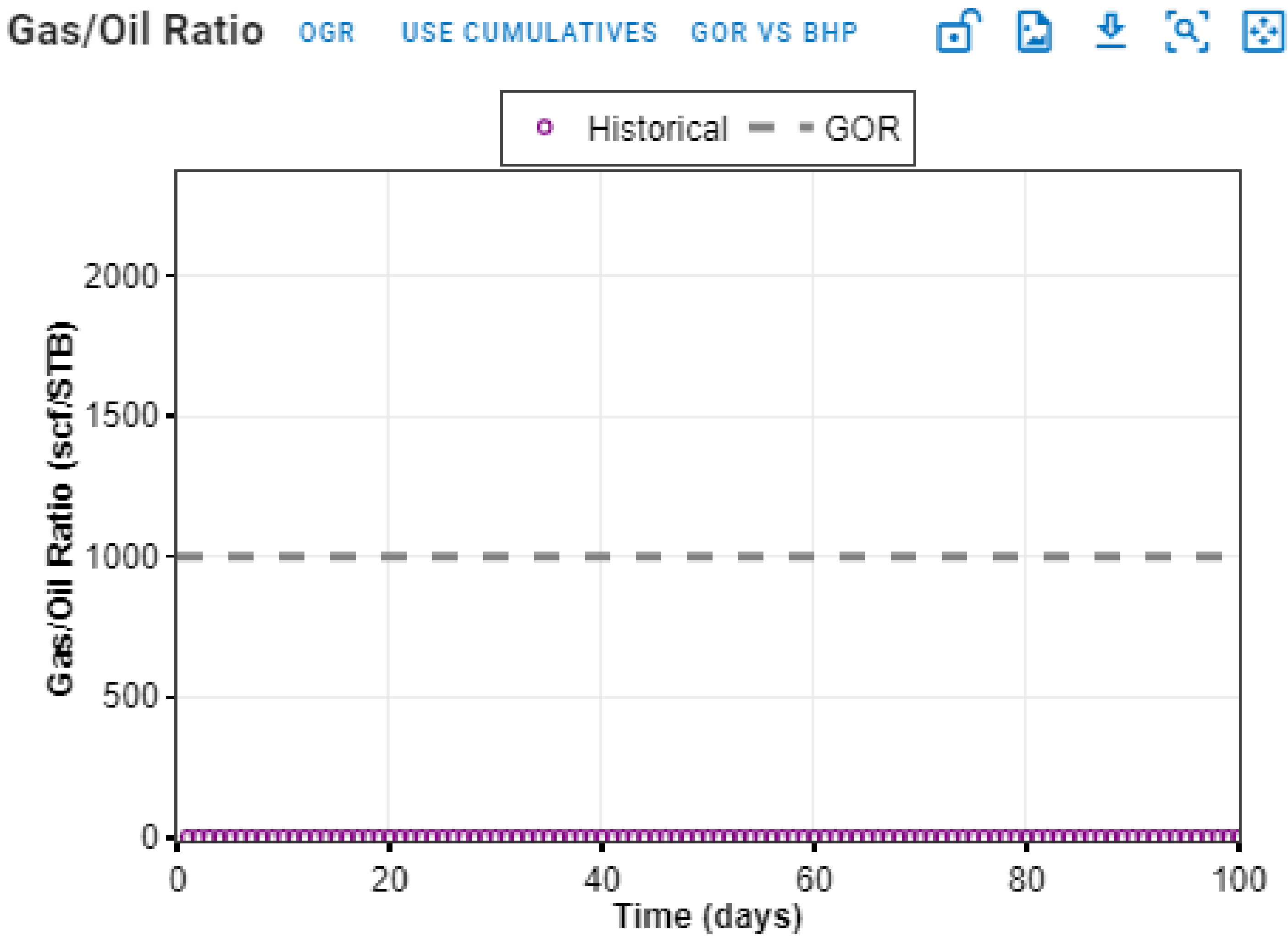
Case Study 19



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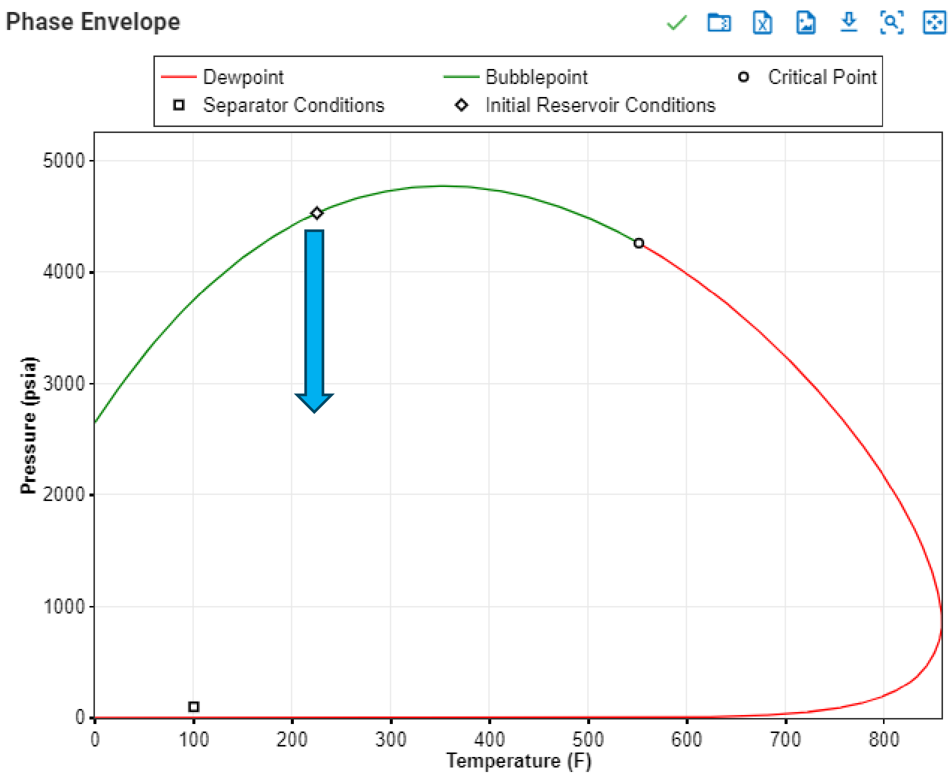
Special Case 1: Saturated Reservoirs



- Initial Conditions: p_i =< p_{sat}
- In the "two-phase party" from day 1
- GOR rising from day 1!
- Initial producing GOR is a function of relative mobilities

$$R_p = [1 + \alpha r_s]^{-1}[R_s + \alpha]$$

$$\alpha = \frac{k_{rg} B_o \mu_o}{k_{ro} B_{gd} \mu_g}$$

- … so isn't as easy as R_{si} (or $1/R_{vi}$) = initial producing GOR

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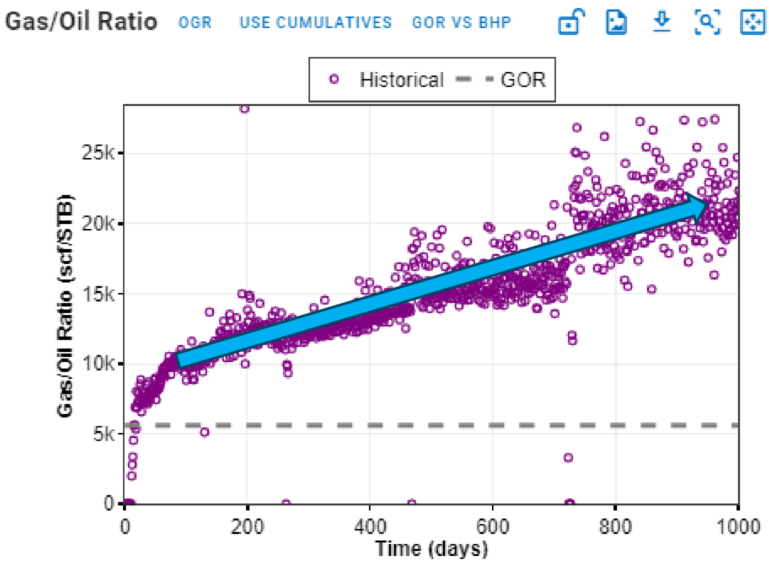
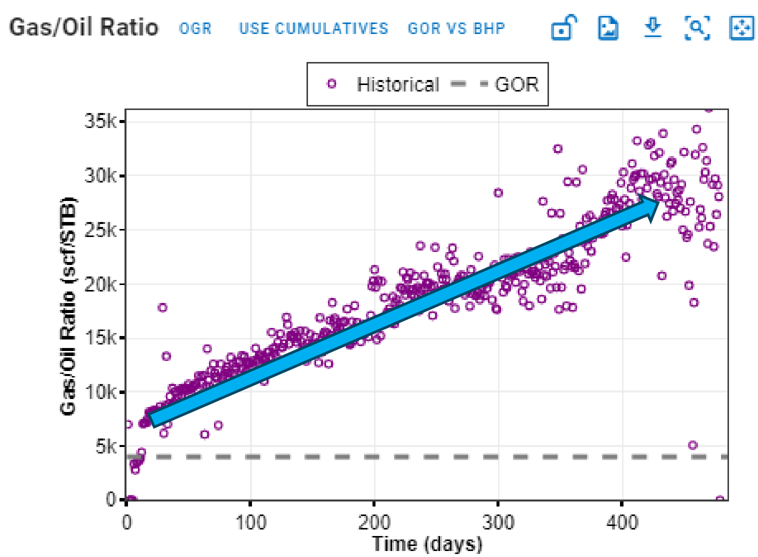
Special Case 1: Saturated Reservoirs





- Initial Conditions: p_i =< p_{sat}
- In the "two-phase party" from day 1
- GOR rising from day 1!
- Initial producing GOR is a function of relative mobilities

$$R_p = [1 + \alpha r_s]^{-1}[R_s + \alpha]$$

$$\alpha = \frac{k_{rg} B_o \mu_o}{k_{ro} B_{gd} \mu_g}$$

- … so isn't as easy as R_{si} (or $1/R_{vi}$) = initial producing GOR

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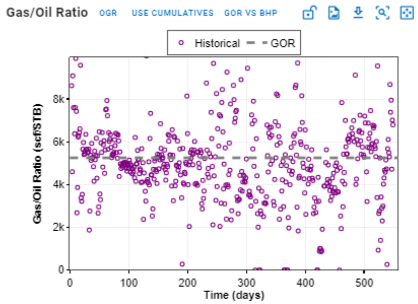
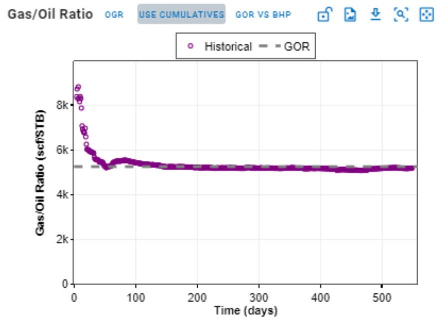
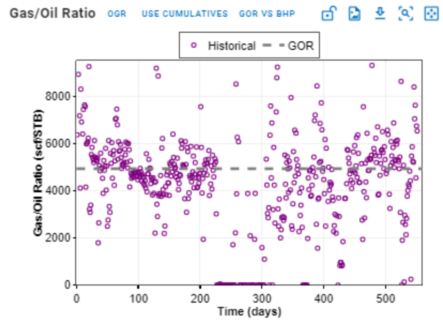
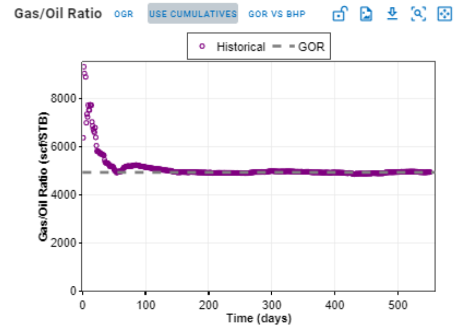
Special Case 2: Constant GOR as $p_{wf} < p_{sat}$









Either …

1. Wrong p_{sat} (i.e. it should be lower), p_{wf} is still above p_{sat}
2. Large pressure loss from matrix to wellbore (e.g. low F_{cd})
3. Dual PVT system (e.g. one oil layer and one gas layer)

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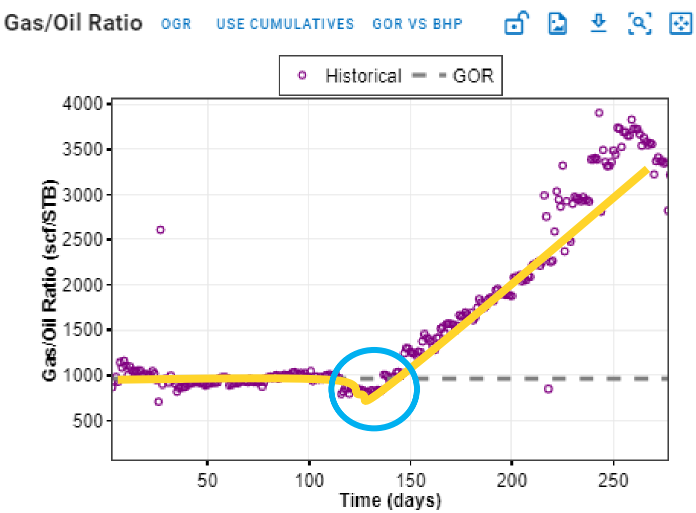
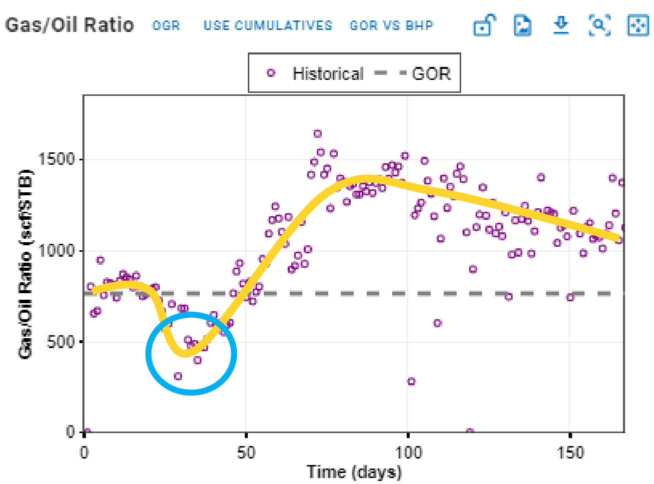
Special Case 3: GOR goes down, before up!





Solution gas drive reservoirs

Pure solution gas drive reservoirs are subject to different stages of idealized production.

In chronological order, the stages are typically ..

1. Production while undersaturated ($p_{wf} > p_{sat}$)

2. Production while saturated but the free gas is immobile (producing gas-oil ratio goes down)

3. Production while saturated and the free gas is mobile (the producing gas-oil ratio is increasing)

More: https://petrowiki.spe.org/Solution_gas_drive_reservoirs

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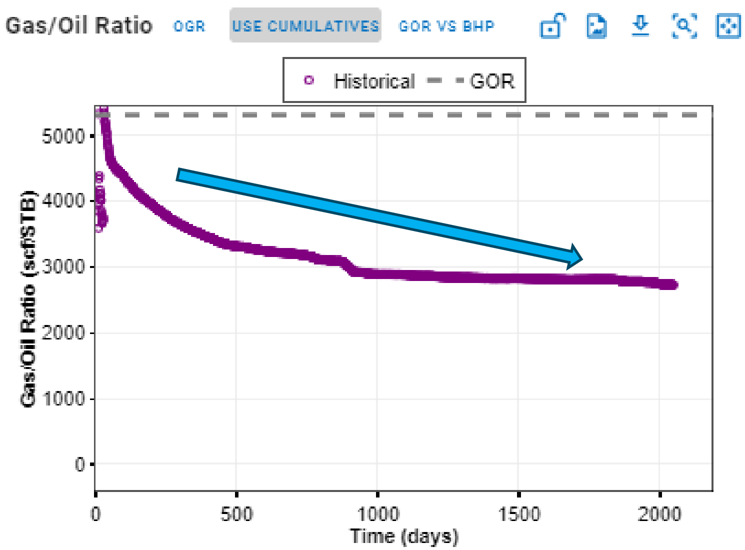
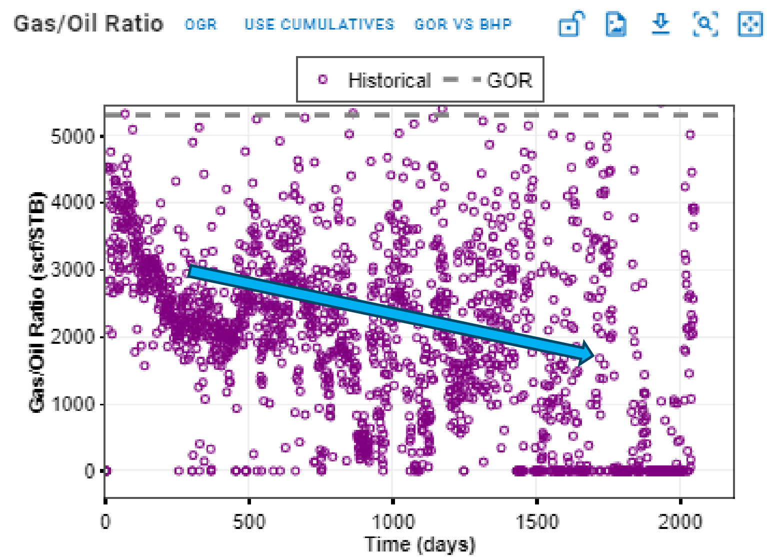
Special Case 4: Decreasing GOR …





Can be explained with a dual PVT system.

High GOR (or gas) layer depletes first (lower viscosity).

Low GOR layer depletes later (higher viscosity).

Sources: SPE-200014, URTeC-2882502, SPE-190797

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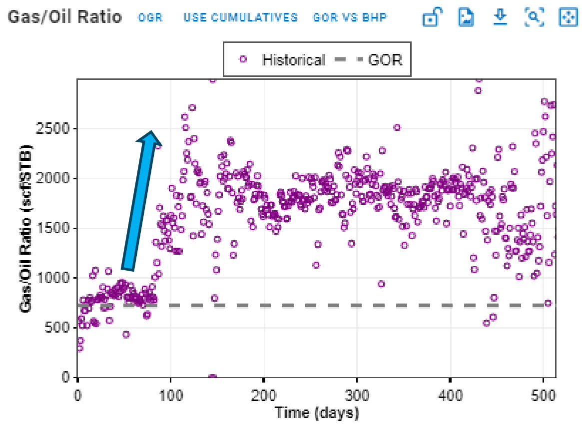
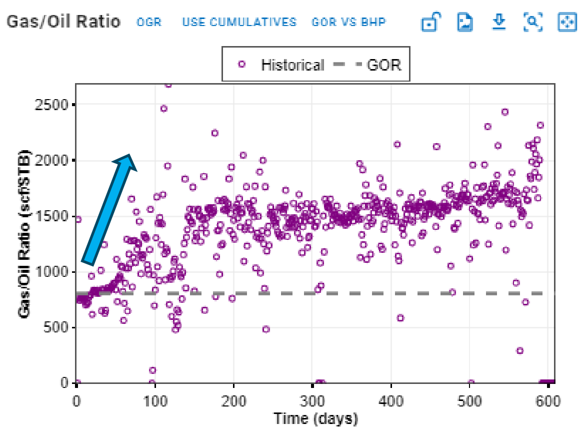
Note: GOR Trends as $p_{wf} < p_{sat}$

Infinite conductive fractures

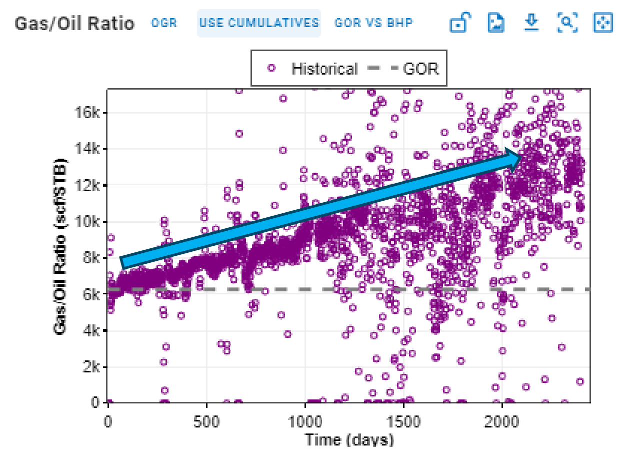
(GOR shoots up as $p_{wf} < p_{sat}$)

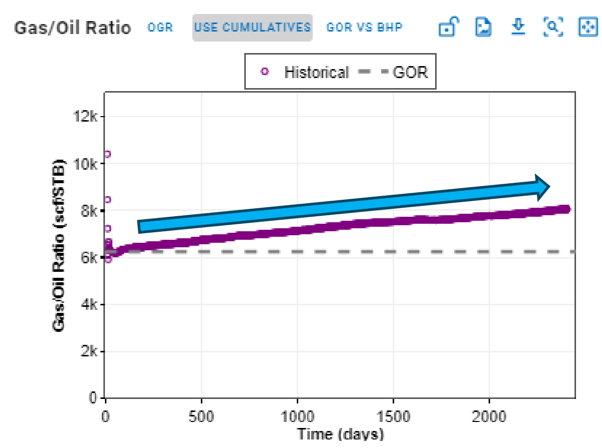




Low Fracture Conductivity

(Linearly increasing GORs)





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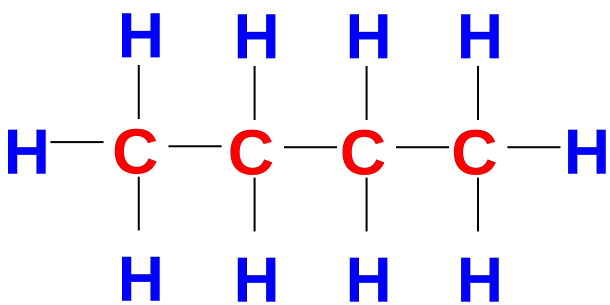
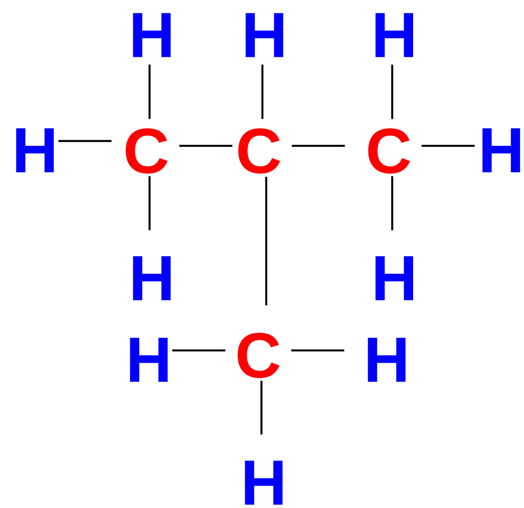
Petroleum Fluids

Alkanes (Paraffins)

Structure Formula

$$C_nH_{2n+2}$$





$n\text{-}C_4H_{10}$: normal-butane

$i\text{-}C_4H_{10}$: iso-butane

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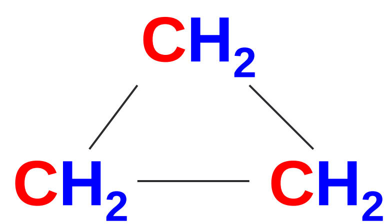
Cyclo-alkanes (Naphtenes)

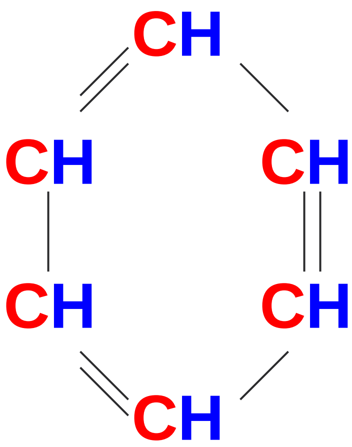
Structure Formula

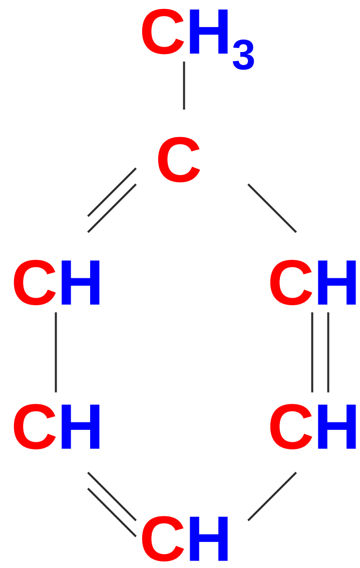
C_nH_{2n}



C_3H_6 : cyclo-butane

Aromatics





Benzene

Toluene

Watson's Characterization Factor

$$K_w \approx 4.5579\, M^{0.15178} \gamma^{-0.84573} \quad (5.35)$$

K_w varies roughly from 8.5 to 13.5. For paraffinic compounds, $K_w = 12.5$ to 13.5; for naphthenic compounds, $K_w = 11.0$ to 12.5; and for aromatic compounds, $K_w = 8.5$ to 11.0. Some overlap in K_w exists among these three families of hydrocarbons, and a combination of paraffins and aromatics will obviously "appear" naphthenic.

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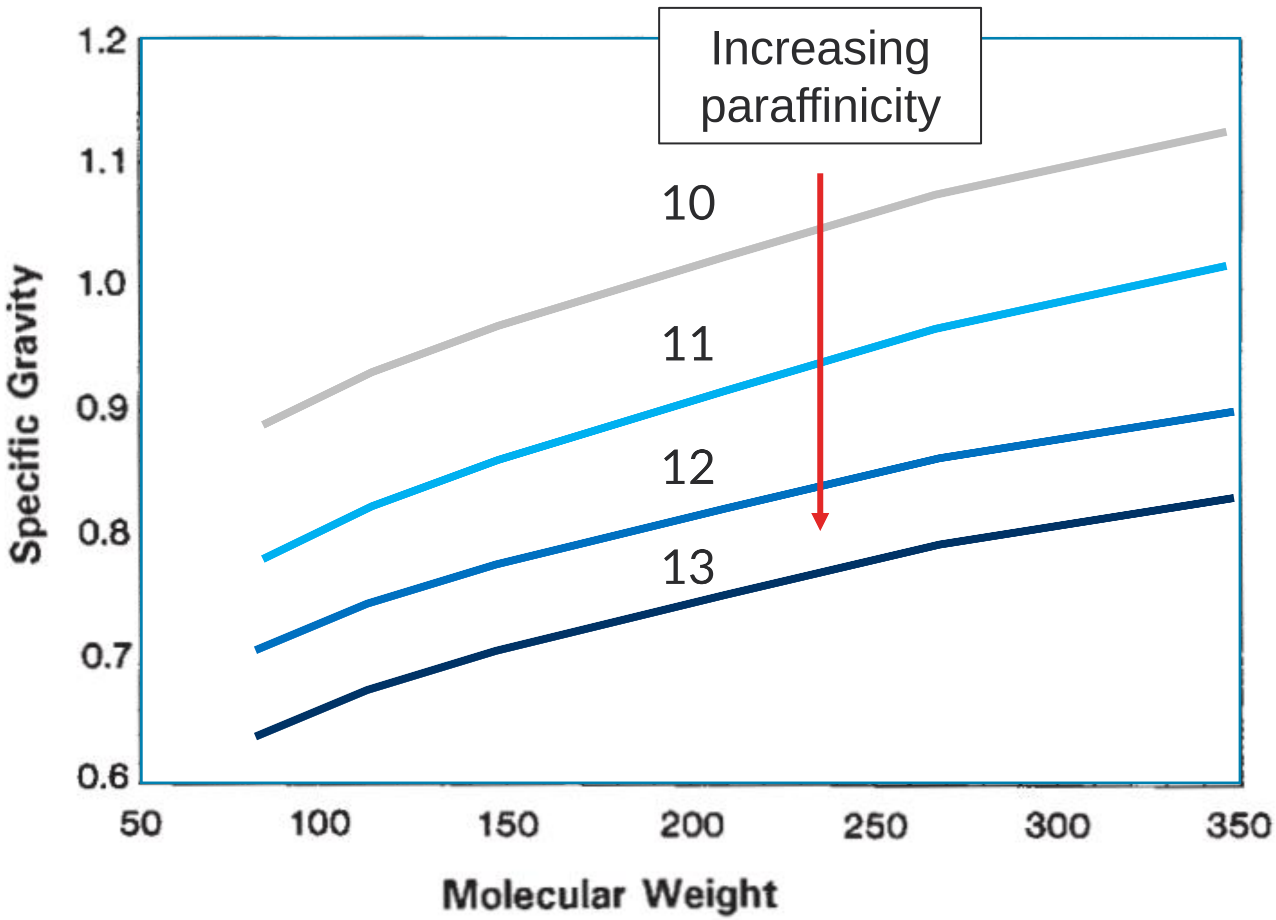
Watson's Characterization Factor



Paraffinic: K_w ~ 12.5-13.5

Naphthenic: K_w ~ 11-12.5

Aromatic: K_w ~ 8.5-11

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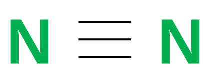
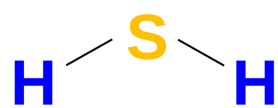
Non-Hydrocarbons

- *Typically found in reservoir fluids.*
- *CO_2 and H_2S are unwanted & costly to deal with.*
- *N_2 reduces heating value.*





N_2 : Nitrogen

H_2S : Hydrogen Sulfide

CO_2 : Carbon Dioxide

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NGL, LPG and LNG – what's the difference?

Might be confusing …

- LNG – liquefied natural gas ~ C_1
- LPG – liquified petroleum gas ~ C_3 and C_4
- NGL – natural gas liquids ~ C_2, C_3, C_4, C_5
- Crude oil – C_{5+}/C_{6+}

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Enough compositions already … Back to everyday life!

C_1 – methane – used for heating

C_2 – ethane → ethylene → plastic

C_3 – propane → mainly heating (also plastic)

C4 – butane → heating, cooking

C_3/C_4 – "Autogas", fuel in Europe, Turkey, Australia

C_{5+} - Natural gasoline / various kinds of fuel

Source: https://www.eia.gov/todayinenergy/detail.php?id=5930

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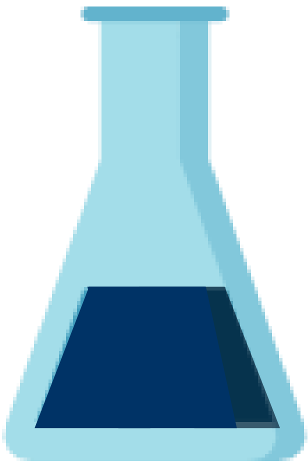
Fluid Sampling

Why Sample?



Compositions

- Separator gas
- Separator oil
- Wellstream
- In-situ Reservoir

PVT Data

- Direct use
- Developing a PVT Model
- Validating an existing PVT model
- Fluid initialization

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General Recommendation …

Collect samples early in a well's lifetime at low drawdowns and stabilized rates (GOR)

Strongly Recommend that the following data reported

1. Separator GOR in scf/sep.bbl
2. Separator conditions at sampling
3. Field shrinkage factor used (=SF)
4. Flowing bottomhole pressure (FBHP) at sampling (or wellhead pressures)
5. Initial reservoir pressure
6. Time and date of sampling
7. Production rates during sampling
8. Dimensions of sample container
9. Total number and types of samples collected
10. Target formation

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"Representative" Samples

"Reservoir Representative"

Any uncontaminated fluid sample produced from a reservoir is automatically representative of that reservoir

"In-situ Representative"

A sample representative of the original fluid(s) in place

Accuracy of PVT Data ≠ "In-situ Representivity" of Sample

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“Representative” Fluid Samples

Insitu-representative Samples:

- Represents the original fluid(s) in the volume drained by the well during sampling.
- May vary as a function of depth, from one fault block to another, and between non-communicating layers.
- May be difficult to measure directly, due to near-wellbore multiphase behavior in saturated, slightly undersaturated, and low-permeability reservoirs
- Accurate insitu-representative samples are used to determine the initial hydrocarbons (oil and gas) in place.

Reservoir-representative Samples:

- Represents any fluid produced from the reservoir.
- Are easily obtained.
- May be used to create estimates of the insitu-representative fluids!
- All reservoir-representative samples (having reliable PVT data and compositions) should be used in developing an EOS fluid characterization.

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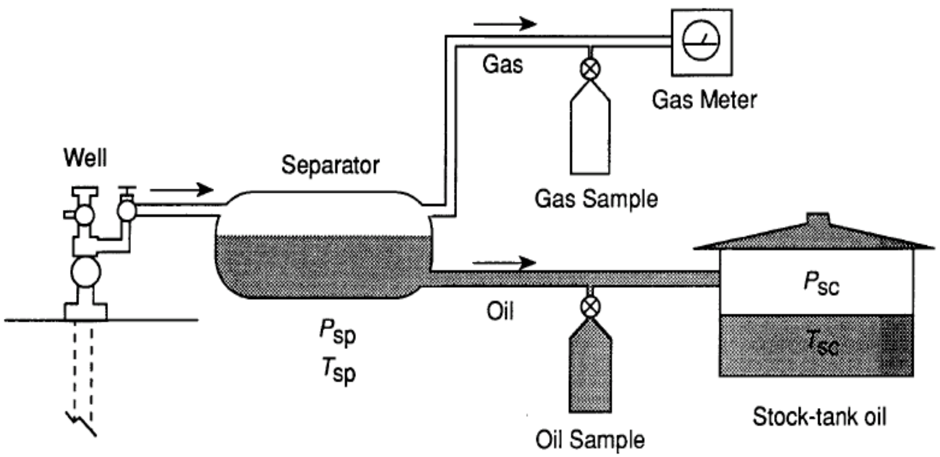
Production Test Sampling



Separator gas composition – y_{spi}

- Biggest uncertainty is C_{6+} amount
- Important for GP (LPG & NGL) design
- Useful in “Simplified EOS Approach”

Stock-tank oil API – γ_{API}

- Key data for EOS modeling
- Field measurement ±1-2 ^{o}API

Separator oil composition – x_{spi}

- Not always measured
- Reported density should not be used, as it is not measured

Reservoir temperature – T_R

- Reservoir representative
- In-situ representative

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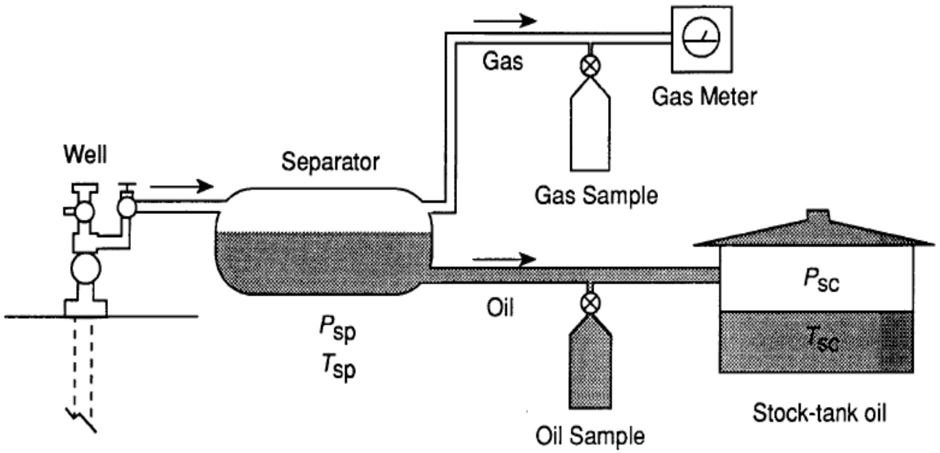
Separator Sampling



Separator gas composition – y_{spi}

- 20-liter container; duplicate containers
- Opening pressure QC

Separator oil composition – x_{spi}

- Flash-GC compositional measurement
- C_{7+} extended GC distribution
- C_{7+} MW and SG important data

Recombination GOR – R_{sp} (r_{sp})

- Unit: scf/separator-bbl !
- Includes only 1st-stage separator gas

Separator Sampling Conditions (T_{sp},p_{sp})

- QC: Hoffman plot | $p_b(T_{sp})=p_{sp}$

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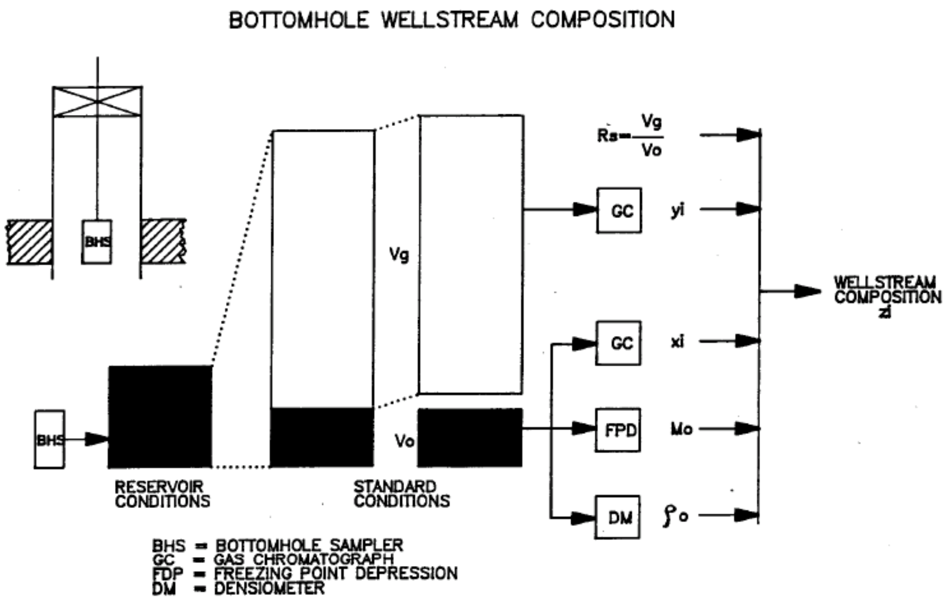
Bottomhole Sampling



When is bottomhole sampling recommended?

- Undersaturated oils
- Flowing BHP higher than saturation pressure

When is bottomhole sampling not recommended?

- Gas Condensates
- Foaming oils
- Highly viscous oils

Quality check:

- BH pressure during sampling
- Production conditions prior to sampling
- Perforation interval
- Characterization Factor (Multiple samples)

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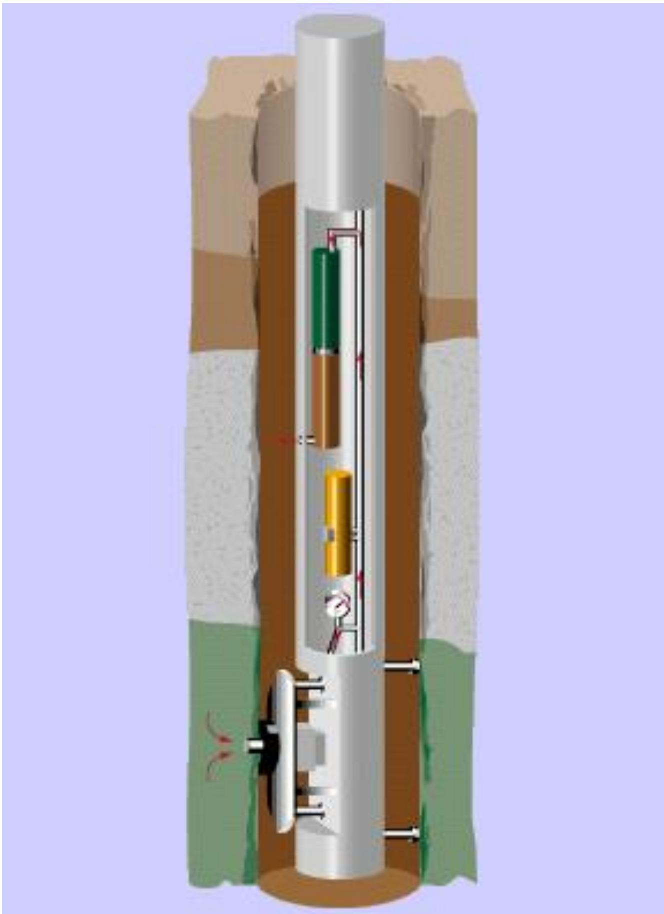
Openhole Formation Testing (OFT) Samples



When is OFT sampling recommended?

- Oil reservoirs
- Gas and gas condensate reservoirs
- Layered reservoirs with different fluid
- Compositional grading reservoirs

When is OFT not recommended?

- Highly viscous crude
- Low permeability reservoirs
- Carefully when oil-based drilling mud (OBM) has been used

Quality checks:

- Saturation pressure and
- Sampling transfer
- Volume of sample

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Sampling Summary

Advantages of Subsurface sampling

- Collect desired sample directly
- Can maintain full pressure of sample
- Avoids use of surface separators (surface metering uncertainties)
- Avoids recombination errors
- Less sampling information transmitted to PVT laboratory

Advantages of OFT samples

- Collects the fluid sample directly the formation
- Fluid sample from a very narrow depth interval
- Not affected by fluid segregation in the well

Advantages of separator samples

- Large fluid volumes can be taken
- Easy, convenient and less expensive when surface separators are already on location
- No tools in the borehole
- Does not require single phase fluid in the well bore

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PVT Report 1.01

PVT Report 1.01

1. How does a PVT report look like?
2. Lab experiments and what they measure
3. Most data in a PVT report is not measured
4. Compositions - the most uncertain lab experiment
5. API gravity are defined at stock tank conditions
6. We don’t put the PVT reports into a simulator

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1 PVT Report Example

Weatherford® LABORATORIES

Encana Corporation

Reservoir Fluid Study
Field: Kaybob
Formation: Duvernay
Well: ECA Hz Wahigan
04-12-064-23W5
CL-70073
August 2015

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TABLE 1
ENCANA CORPORATION
WELL ECA HZ WAHIGAN 04-12-064-23W5 – RECOMBINED SAMPLE
RESERVOIR FLUID STUDY
COMPOSITIONAL ANALYSIS OF RESERVOIR FLUID

Boiling Point (C)			Mole Fraction	Mass Fraction	Calculated Properties	
-195.8	Nitrogen	N2	0.0095	0.0046	**Total Sample**	
-78.5	Carbon Dioxide	CO2	0.0043	0.0033		
-60.3	Hydrogen Sulphide	H2S	0.0000	0.0000	Molecular Weight	57.16
-161.7	Methane	C1	0.4825	0.1355		
-88.9	Ethane	C2	0.1254	0.0659		
-42.2	Propane	C3	0.0822	0.0634	**C6+ Fraction**	
-11.7	i-Butane	i-C4	0.0140	0.0143		
-0.6	n-Butane	n-C4	0.0356	0.0362	Molecular Weight	167.92
27.8	i-Pentane	i-C5	0.0129	0.0163	Mole Fraction	0.2181
36.1	n-Pentane	n-C5	0.0156	0.0197	Density (g/cc)	0.8200
36.1 - 68.9	Hexanes	C6	0.0244	0.0368		
68.9 - 98.3	Heptanes	C7	0.0223	0.0391		
98.3 - 125.6	Octanes	C8	0.0245	0.0490	**C7+ Fraction**	
125.6 - 150.6	Nonanes	C9	0.0179	0.0402		
150.6 - 173.9	Decanes	C10	0.0136	0.0339	Molecular Weight	178.73
173.9 - 196.1	Undecanes	C11	0.0122	0.0313	Mole Fraction	0.1928
196.1 - 215	Dodecanes	C12	0.0097	0.0272	Density (g/cc)	0.8302
215 - 235	Tridecanes	C13	0.0095	0.0292		
235 - 252.2	Tetradecanes	C14	0.0079	0.0262		
252.2 - 270.6	Pentadecanes	C15	0.0058	0.0208	**C12+ Fraction**	
270.6 - 287.8	Hexadecanes	C16	0.0047	0.0181		
287.8 - 291.7	Heptadecanes	C17	0.0040	0.0167	Molecular Weight	275.39
291.7 - 317.2	Octadecanes	C18	0.0039	0.0170	Mole Fraction	0.0754
317.2 - 330	Nonadecanes	C19	0.0034	0.0159	Density (g/cc)	0.8780
330 - 344.4	Eicosanes	C20	0.0028	0.0133		
344.4 - 357.2	Heneicosanes	C21	0.0024	0.0122		
357.2 - 369.4	Docosanes	C22	0.0021	0.0114		
369.4 - 380	Tricosanes	C23	0.0019	0.0106		
380 - 391.1	Tetracosanes	C24	0.0017	0.0097		
391.1 - 401.7	Pentacosanes	C25	0.0015	0.0092		
401.7 - 412.2	Hexacosanes	C26	0.0013	0.0084		
412.3 - 422.2	Heptacosanes	C27	0.0012	0.0076		
422.3 - 431.7	Octacosanes	C28	0.0011	0.0072		
431.7 - 441.1	Nonacosanes	C29	0.0009	0.0066		
Above 441.1	Tricontanes Plus	C30+	0.0097	0.0961		
48.9	Cyclopentane	C5H10	0.0009	0.0011		
72.2	Methylcyclopentane	C6H12	0.0039	0.0058		
81.1	Cyclohexane	C6H12	0.0033	0.0048		
101.1	Methylcyclohexane	C7H14	0.0088	0.0151		
80.0	Benzene	C6H6	0.0005	0.0007		
110.6	Toluene	C7H8	0.0022	0.0035		
136.1 - 138.9	Ethylbenzene & p,m-Xylene	C8H10	0.0025	0.0046		
144.4	o-Xylene	C8H10	0.0020	0.0037		
168.9	1, 2, 4-Trimethylbenzene	C9H12	0.0037	0.0078		
Total			**1.0000**	**1.0000**		

Types of PVT Lab Tests

Compositional Measurements	Gas Chromatography (GC)	w_i
	TBP Distillation	w_i, M_i, γ_i
Standard PVT Experiments	CCE	psat
	Depletion Tests (DLE/CVD)	$V_{L,rel}$
	Multistage Separator Test	B_o
	Viscosity Experiment	μ_o
Gas EOR Experiments	Slimtube Experiment	MMP_{MC}
	Swelling Test	MMP_{FC}
	Multi-Contact Vaporization	E_v

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2 Accuracy in Measured Data

- ***Saturation pressure:***
  - Generally within +/- 5 bar.
  - Gas condensate might have larger uncertainties.
- ***Gas Z-factors:***
  - Generally between 1-3%.
- ***Stock tank oil densities:***
  - Within 1-2%
- ***STO (and C_{7+}) Molecular Weight:***
  - Generally within 5%
  - Not uncommon to see variation between different labs of 5+%.

Reservoir oil densities:

- Pycnometer densities generally within 1-2%.
- DLE densities within 2-4% (except last stage!).

Separator Bo:

- Generally 1-2%.

Separator GOR:

- Within 5-10%
- Could be higher for lean gas condensates

2 Accuracy in Measured Data

DLE GOR (Released gas):

- Last stage (bleeding process) should not be weighted!
- Generally within 3 %
- Gas composition C_{6+} content not accurate!

CVD gas compositions:

- High quality laboratories should get C_{7+} within +/- 0.2 mole-%.
- Challenge in lean gas condensates
- Material balance check is ALWAYS needed – a lot of bad data exists.

CVD cumulative gas produced:

- Generally within 2-3 recovery-%

CCE and CVD oil relative volumes:

- Generally within 5% for volatile oil and rich gases depending on type of the cell
- Large errors can be expected for very lean and near-critical fluids.

Minimum Miscibility Pressure:

- High quality measurements should give oil recoveries above MMP higher than 95%
- With a well-designed experiment (pressure selection) MMP should be within +/- 5 bar.

Viscosities:

- *Oil:* Large uncertainties, generally 10-20%
- *Gas:* Usually not measured

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What is Measured vs Calculated?

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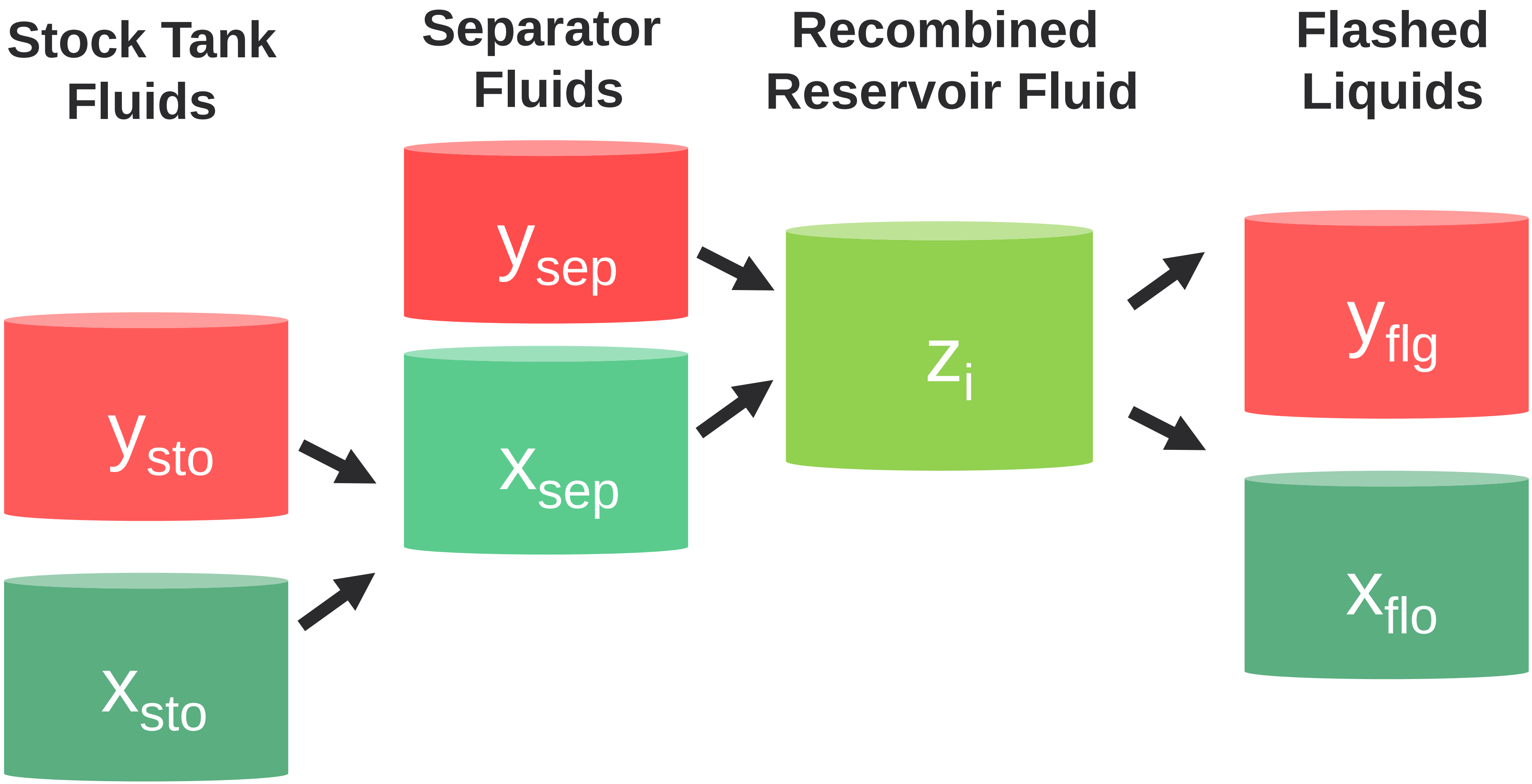
168.9	1, 2, 4-Trimethylbenzene	C9H12	0.0037	0.0078		
Total			**1.0000**	**1.0000**		

A "Recombined" Composition



3

Mathematical Recombination

$$z_i = x_i(1 - F_g) + y_i F_g$$

$$F_g = (1 + \frac{2130\rho_o}{M_o GOR})^{-1}$$

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Petroleum System Components

- Non-hydrocarbons (CO2, H2S, N2)
- Pure compounds with known molecular weight
  - Hydrocarbons (C1, C2, C3, iC4, … , C6)
  - Isomers (e.g. Benzene, Toluene)
- Single-Carbon Number (SCN) components
  - e.g. C10, C11, C12

(Oil based mud compounds ~$C_{12} – C_{20}$)

Component	MW[1] g/mol
CO2	44.01
H2S	34.08
N2	28.01
C1	16.04
C2	30.07
C3	44.10
i-C4	58.12
n-C4	58.12
i-C5	72.15
n-C5	72.15
C6	84.00
Mcyclo-C5	84.16
Benzene	78.11
Cyclo-C6	84.16
C7	100.21
Mcyclo-C6	98.19
Toluene	92.14
C8	114.23
C2-Benzene	106.17
m&p-Xylene	106.17
o-Xylene	106.17
C9	128.26
C10	134.00
C11	147.00
C12	161.00
⋮	⋮

Non-HC

Pure compounds

Mix of isomers & SCN components

SCN components

4 Compositional Measurement

- **<u>Mass</u>** of the individual components is measured using a gas chromatograph (GC)
- Weight fractions, w_i, of each component is **<u>converted to moles</u>** by using the total sample molecular weight, M, and the individual component molecular weight, M_i

From GC, might be uncertain

Measurement accuracy ±5-10%

$$z_i = w_i \frac{M}{M_i}$$

a) Pure compounds: Known
b) SCN: estimated
c) C_{n+}: unknown

No	Component	Katz	Whitson
		g/mol	g/mol
1	CO2	44.01	44.01
2	H2S	34.08	34.08
3	N2	28.01	28.01
4	C1	16.04	16.04
5	C2	30.07	30.07
6	C3	44.10	44.10
7	i-C4	58.12	58.12
8	n-C4	58.12	58.12
9	i-C5	72.15	72.15
10	n-C5	72.15	72.15
11	C6	84.00	84.00
12	Mcyclo-C5	84.16	84.16
13	Benzene	78.11	78.11
14	Cyclo-C6	84.16	84.16
15	C7	96.00	96.00
16	Mcyclo-C6	98.19	98.19
17	Toluene	92.14	92.14
18	C8	107.00	107.00
19	C2-Benzene	106.17	106.17
20	m&p-Xylene	106.17	106.17
21	o-Xylene	106.17	106.17
22	C9	121.00	121.00
23	C10	134.00	134.00
24	C11	147.00	147.00
25	C12	161.00	161.00
26	C13	175.00	175.00
27	C14	190.00	190.00
28	C15	206.00	206.00
29	C16	222.00	222.00
30	C17	237.00	237.00
31	C18	251.00	251.00
32	C19	263.00	[illegible]
33	C20	275.00	275.00
34	C21	291.00	291.00
35	C22	305.00	300.00
36	C23	318.00	312.00
37	C24	331.00	324.00
38	C25	345.00	337.00
39	C26	359.00	349.00
40	C27	374.00	360.00
41	C28	388.00	372.00
42	C29	402.00	382.00

Known

Estimated

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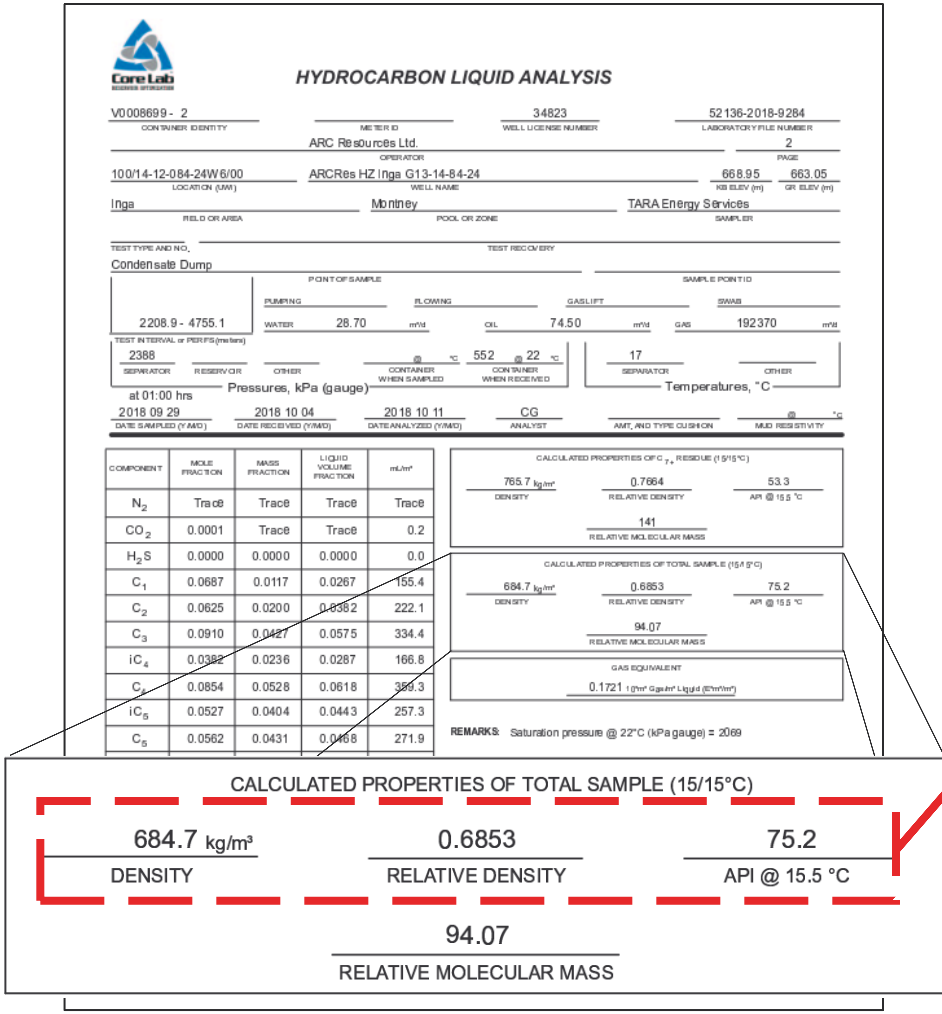
Warning! Sep. Oil Liquid Analysis Density



HYDROCARBON LIQUID ANALYSIS

CONTAINER IDENTITY	V0008699 - 2
METER ID	
WELL LICENSE NUMBER	34823
LABORATORY FILE NUMBER	52136-2018-9284
OPERATOR	ARC Resources Ltd.
PAGE	2
LOCATION (UWI)	100/14-12-084-24W6/00
WELL NAME	ARCRes HZ Inga G13-14-84-24
KB ELEV (m)	668.95
GR ELEV (m)	663.05
FIELD OR AREA	Inga
POOL OR ZONE	Montney
SAMPLER	TARA Energy Services
TEST TYPE AND NO.	
TEST RECOVERY	
POINT OF SAMPLE	Condensate Dump
SAMPLE POINT ID	
TEST INTERVAL or PERFS (meters)	2208.9 - 4755.1
PUMPING / FLOWING / GASLIFT / SWAB	
WATER	28.70 m³/d
OIL	74.50 m³/d
GAS	192370 m³/d
Pressures, kPa (gauge): SEPARATOR	2388 at 01:00 hrs
RESERVOIR	
OTHER	
CONTAINER WHEN SAMPLED	@ °C
CONTAINER WHEN RECEIVED	552 @ 22 °C
Temperatures, °C: SEPARATOR	17
OTHER	
DATE SAMPLED (Y/M/D)	2018 09 29
DATE RECEIVED (Y/M/D)	2018 10 04
DATE ANALYZED (Y/M/D)	2018 10 11
ANALYST	CG
AMT. AND TYPE CUSHION	
MUD RESISTIVITY	@ °C

COMPONENT	MOLE FRACTION	MASS FRACTION	LIQUID VOLUME FRACTION	mL/m³
N_2	Trace	Trace	Trace	Trace
CO_2	0.0001	Trace	Trace	0.2
H_2S	0.0000	0.0000	0.0000	0.0
C_1	0.0687	0.0117	0.0267	155.4
C_2	0.0625	0.0200	0.0382	222.1
C_3	0.0910	0.0427	0.0575	334.4
iC_4	0.0382	0.0236	0.0287	166.8
C_4	0.0854	0.0528	0.0618	359.3
iC_5	0.0527	0.0404	0.0443	257.3
C_5	0.0562	0.0431	0.0468	271.9

CALCULATED PROPERTIES OF C_{7+} RESIDUE (15/15°C)

765.7 kg/m³ DENSITY — 0.7664 RELATIVE DENSITY — 53.3 API @ 15.5 °C

141 RELATIVE MOLECULAR MASS

CALCULATED PROPERTIES OF TOTAL SAMPLE (15/15°C)

684.7 kg/m³ DENSITY — 0.6853 RELATIVE DENSITY — 75.2 API @ 15.5 °C

94.07 RELATIVE MOLECULAR MASS

GAS EQUIVALENT

0.1721 10⁶m³ Gas/m³ Liquid (E⁶m³/m³)

REMARKS: Saturation pressure @ 22°C (kPa gauge) = 2069

CALCULATED PROPERTIES OF TOTAL SAMPLE (15/15°C)

684.7 kg/m³	0.6853	75.2
DENSITY	RELATIVE DENSITY	API @ 15.5 °C

94.07

RELATIVE MOLECULAR MASS

The lab reported density should **not** be used as it is not at separator conditions.

API gravity and specific gravity is by definition at stock tank conditions.

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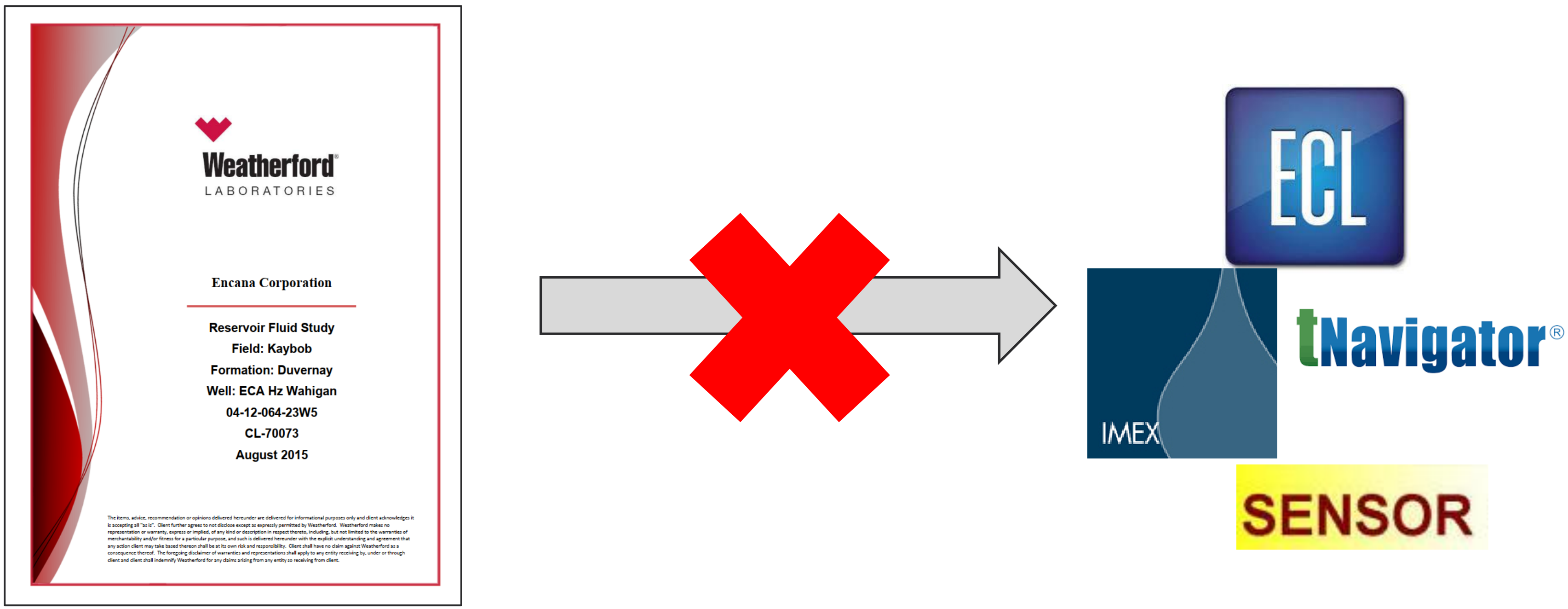
6 We don't put the PVT reports into a Simulator



"We need to build a model that replicate the data (i.e. EOS or BOT)!"

PVT Models

PVT Models

Models used to establish p-V-T relationship for different fluids produced from a basin/field/reservoir

All engineering calculations require the following for a given pressure, temperature and composition:

- Amount of each phase
- Density of phase
- Viscosity of each phase

Two types of PVT models are generally used:

- Compositional (EOS) model
- Black oil PVT (BOPVT) model (derived from EOS models)

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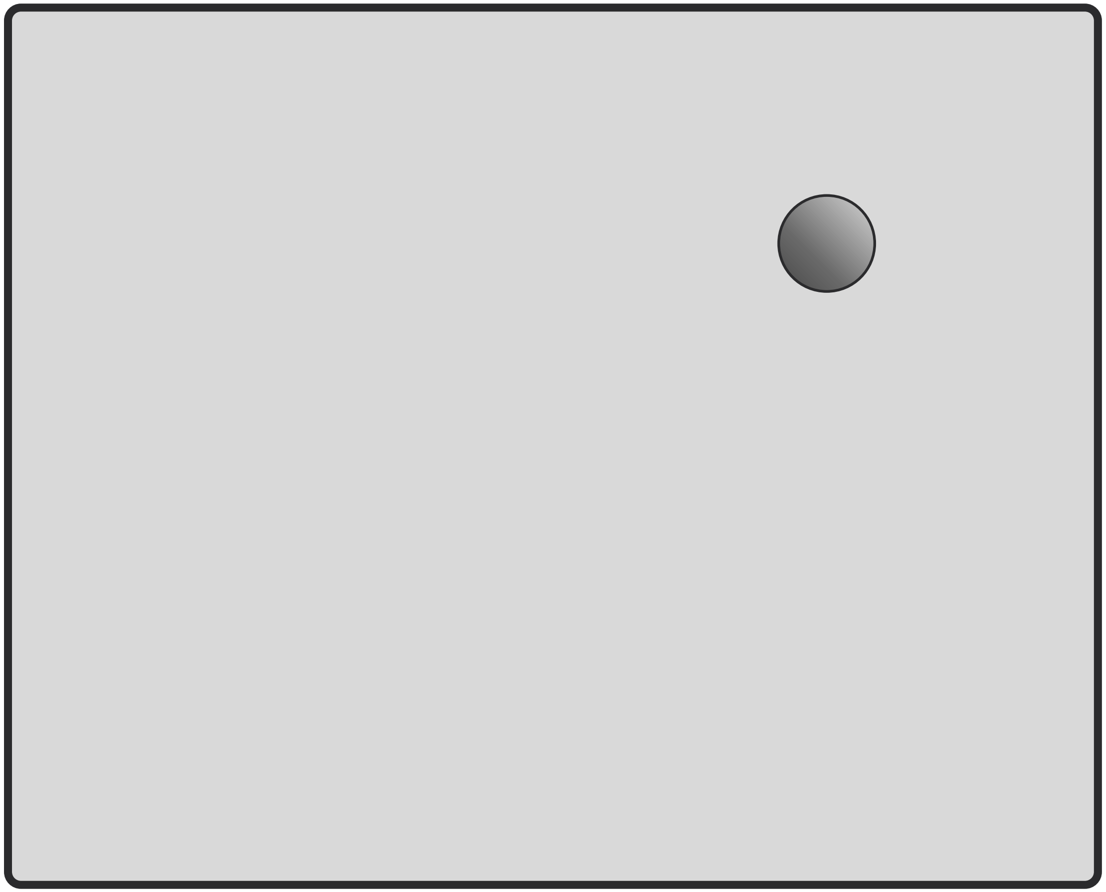
EOS Models Overview

Main Variables of EOS Model

- Tank model (base case):

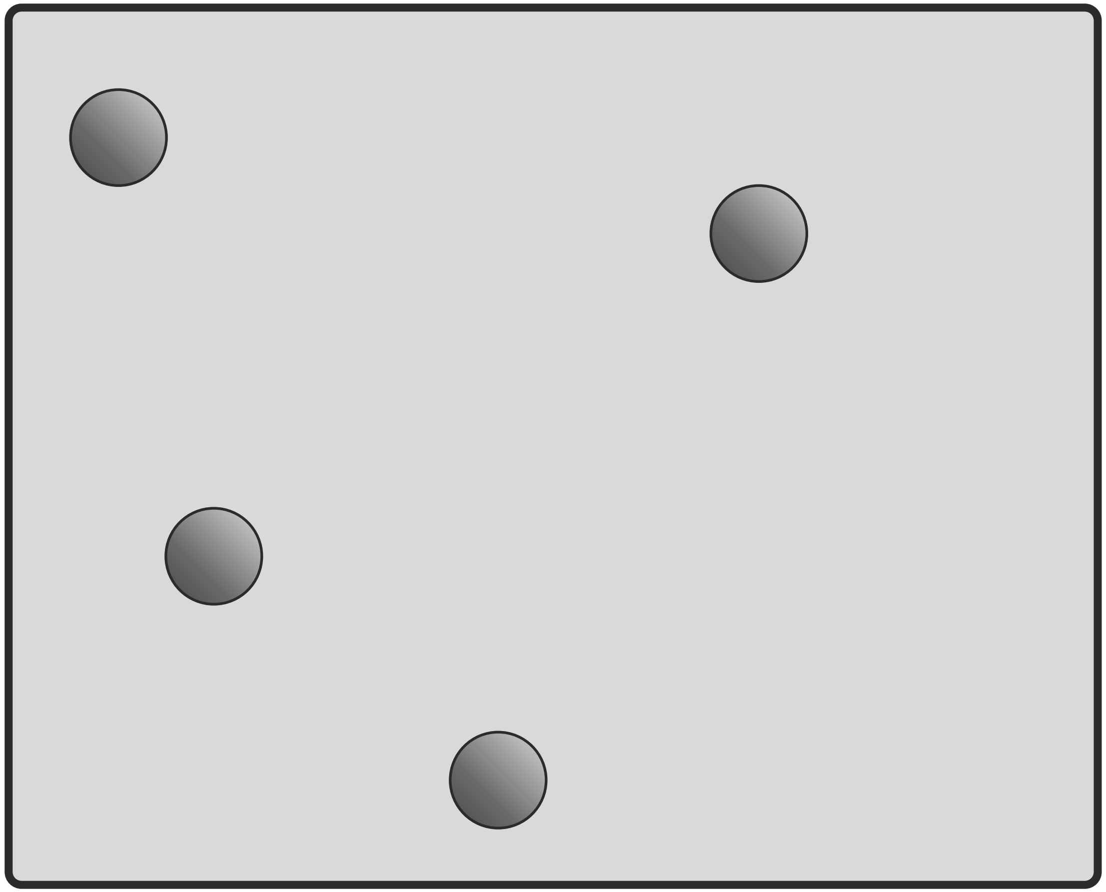


Pressure is defined by the average force on the tank wall or p=F/A

Courtesy: Markus Hays Nielsen

Main Variables of EOS Model

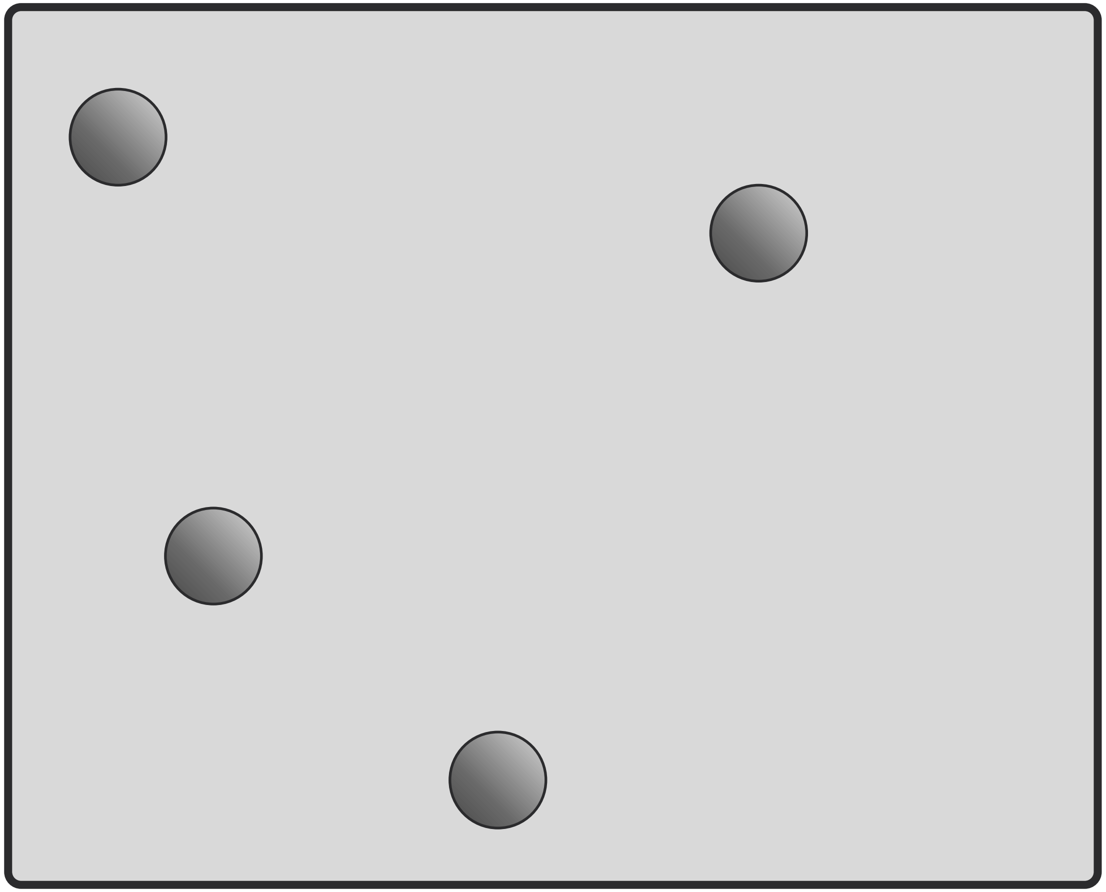
- Tank model (base case):



Courtesy: Markus Hays Nielsen

Main Variables of EOS Model

- Tank model (double speed): **Increasing temperature**



Courtesy: Markus Hays Nielsen

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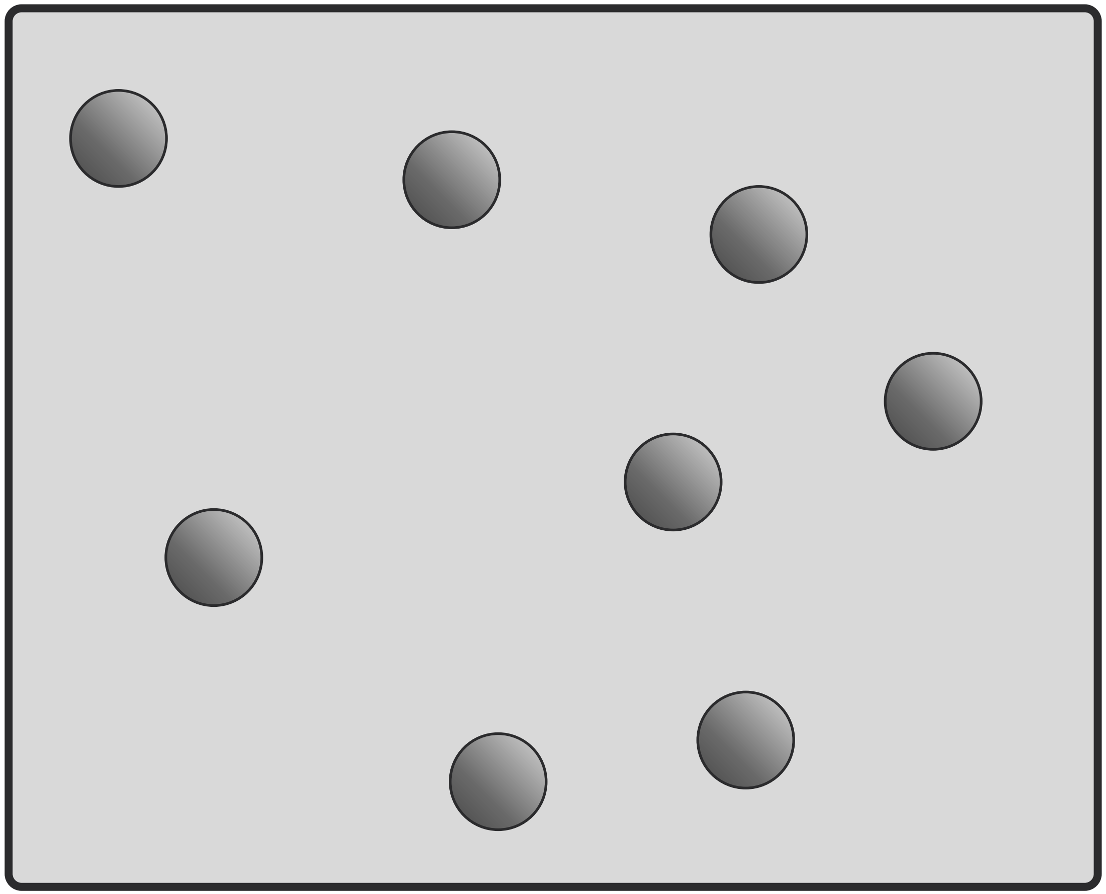
Main Variables of EOS Model

- Tank model (double number of particles):



Increasing molar amount

Courtesy: Markus Hays Nielsen

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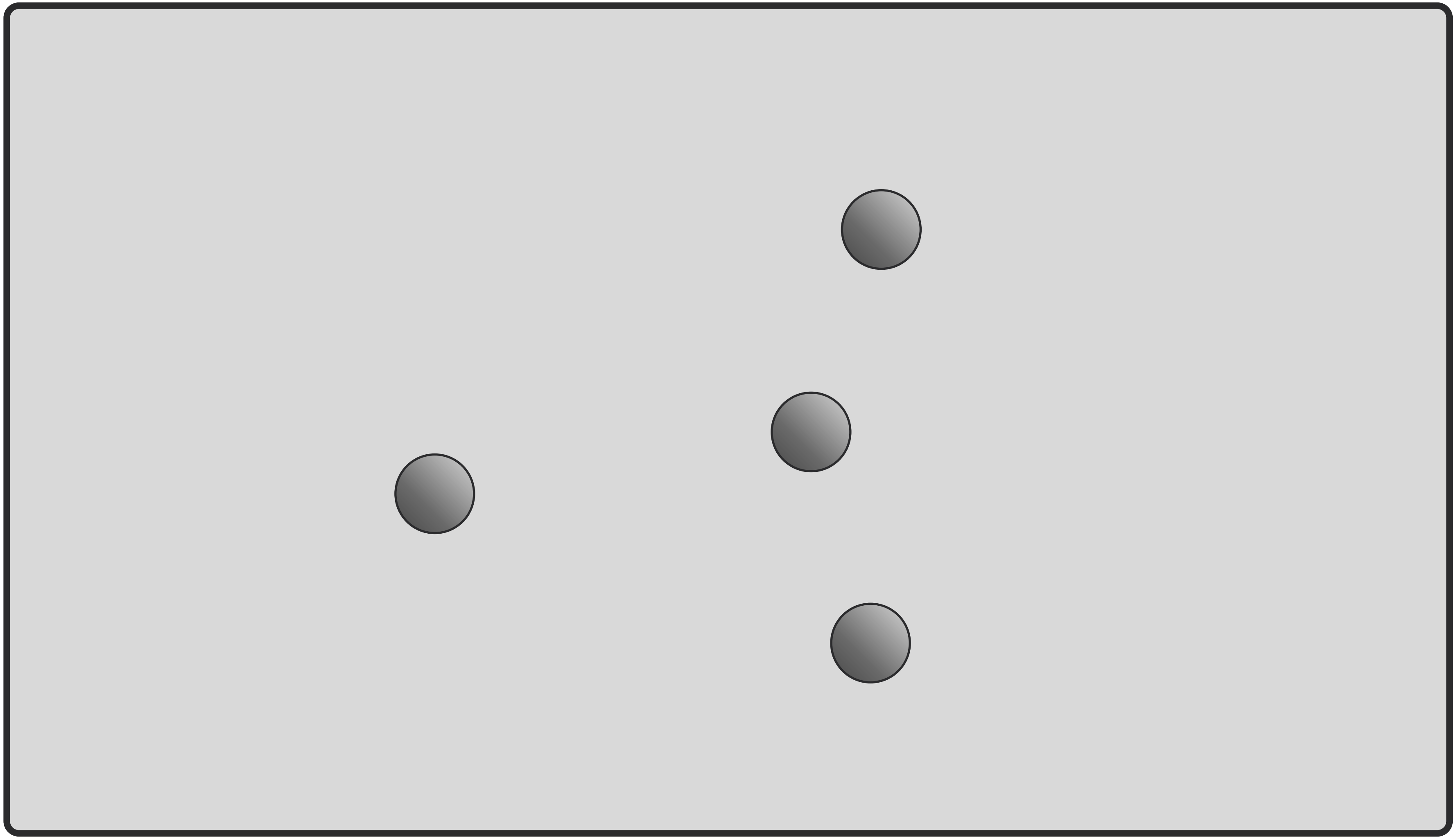
Main Variables of EOS Model

- Tank model (increase volume): **Increasing volume**



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Main Variables of EOS Model

- Tank model must follow the following:
  - $p \propto T$
  - $p \propto n$
  - $p \propto 1/V$
- Result: Ideal Gas Law $p = \frac{nRT}{V}$

Courtesy: Markus Hays Nielsen

The evolution towards the modern EOS

An equation of state:
Thermodynamic equation relating pressure, volume, temperature and internal energy of fluids.

$$p = \frac{RT}{(v-b)} - \frac{a}{(v-b+\alpha b)(v-b+\beta b)}$$

SRK (1972) – α = 1 and β = 2
PR (1976, 1978) – α = 0 and β = 2

$$p = \frac{RT}{v-b} - \frac{a}{v^2}$$

Van der Waals (1873)

$$p = \frac{RT}{v}$$

The ideal gas law (1834)

Courtesy: Knut Uleberg, Equinor

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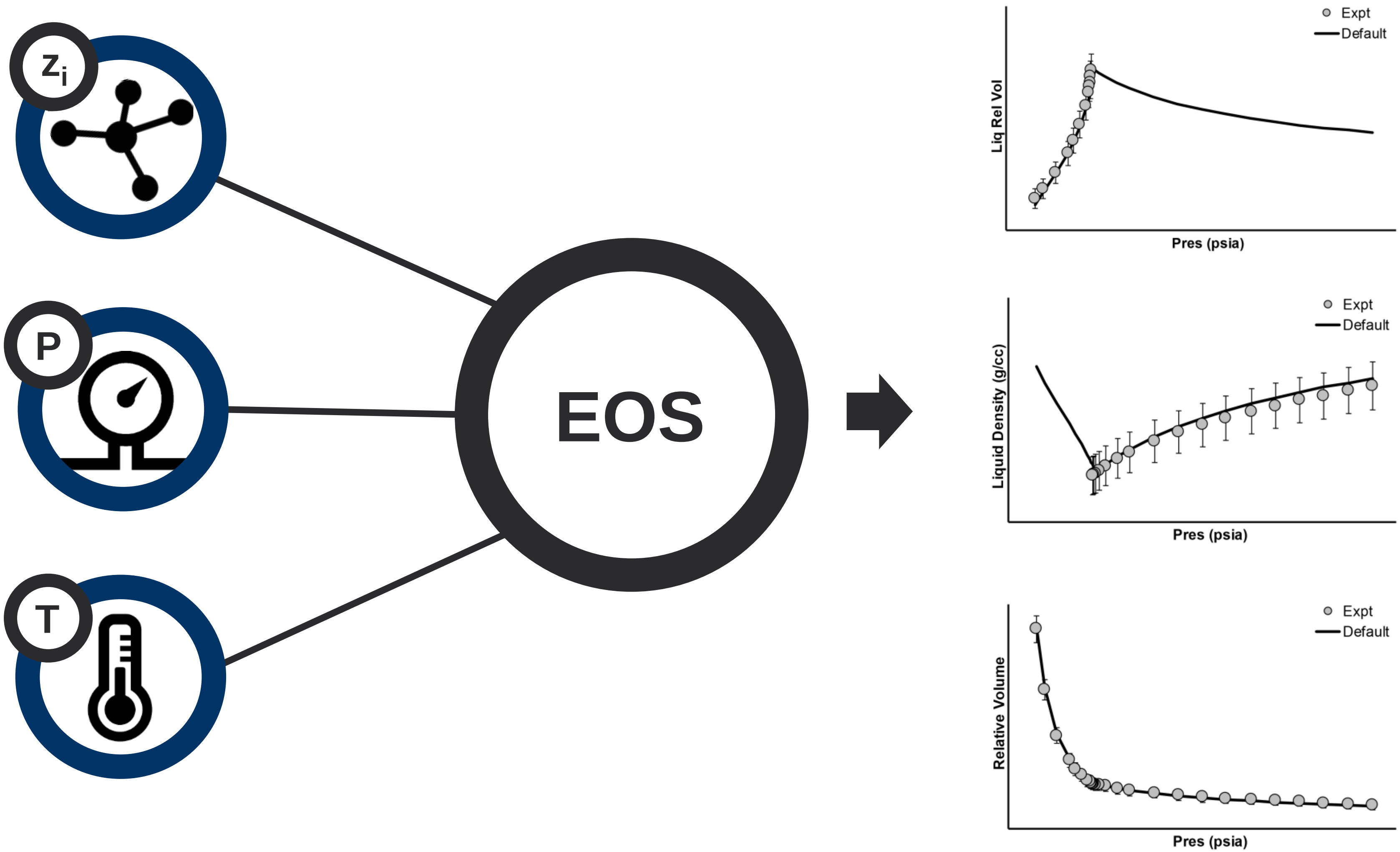
What is an EOS Model?



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What is an EOS Model?

Equation

Peng Robinson (PR)

Soave-Redlich-Kwong (SRK)

Component Properties

Table 3. PERA EOS model parameters.

	MW	P_c, psia	T_c, R	Acentric factor	Volume shift	Z_c	Parachor
N2	28.014	227.16	492.84	0.03700	-0.16758	0.29178	41.0
CO2	44.010	547.42	1069.51	0.22500	0.00191	0.27433	78.0
C1	16.043	343.01	667.03	0.01100	-0.14996	0.28620	77.3
C2	30.070	549.58	706.62	0.09900	-0.06280	0.27924	108.9
C3	44.097	665.69	616.12	0.15200	-0.06381	0.27630	151.9
i-C4	58.123	734.13	527.94	0.18600	-0.06197	0.28199	181.5
n-C4	58.123	765.22	550.56	0.20000	-0.05393	0.27385	191.7
i-C5	72.150	828.70	490.37	0.22900	-0.05646	0.27231	225.0
n-C5	72.150	845.46	488.78	0.25200	-0.02927	0.26837	233.9
C6	83.282	922.39	480.00	0.24969	-0.00554	0.26895	271.0
C7	98.471	995.73	440.38	0.28313	0.06868	0.30797	289.7
C8	109.871	1043.29	414.35	0.31047	0.07534	0.30367	316.4
C9	123.394	1095.51	384.77	0.34698	0.08893	0.29870	348.0
C10	136.625	1141.53	359.49	0.38361	0.10107	0.29424	379.0
C11	149.763	1183.17	337.50	0.42051	0.11208	0.29011	409.7
C12	162.811	1221.14	318.26	0.45752	0.12203	0.28621	440.3
C13	175.766	1255.99	301.35	0.49116	0.13096	0.28249	470.6
C14	188.627	1288.14	286.42	0.52632	0.13892	0.27890	500.7
C15	[illegible]	[illegible]	[illegible]	[illegible]	0.14596	0.27542	530.6
C16	214.052	1345.65	261.34	0.59542	0.15213	0.27203	560.2
C17	[illegible]	[illegible]	[illegible]	[illegible]	0.15747	0.26873	589.6
C18	[illegible]	[illegible]	[illegible]	[illegible]	0.16207	0.26551	618.7
C19	251.410	1418.61	232.70	[illegible]	0.16596	0.26237	647.6
C20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.25931	676.2
C21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.25632	704.6
C22	287.809	1479.65	211.49	0.79124	0.17396	0.25342	732.8
C23	299.729	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	760.7
C24	311.544	1515.27	200.27	[illegible]	0.17672	0.24783	788.3
C25	323.256	[illegible]	195.34	[illegible]	0.17746	0.24516	815.7
C26	334.866	[illegible]	[illegible]	[illegible]	[illegible]	0.24256	842.9
C27	346.376	1562.75	186.61	0.94018	0.17785	0.24003	869.8
C28	357.787	1577.23	[illegible]	[illegible]	[illegible]	[illegible]	896.5
C29	369.102	1591.11	[illegible]	[illegible]	[illegible]	[illegible]	923.0
C30	380.322	1604.46	175.77	[illegible]	0.17616	0.23288	949.3
C31	391.450	1617.29	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
C32	402.489	1629.65	169.74	[illegible]	[illegible]	[illegible]	[illegible]
C33	413.439	1641.57	167.01	1.10194	0.17236	0.22633	1026.7
C34	424.304	1653.08	164.45	1.12718	0.17072	0.22427	1052.2
C35	435.085	1664.20	162.05	1.15193	0.16892	0.22227	1077.4
C36+	579.660	1827.35	152.94	1.22050	0.06623	0.19914	1415.7

Component Name

Molecular Weight

Critical Pressure

Critical Temperature

Acentric Factor

Volume Shift

Critical Z-factor

Binary Interaction Parameters (BIPS)

Table 6. PERA EOS Binary Interaction Parameters for C_7, with C_7 to C_{21}.

	c7	c8	c9	c10	c11	c12	c13	c14	c15	c16	c17	c18	c19	c20	c21
c7															
c8	0.00014														
c9	0.00063	0.00018													
c10	0.00138	0.00065	0.00015												
c11	0.00232	0.00133	0.00053	0.00012											
c12	0.00338	0.00216	0.00109	0.00044	0.00010										
c13	0.00453	0.00310	0.00179	0.00091	0.00037	0.00009									
c14	0.00573	0.00411	0.00257	0.00150	0.00077	0.00031	0.00007								
c15	0.00697	0.00517	0.00342	0.00216	0.00126	0.00065	0.00027	0.00006							
c16	0.00821	0.00625	0.00431	0.00288	0.00183	0.00107	0.00055	0.00023	0.00005						
c17	0.00945	0.00734	0.00523	0.00364	0.00244	0.00155	0.00091	0.00047	0.00019	0.00004					
c18	0.01068	0.00843	0.00616	0.00442	0.00309	0.00208	0.00132	0.00078	0.00040	0.00017	0.00004				
c19	0.01188	0.00950	0.00708	0.00521	0.00376	0.00263	0.00177	0.00113	0.00067	0.00035	0.00014	0.00003			
c20	0.01305	0.01056	0.00800	0.00601	0.00443	0.00320	0.00225	0.00152	0.00097	0.00057	0.00030	0.00012	0.00003		
c21	0.01419	0.01159	0.00890	0.00680	0.00512	0.00379	0.00274	0.00193	0.00130	0.00084	0.00049	0.00026	0.00011	0.00002	
c22	0.01530	0.01259	0.00979	0.00757	0.00580	0.00438	0.00325	0.00235	[illegible]	0.00112	0.00072	0.00043	0.00022	0.00009	0.00002
c23	0.01637	0.01357	0.01065	0.00834	0.00647	0.00496	0.00376	0.00279	[illegible]	[illegible]	0.00097	0.00063	[illegible]	0.00019	0.00008
c24	0.01740	0.01451	0.01149	0.00909	0.00713	0.00555	0.00427	0.00324	0.00241	[illegible]	0.00124	0.00084	[illegible]	[illegible]	0.00017
c25	0.01839	0.01542	0.01231	0.00982	0.00778	0.00612	0.00477	0.00368	0.00280	0.00209	0.00152	0.00108	0.00073	0.00047	0.00028
c26	0.01934	0.01630	0.01310	0.01052	0.00842	0.00669	0.00527	0.00412	0.00318	0.00242	0.00181	0.00132	0.00094	0.00064	0.00041
c27	0.02026	0.01715	0.01386	0.01121	0.00903	0.00724	0.00577	0.00456	0.00357	0.00276	0.00211	0.00158	0.00116	0.00082	0.00056
c28	0.02114	0.01796	0.01460	0.01188	0.00963	0.00778	0.00625	0.00499	0.00395	0.00310	0.00241	0.00184	0.00138	0.00101	0.00072
c29	0.02199	0.01875	0.01531	0.01252	0.01022	0.00831	0.00673	0.00542	0.00433	0.00344	0.00270	0.00210	0.00161	0.00121	0.00089
c30	0.02281	0.01950	0.01600	0.01315	0.01078	0.00882	0.00719	0.00583	0.00471	0.00377	0.00300	0.00236	0.00184	0.00141	0.00106
c31	0.02359	0.02023	0.01666	0.01375	0.01133	0.00932	0.00764	0.00624	0.00507	0.00410	0.00330	0.00263	0.00207	0.00162	0.00124
c32	0.02434	0.02093	0.01730	0.01433	0.01186	0.00980	0.00808	0.00664	0.00543	0.00443	0.00359	0.00289	0.00231	0.00182	0.00142
c33	0.02506	0.02160	0.01791	0.01489	0.01237	0.01027	0.00850	0.00703	0.00579	0.00475	0.00388	0.00315	0.00254	0.00203	0.00161
c34	0.02575	0.02224	0.01850	0.01543	0.01287	0.01072	0.00892	0.00740	0.00613	0.00506	0.00416	0.00340	0.00277	0.00224	0.00179
c35	0.02642	0.02287	0.01907	0.01596	0.01335	0.01116	0.00932	0.00777	0.00647	0.00536	0.00444	0.00366	0.00300	0.00244	0.00198
c36+	0.03359	0.02960	0.02530	0.02171	0.01867	0.01608	0.01387	0.01197	0.01035	0.00895	0.00774	0.00670	0.00580	0.00502	0.00435

C_1-C_2

C_1-C_3

...

C_{36+} – C_{36+}

C_{7+} properties need to be approximated

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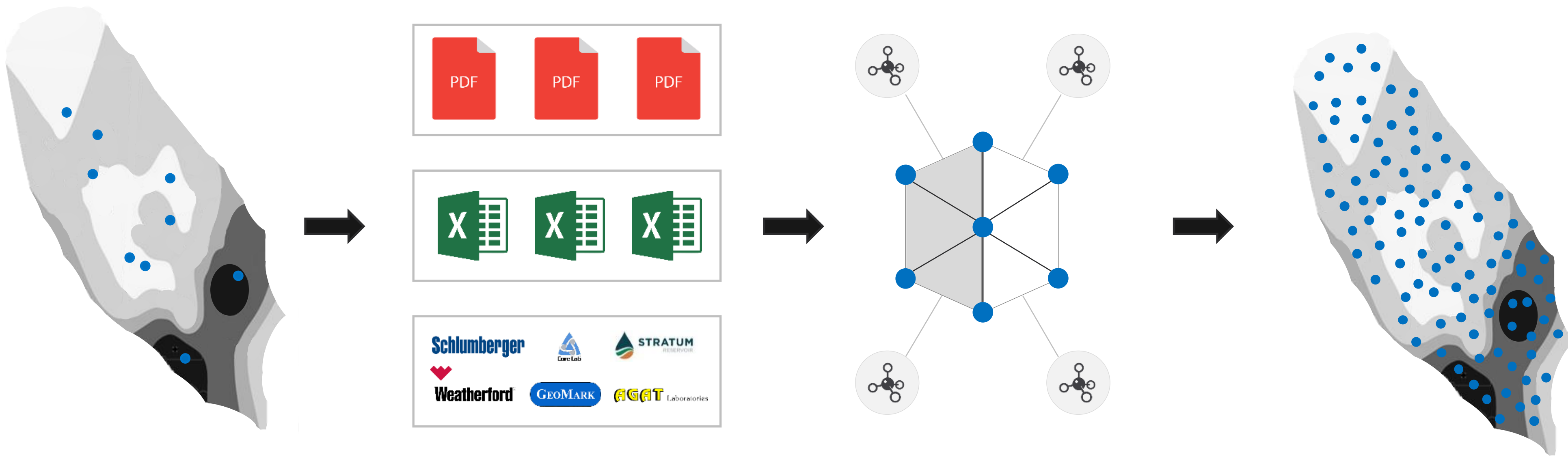
Underlying Technology: Basin-Wide EOS Models

Wells with PVT Data | PVT Reports | EOS Model | All wells



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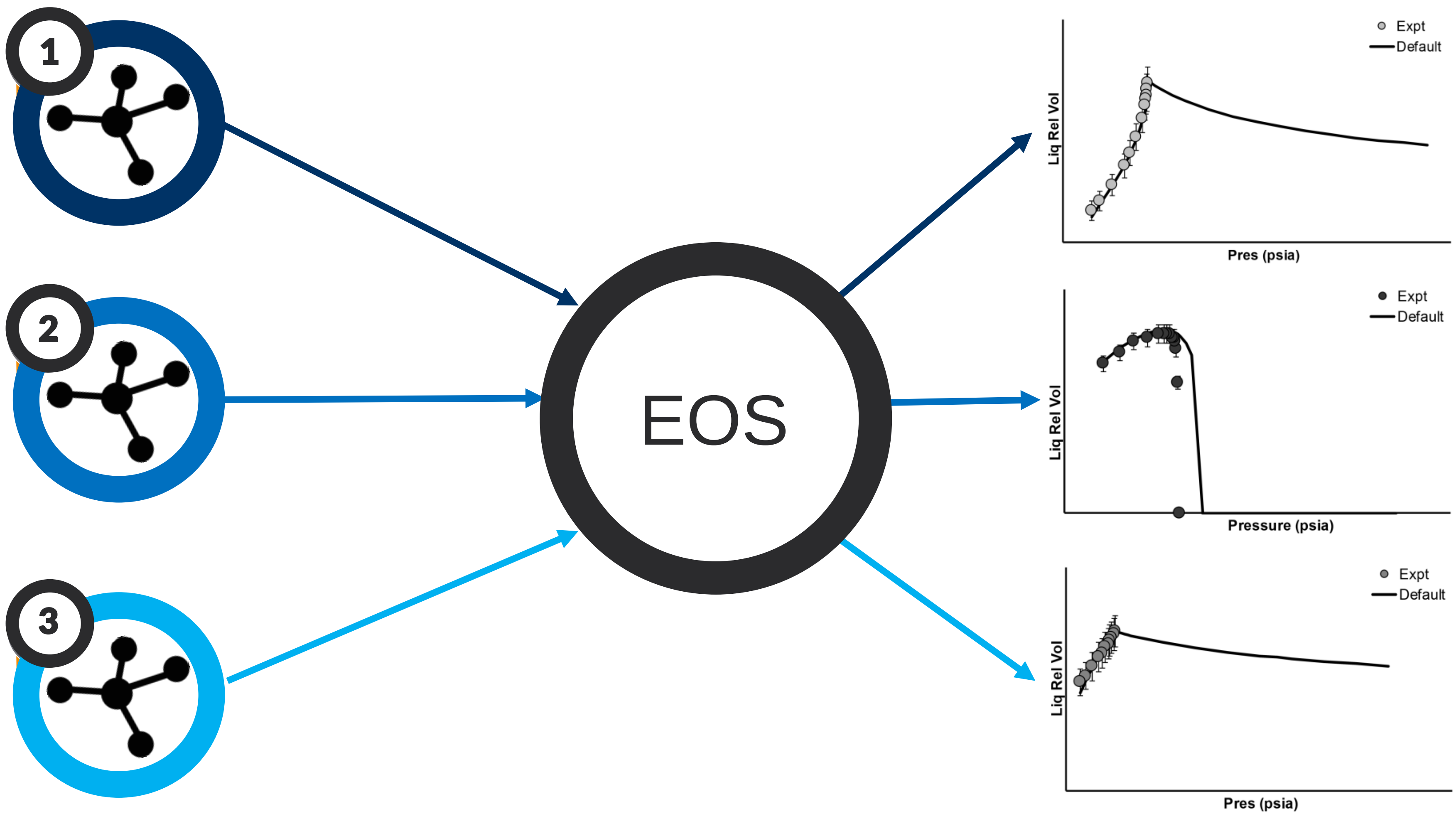
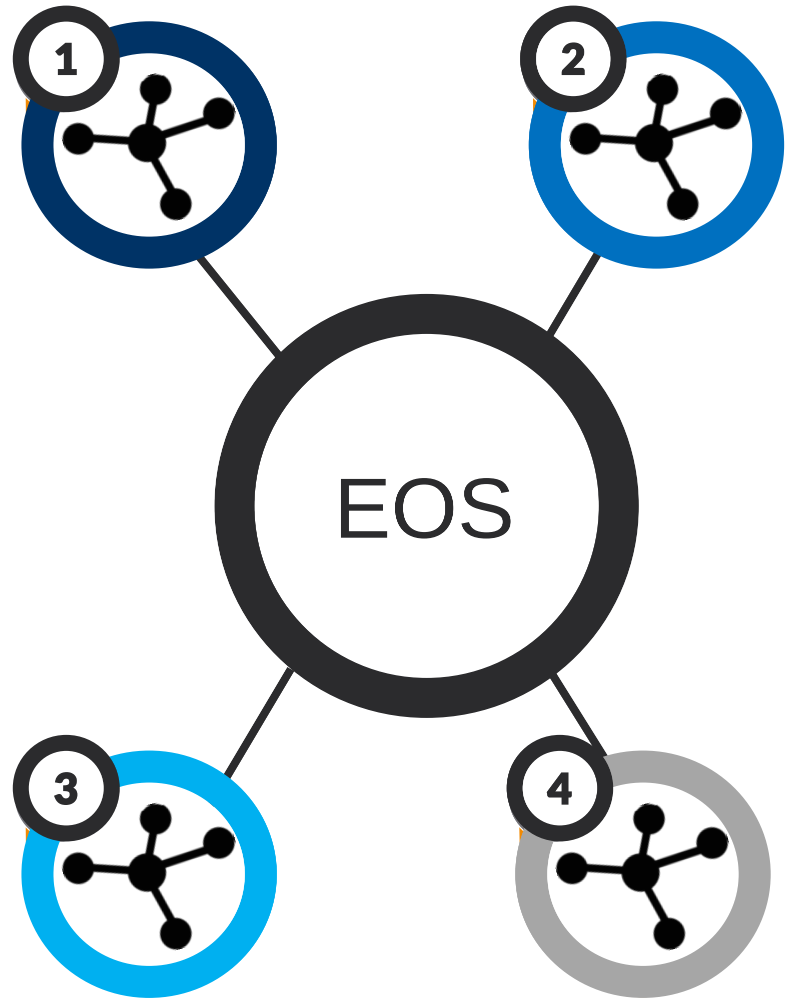
Multi-Sample (Common) EOS Model



Multi-Sample (Common) EOS Model

Each sample is described by the same EOS model, where each sample's unique composition is all that is required to accurately predict PVT data for that specific fluid



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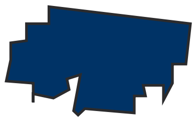
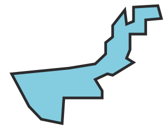
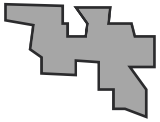
Multi-Sample EOS Models

Basin A	Basin B	Basin C
		

$$(\bar{C}_{11})_A \neq (\bar{C}_{11})_B \neq (\bar{C}_{11})_C$$

$$(\bar{C}_{12})_A \neq (\bar{C}_{12})_B \neq (\bar{C}_{12})_C$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$(\bar{C}_{30p})_A \neq (\bar{C}_{30p})_B \neq (\bar{C}_{30p})_C$$

Can be radically different

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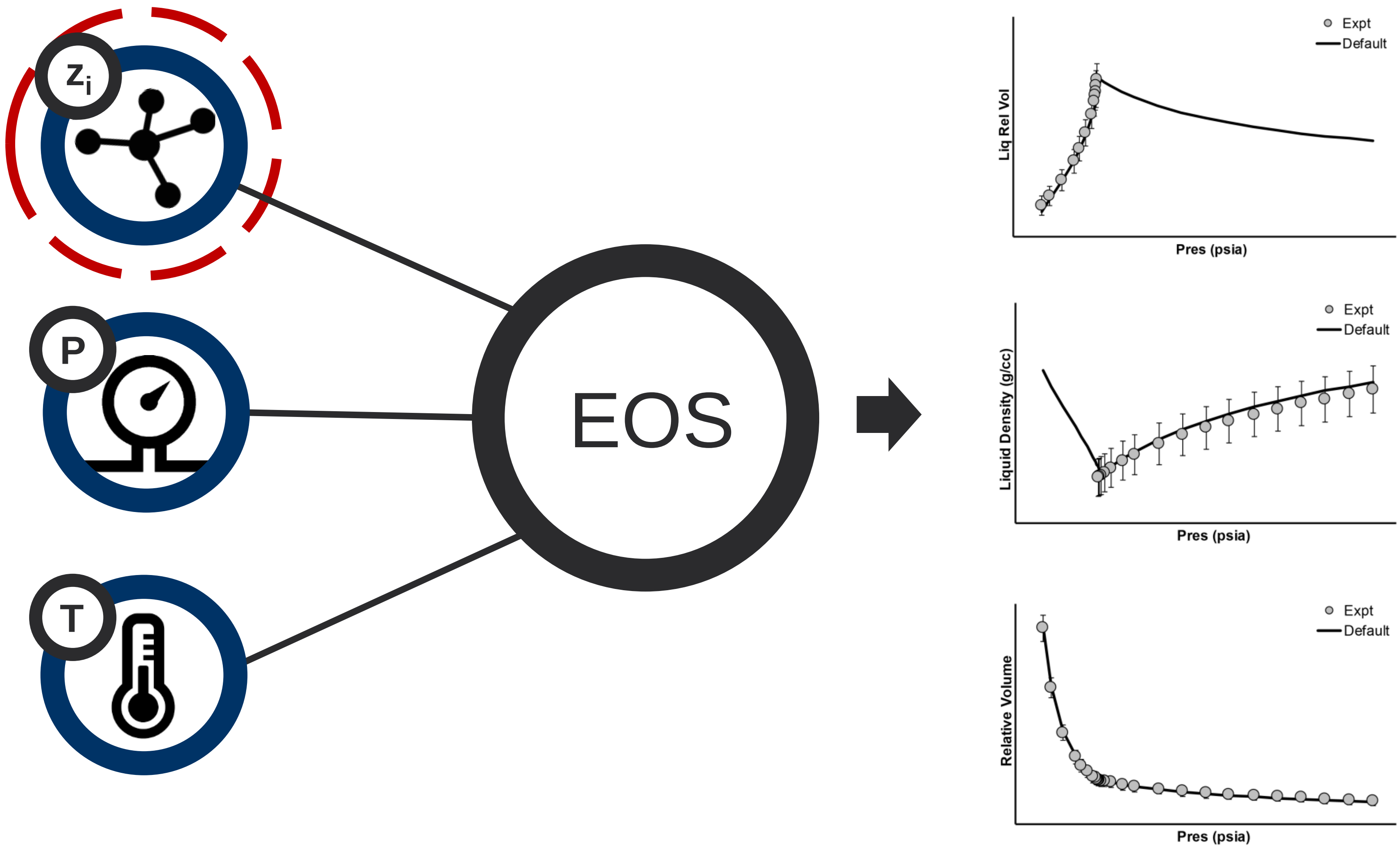
Predict Compositions

Compositions are Needed for EOS Calculations!



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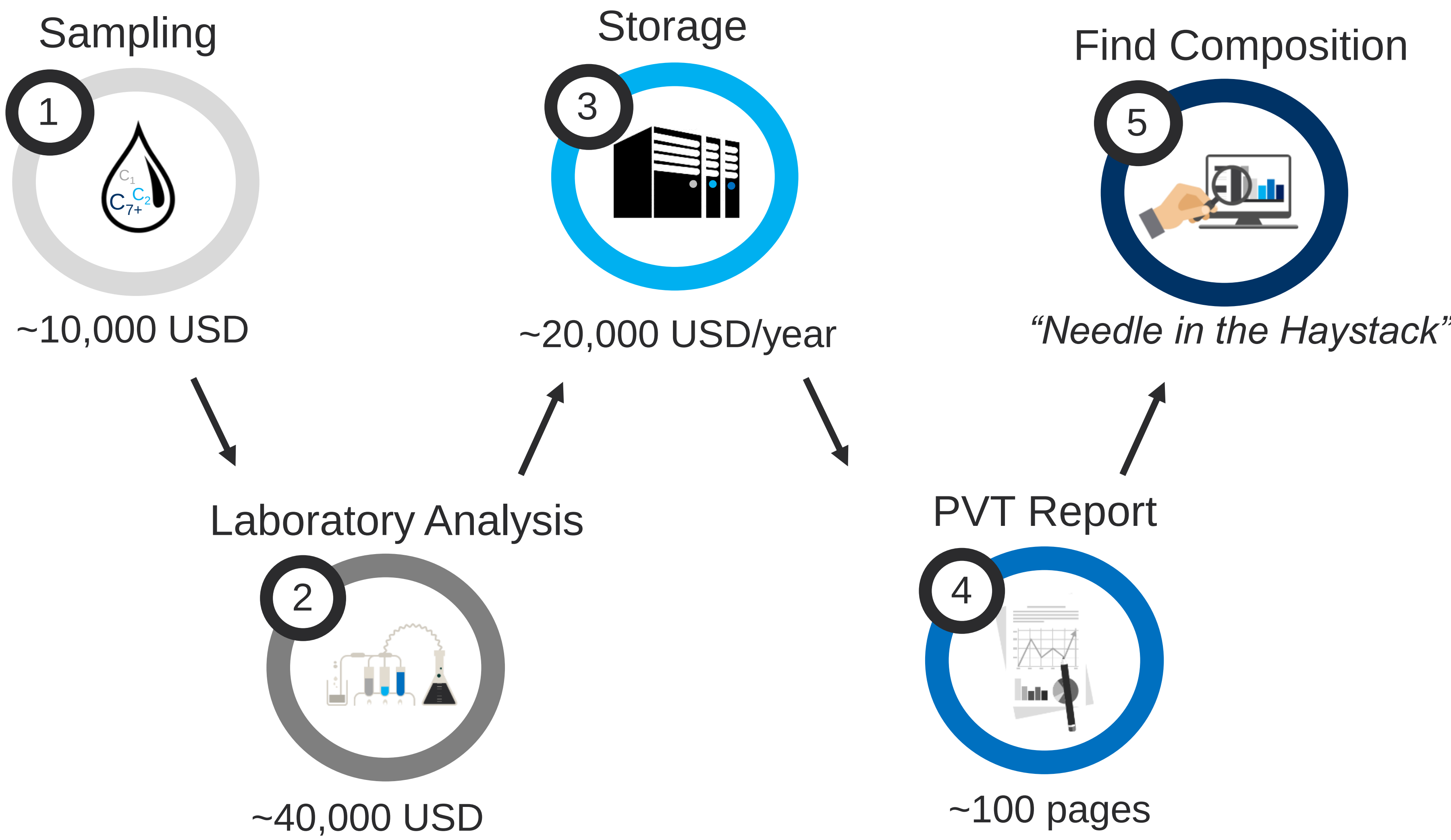
… But how do you get them?



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PVT Report Example

Weatherford
LABORATORIES

Encana Corporation

Reservoir Fluid Study
Field: Kaybob
Formation: Duvernay
Well: ECA Hz Wahigan
04-12-064-23W5
CL-70073
August 2015

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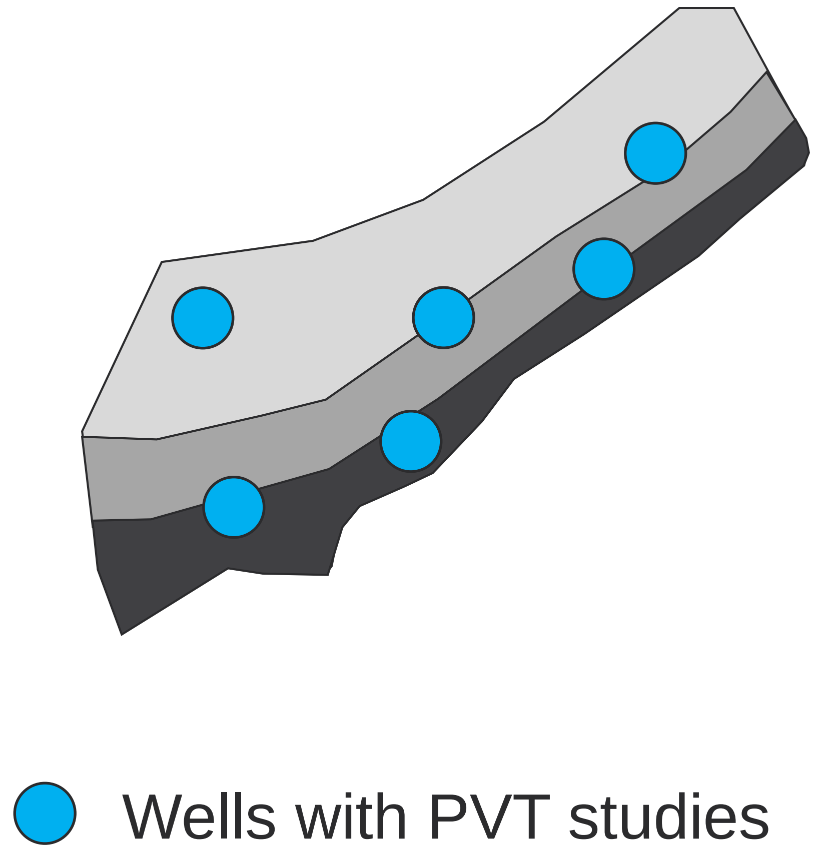
TABLE 1
ENCANA CORPORATION
WELL ECA HZ WAHIGAN 04-12-064-23W5 – RECOMBINED SAMPLE
RESERVOIR FLUID STUDY
COMPOSITIONAL ANALYSIS OF RESERVOIR FLUID

Boiling Point (C)			Mole Fraction	Mass Fraction	Calculated Properties	
-195.8	Nitrogen	N2	0.0095	0.0046	**Total Sample**	
-78.5	Carbon Dioxide	CO2	0.0043	0.0033		
-60.3	Hydrogen Sulphide	H2S	0.0000	0.0000	Molecular Weight	57.16
-161.7	Methane	C1	0.4825	0.1355		
-88.9	Ethane	C2	0.1254	0.0659		
-42.2	Propane	C3	0.0822	0.0634	**C6+ Fraction**	
-11.7	i-Butane	i-C4	0.0140	0.0143		
-0.6	n-Butane	n-C4	0.0356	0.0362	Molecular Weight	167.92
27.8	i-Pentane	i-C5	0.0129	0.0163	Mole Fraction	0.2181
36.1	n-Pentane	n-C5	0.0156	0.0197	Density (g/cc)	0.8200
36.1 - 68.9	Hexanes	C6	0.0244	0.0368		
68.9 - 98.3	Heptanes	C7	0.0223	0.0391		
98.3 - 125.6	Octanes	C8	0.0245	0.0490	**C7+ Fraction**	
125.6 - 150.6	Nonanes	C9	0.0179	0.0402		
150.6 - 173.9	Decanes	C10	0.0136	0.0339	Molecular Weight	178.73
173.9 - 196.1	Undecanes	C11	0.0122	0.0313	Mole Fraction	0.1928
196.1 - 215	Dodecanes	C12	0.0097	0.0272	Density (g/cc)	0.8302
215 - 235	Tridecanes	C13	0.0095	0.0292		
235 - 252.2	Tetradecanes	C14	0.0079	0.0262		
252.2 - 270.6	Pentadecanes	C15	0.0058	0.0208	**C12+ Fraction**	
270.6 - 287.8	Hexadecanes	C16	0.0047	0.0181		
287.8 - 291.7	Heptadecanes	C17	0.0040	0.0167	Molecular Weight	275.39
291.7 - 317.2	Octadecanes	C18	0.0039	0.0170	Mole Fraction	0.0754
317.2 - 330	Nonadecanes	C19	0.0034	0.0159	Density (g/cc)	0.8780
330 - 344.4	Eicosanes	C20	0.0028	0.0133		
344.4 - 357.2	Heneicosanes	C21	0.0024	0.0122		
357.2 - 369.4	Docosanes	C22	0.0021	0.0114		
369.4 - 380	Tricosanes	C23	0.0019	0.0106		
380 - 391.1	Tetracosanes	C24	0.0017	0.0097		
391.1 - 401.7	Pentacosanes	C25	0.0015	0.0092		
401.7 - 412.2	Hexacosanes	C26	0.0013	0.0084		
412.3 - 422.2	Heptacosanes	C27	0.0012	0.0076		
422.3 - 431.7	Octacosanes	C28	0.0011	0.0072		
431.7 - 441.1	Nonacosanes	C29	0.0009	0.0066		
Above 441.1	Tricontanes Plus	C30+	0.0097	0.0961		
48.9	Cyclopentane	C5H10	0.0009	0.0011		
72.2	Methylcyclopentane	C6H12	0.0039	0.0058		
81.1	Cyclohexane	C6H12	0.0033	0.0048		
101.1	Methylcyclohexane	C7H14	0.0088	0.0151		
80.0	Benzene	C6H6	0.0005	0.0007		
110.6	Toluene	C7H8	0.0022	0.0035		
136.1 - 138.9	Ethylbenzene & p,m-Xylene	C8H10	0.0025	0.0046		
144.4	o-Xylene	C8H10	0.0020	0.0037		
168.9	1, 2, 4-Trimethylbenzene	C9H12	0.0037	0.0078		
Total			**1.0000**	**1.0000**		

Setting the Stage

- PVT Studies:
  ~25 – 50 USDk/well
- Sample Storage:
  ~20 USDk/well/year
- Gets expensive fast!
- Typically:
  ~ performed on <1% of Wells in a Basin



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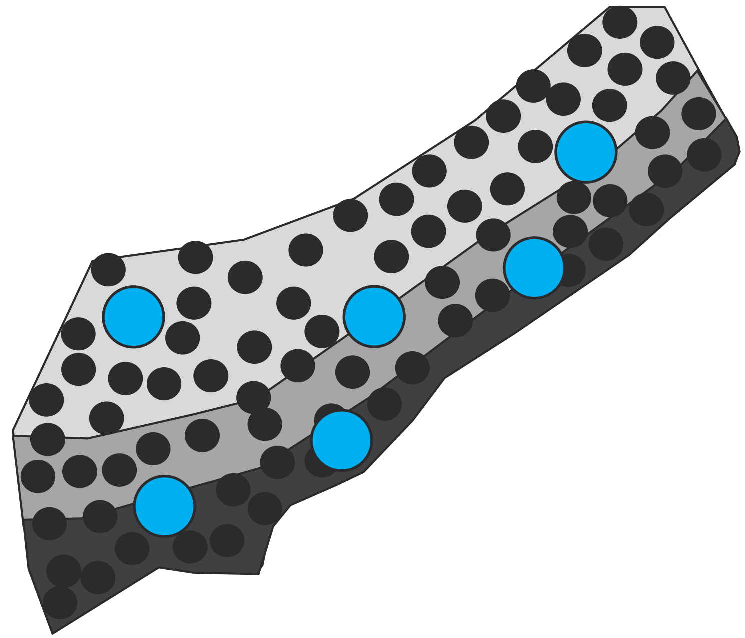
Setting the Stage

What to do
with the >99%
other wells?



Wells with PVT studies

Wells without PVT studies

Use the Available Data

Available Data	whitson+
Initial producing GOR	10000 scf/STB
Initial producing GOR & API gravity	600 scf/STB & 38 API
Initial producing GOR & saturation pressure	1250 scf/sep.bbl & 3000 psia
Dry/wet gas composition	80% C_1, 15% C_2, 5% C_3
Separator compositions	**See Example Later**

Source: https://manual.whitson.com/modules/fluid-definition/

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Black Oil PVT

PVT Properties are a function of

$$\boxed{\mathrm{PVT} = f(p, T, z_i)}$$

- Pressure
- Temperature
- Composition

"PVT" means the collection of intensive properties (independent on amount), e.g. psat, density

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PVT Properties

$$\boxed{\mathrm{PVT} = f(p, T, z_i)}$$

- 2+(n-1) dimensions
- n: is the number of components
- n = 2 → "Black oil model"

Important

The Black Oil Model can be used for ALL Reservoir Fluid Systems

… and NOT only for black oil!!!

So.. why is it Called "Black Oil" Model?

- Just tradition
- Two component PVT model

  Oil in the tank – *"the oil in the tank was always black"*

  Surface gas

"Should have been called the two-component PVT model"

- **Keith Coats** (1934-2016), Pioneer in Reservoir Simulation

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Black Oil PVT Model

- Two components: Surface oil and surface gas
- Model Parameters: B_o, R_s, μ_o | B_{gd}, r_s, μ_g
- Compositions of reservoir oil and gas phase: R_s | r_s
- Model is dependent on surface processing

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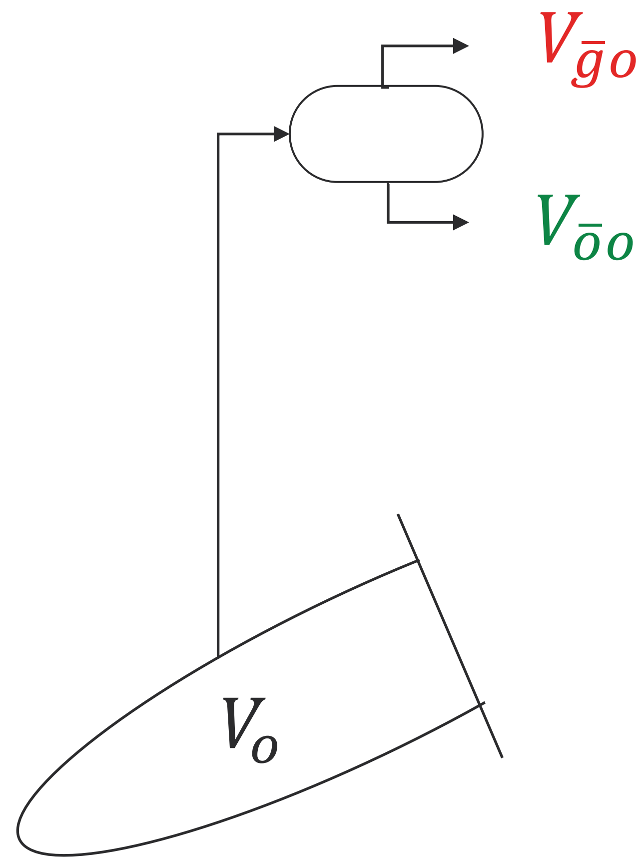
Oil Reservoir

V_o : ***"Reservoir Oil"***

$V_{\bar{o}o}$: ***"Surface Oil Originating from Reservoir Oil"***

$V_{\bar{g}o}$: ***"Surface Gas Originating from Reservoir Oil"***



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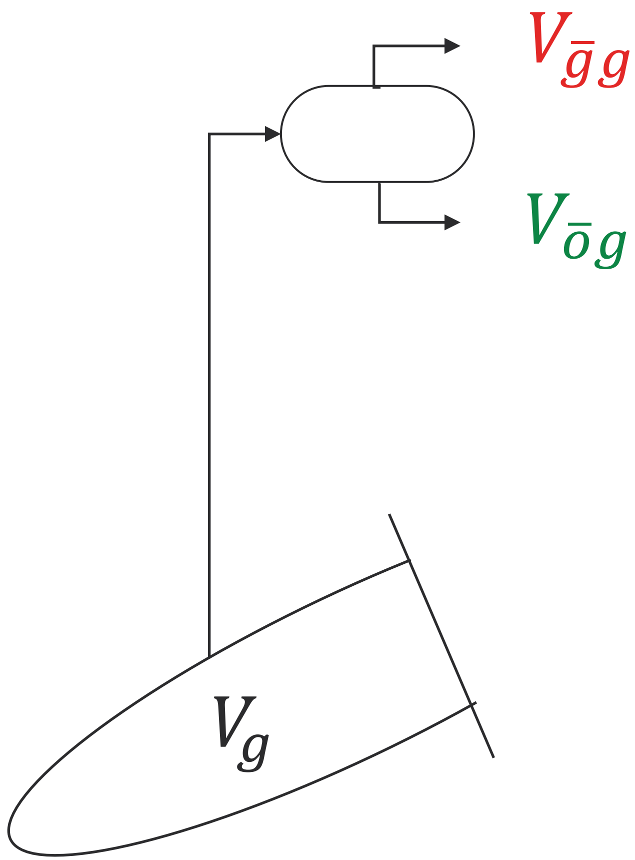
Gas Reservoir

V_g : *"Reservoir Gas"*

$V_{\bar{o}g}$: *"Surface Oil Originating from Reservoir Gas"*

$V_{\bar{g}g}$: *"Surface Gas Originating from Reservoir Gas"*



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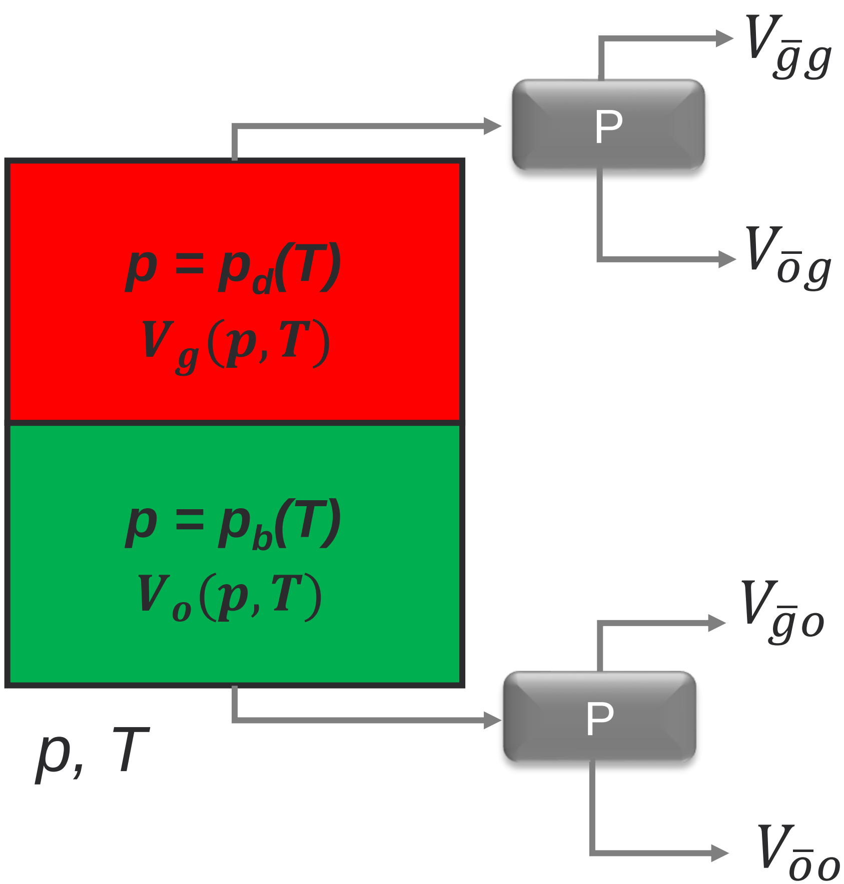
Black Oil PVT Properties



Process Dependent

$$B_{gd} = \frac{V_g}{V_{\bar{g}g}}$$

$$r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}}$$

$$B_o = \frac{V_o}{V_{\bar{o}o}}$$

$$R_s = \frac{V_{\bar{g}o}}{V_{\bar{o}o}}$$

Process Independent

μ_g

μ_o

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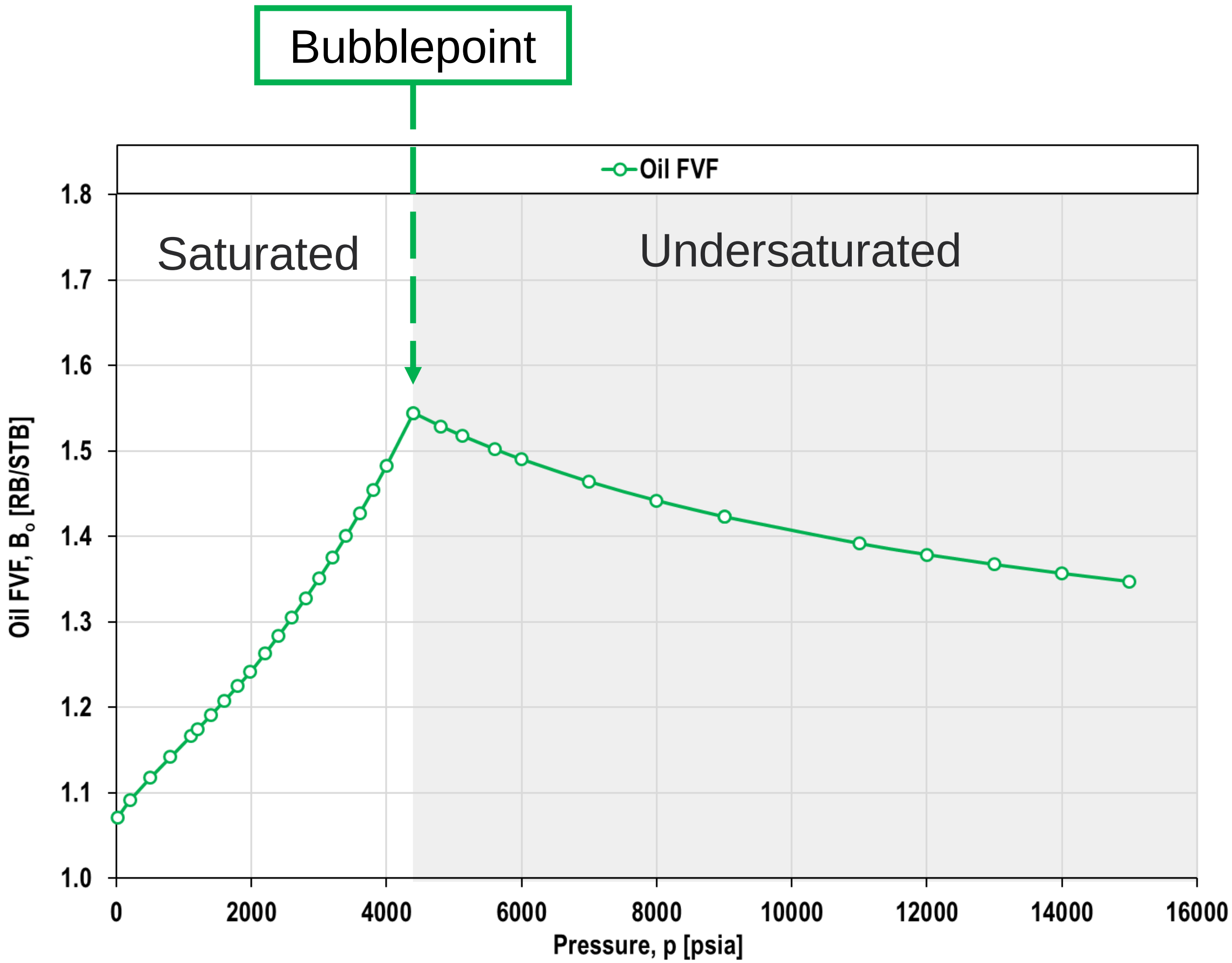
Oil Formation Volume Factor, B_o



$$B_o = \frac{V_o}{V_{\bar{o}o}}$$

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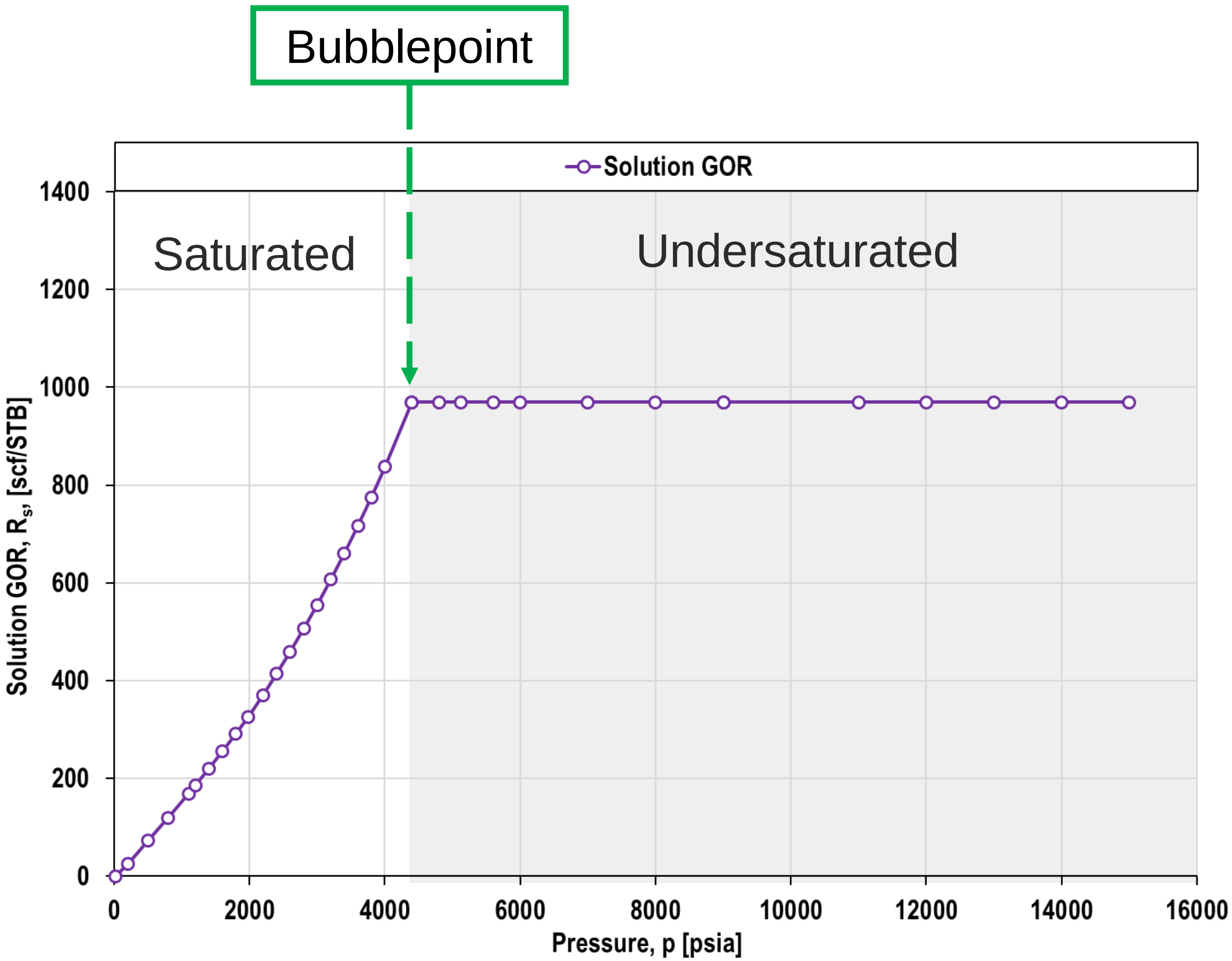
Solution GOR, R_s



$$R_s = \frac{V_{\bar{g}o}}{V_{\bar{o}o}}$$

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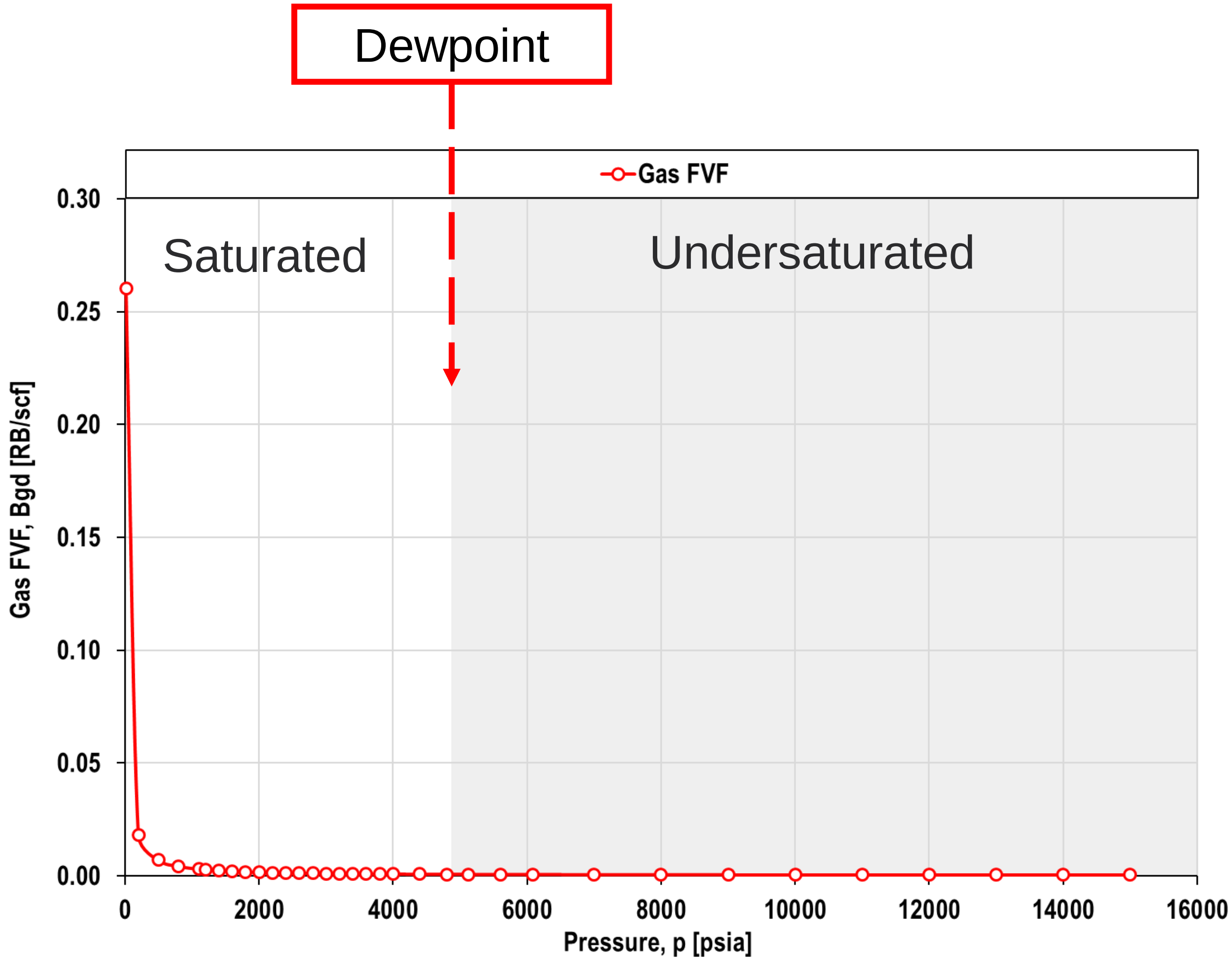
Gas Formation Volume Factor, B_{gd}



$$B_{gd} = \frac{V_g}{V_{\bar{g}g}}$$

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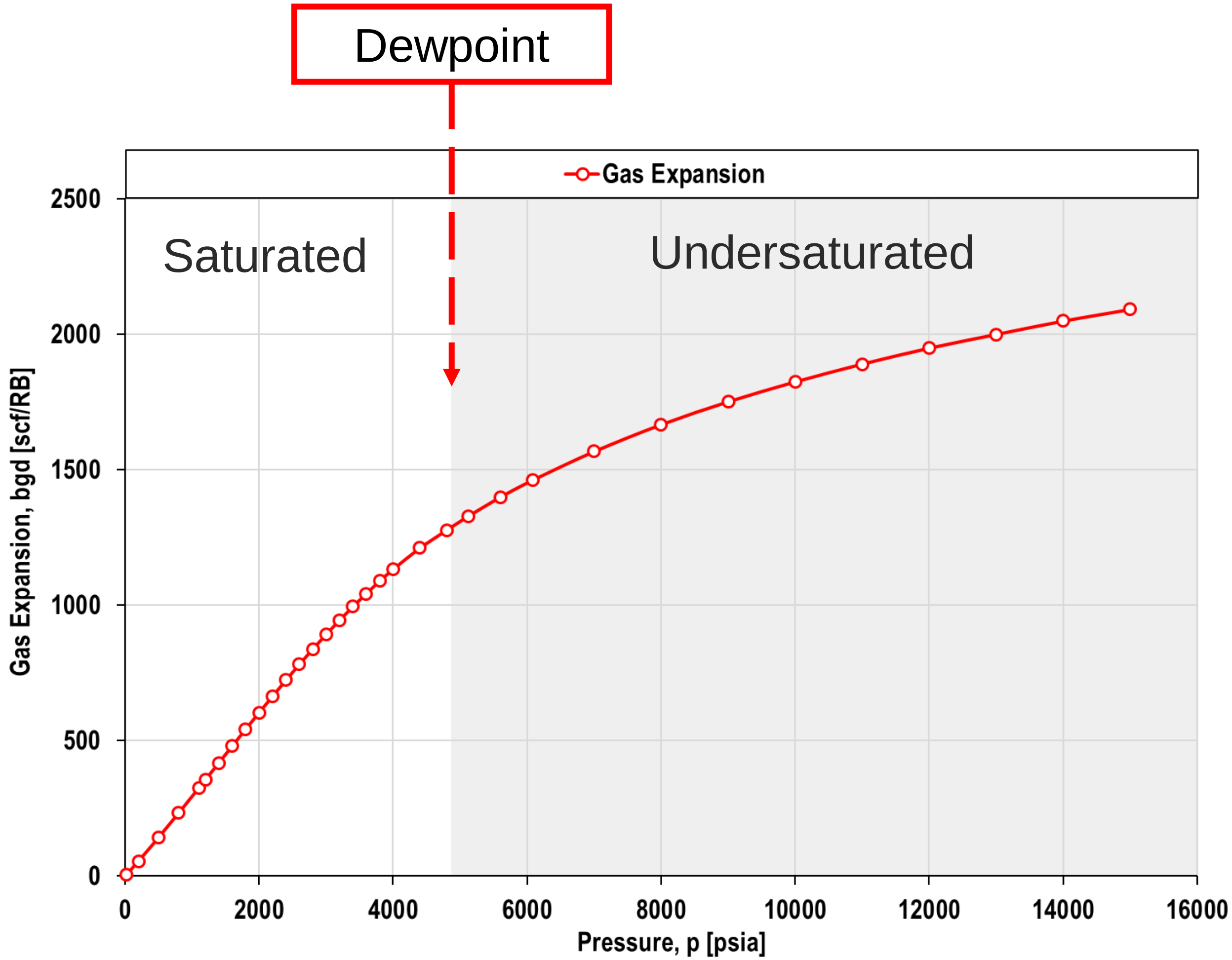
Gas Expansion Factor, b_{gd}



$$b_{gd} = \frac{V_{\bar{g}g}}{V_g}$$

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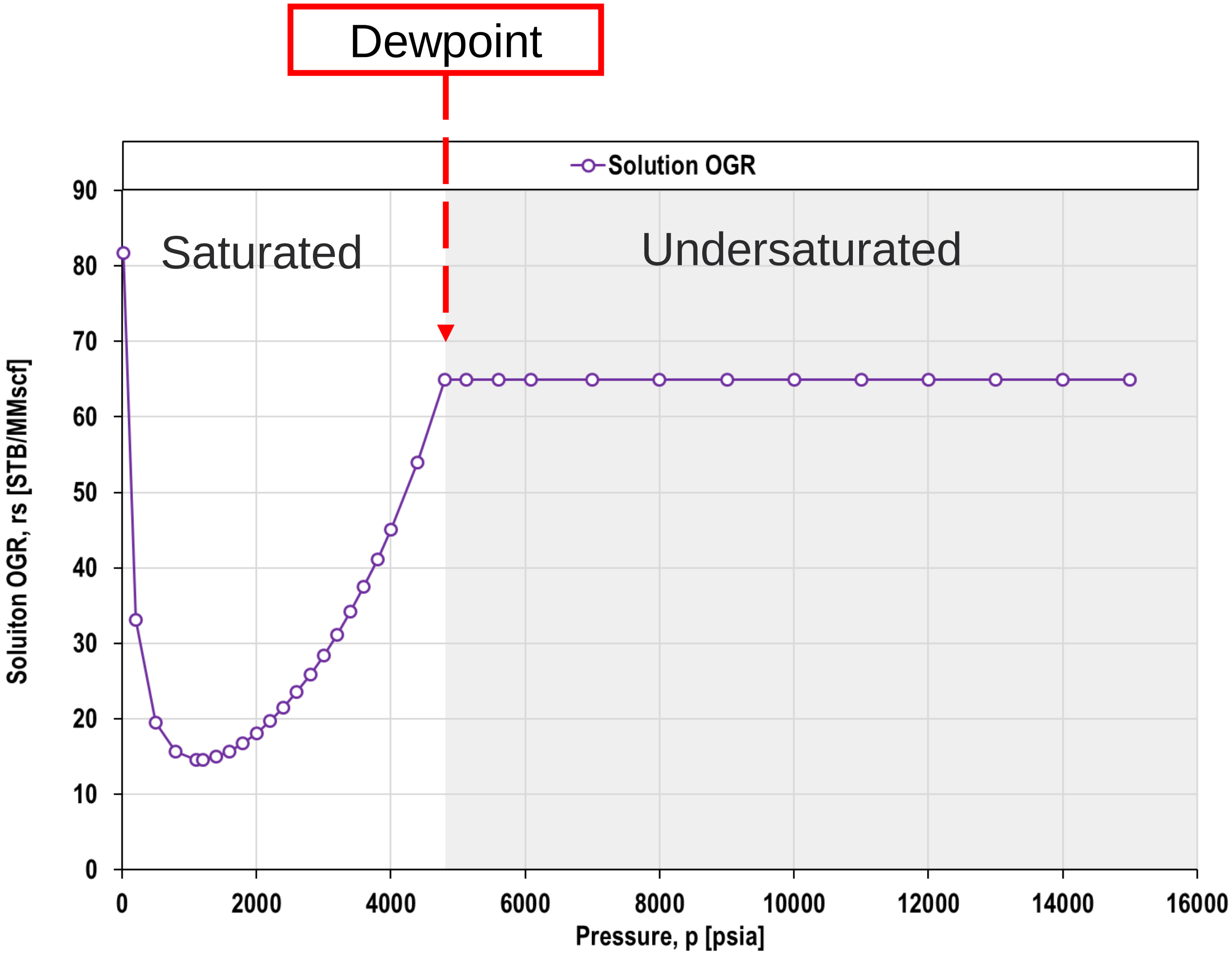
Solution OGR, r_s (=R_v)



$$r_s = \frac{V_{\bar{o}g}}{V_{\bar{g}g}}$$

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Equilibrium Ratios (K-values)

K-Values

$$K_i \equiv y_i / x_i$$

K_i represents the relative preference of component i to "be" in the gas phase or oil phase:

1. *Relative preference is to be in gas phase: Ki > 1*
2. *Relative preference is to be in the oil phase: Ki <1*

K-values

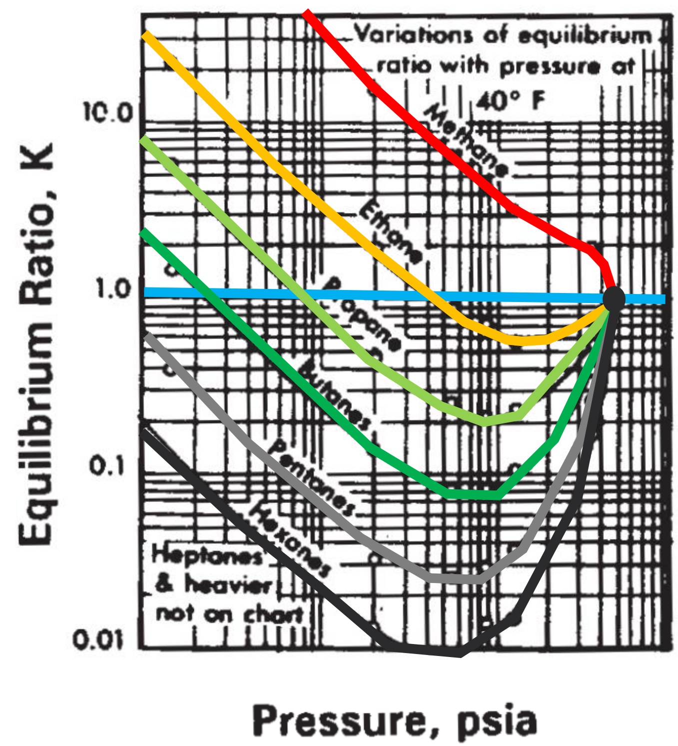
$$K_i = \frac{y_i}{x_i}$$

Preference of a component to be in the vapor phase compared to liquid phase

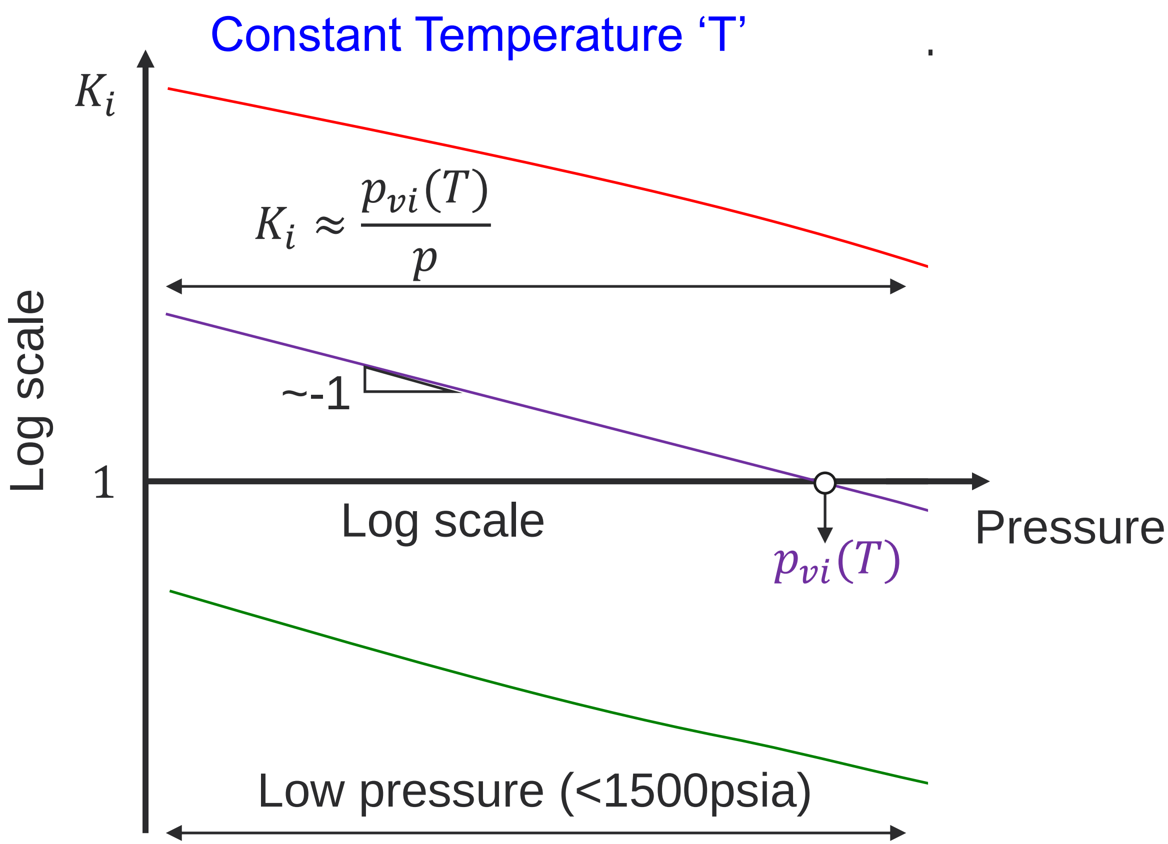
E.g. $K_{C1} > K_{C10}$

Physically relevant when a fluid system exists in two phases at given p and T

For a given **temperature (T)** and **composition (zi)**

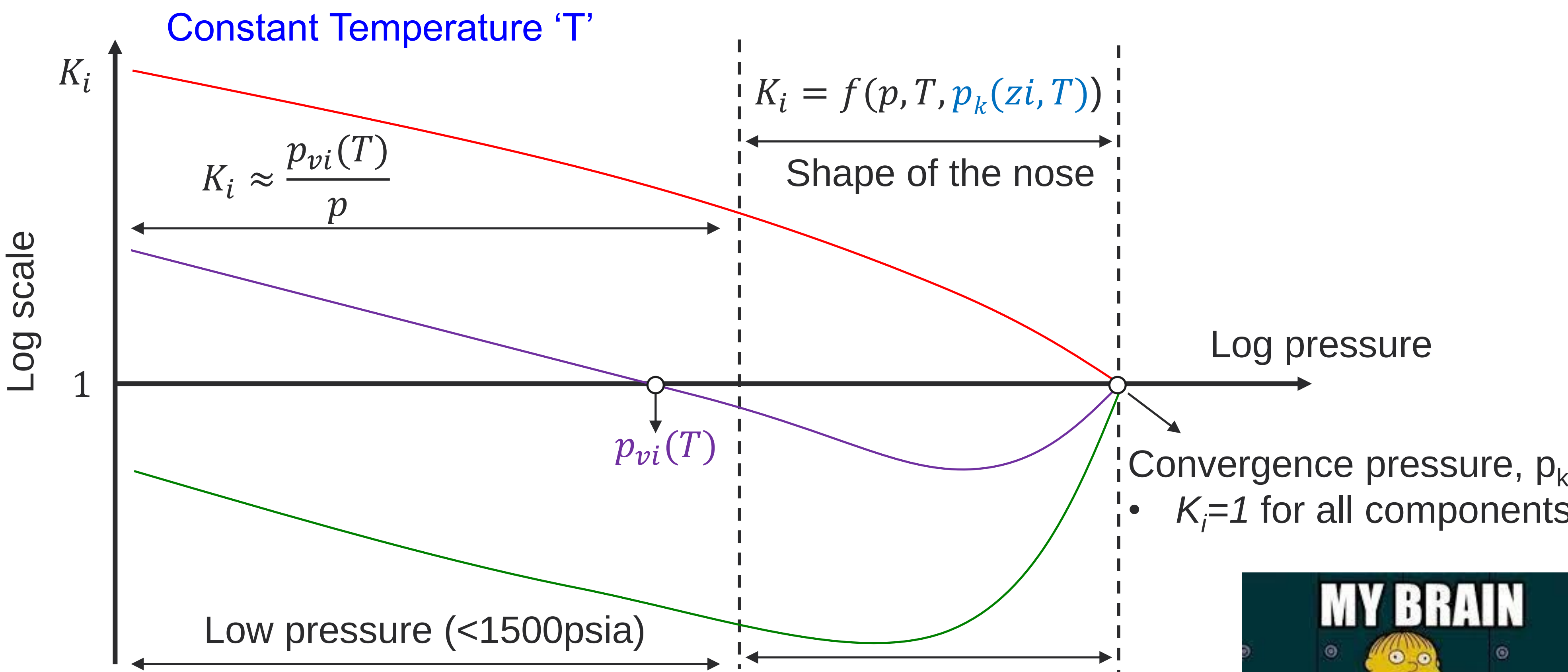


K-values (low pressure range)



Relevant mainly for surface processing where "T" is also lower

K-values (high pressures range)



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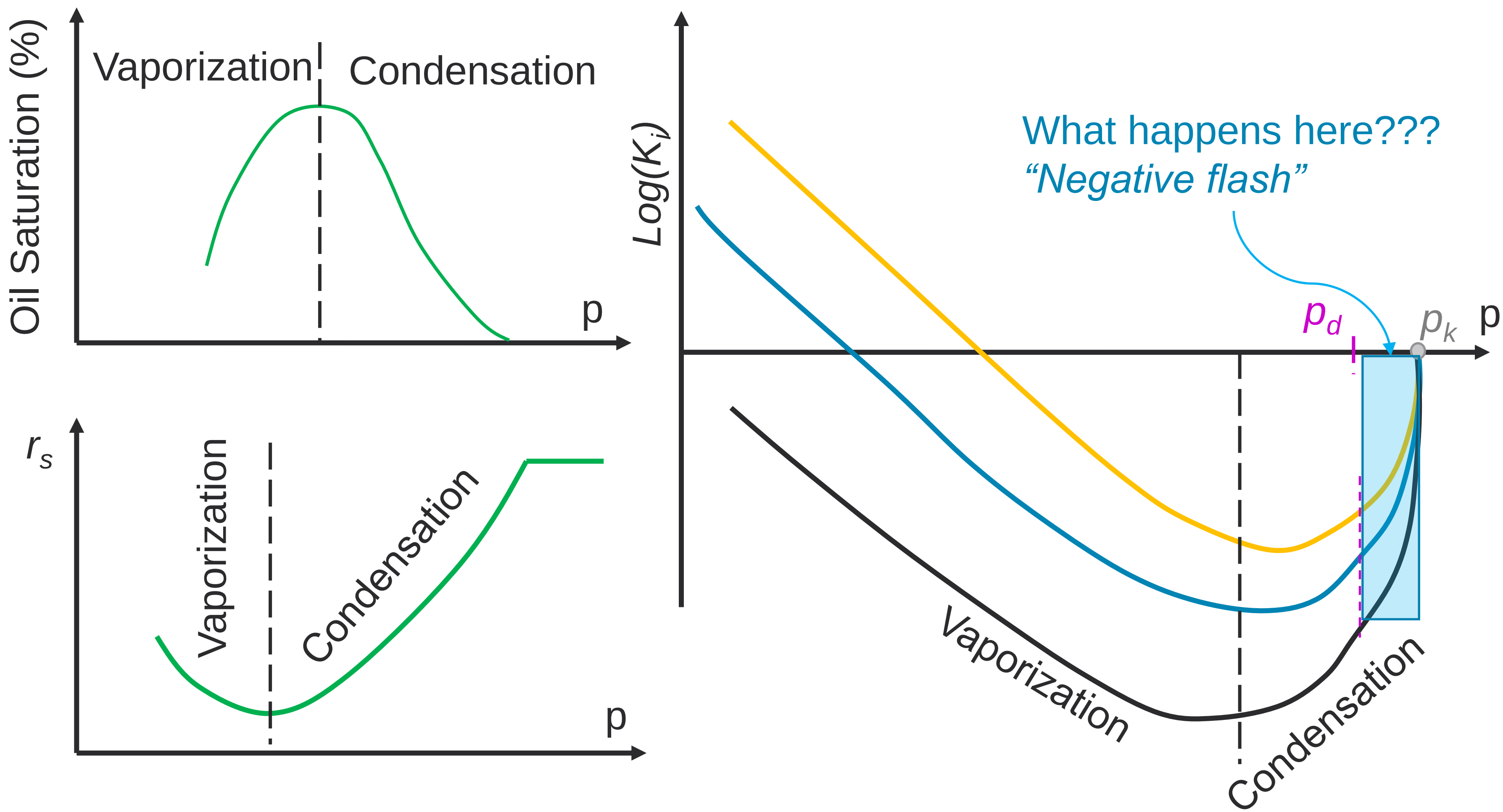
Retrograde Condensation



- Heavier the component – longer the condensation region

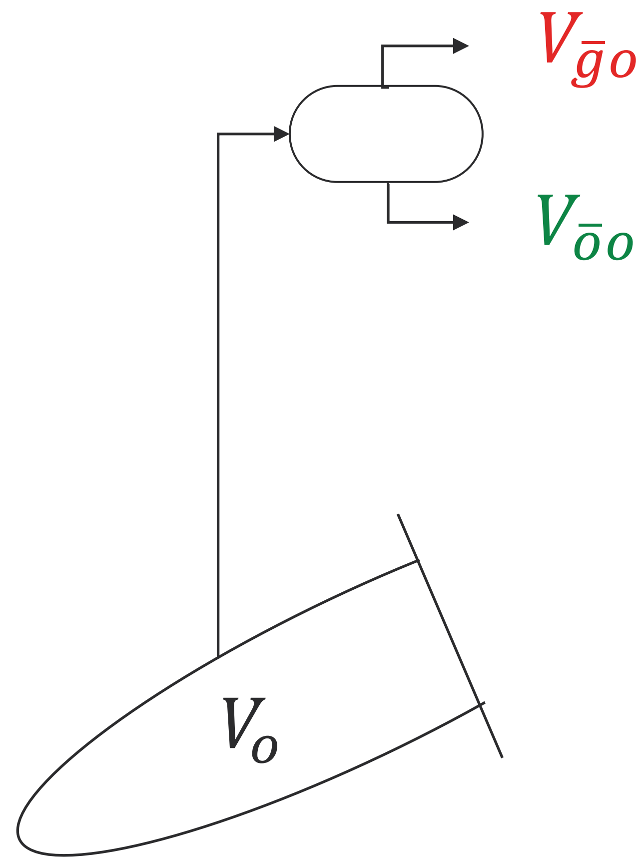
Initial Fluids in Place

Oil Reservoir – In-place Numbers

$$N_o = OOIP_o = \frac{V_o}{B_{oi}}$$

$$= \frac{7758\, A\, h\, \varphi(1-Swi)}{B_{oi}} \text{ [STB]}$$

$$G_o = OGIP_g = N_o R_{si} \text{ [scf]}$$



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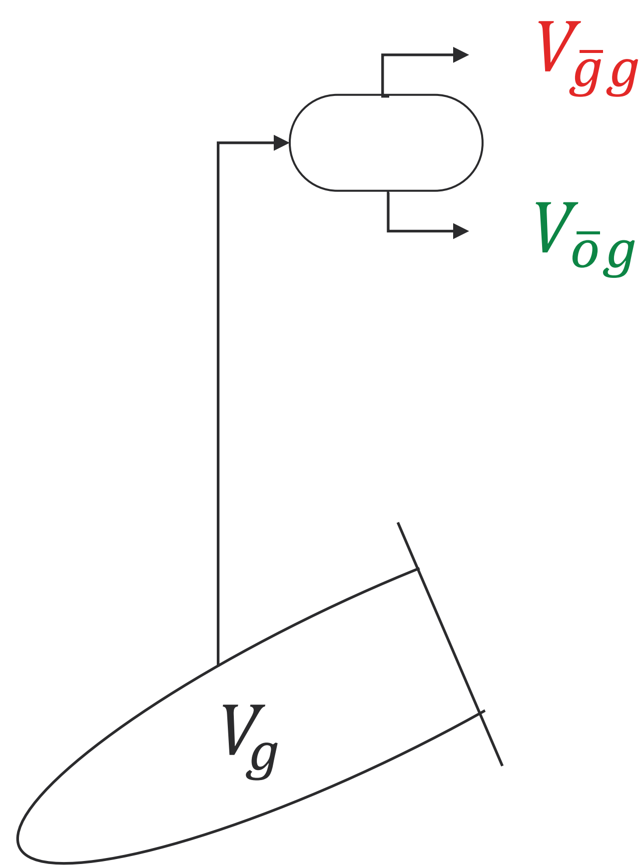
Gas Reservoir – In-place Numbers

$$G_g = OGIP_g = \frac{V_g}{B_{gdi}}$$

$$= \frac{7758\ A\ h\ \varphi(1-Swi)}{B_{gdi}} \text{ [scf]}$$

$$N_g = OOIP_g = G_g r_{si} \text{ [STB]}$$



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In-place volumes: All Reservoir Fluids, Two Equations

$$N = \frac{HCPV}{FVF_{tot}}$$

original oil in place

$$G = N * GOR_{tot}$$

original gas in place

Source: https://manual.whitson.com/modules/bot/

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Total Formation Volume Factor (FVF_{tot})

$$FVF_{\mathrm{tot}} = \frac{100}{\frac{S_{\mathrm{o}}}{B_{\mathrm{o}}} + \frac{S_{\mathrm{g}}}{B_{\mathrm{gd}}/r_{\mathrm{s}}}}$$

which for a single-phase oil reservoir type ($S_{\mathrm{o}} = 100\%$) will simplify to $FVF_{\mathrm{tot}} = B_{\mathrm{o}}$ and for a single-phase gas reservoir type ($S_{\mathrm{g}} = 100\%$) will simplify to $FVF_{\mathrm{tot}} = \frac{B_{\mathrm{gd}}}{r_{\mathrm{s}}}$. For a two-phase saturated case, the total FVF will represent a saturation weighted oil FVF.

Source: https://manual.whitson.com/modules/bot/

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Total Gas-Oil Ratio (GOR_{tot})

$$GOR_{\mathrm{tot}} = \frac{\frac{S_g}{B_{gd}} + R_s \frac{S_o}{B_o}}{r_s \frac{S_g}{B_{gd}} + \frac{S_o}{B_o}}$$

which for a single-phase oil reservoir type ($S_\mathrm{o} = 100\%$) will simplify to $GOR_\mathrm{tot} = R_\mathrm{s}$ and for a single-phase gas reservoir type ($S_\mathrm{g} = 100\%$) will simplify to $GOR_\mathrm{tot} = \frac{1}{r_\mathrm{s}}$. For a two-phase saturated case, the total GOR will represent a saturation weighted GOR.

Source: https://manual.whitson.com/modules/bot/

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Exercise: What is OGIP and OOIP?

HCPV = 5000 MRB

	Oil	Gas	Two-Phase
Total FVF	1.93 RB/STB	5.91 RB/STB	2.46 RB/STB
Total GOR	2000 scf/STB	10000 scf/STB	2000 scf/STB
OOIP			
OGIP			

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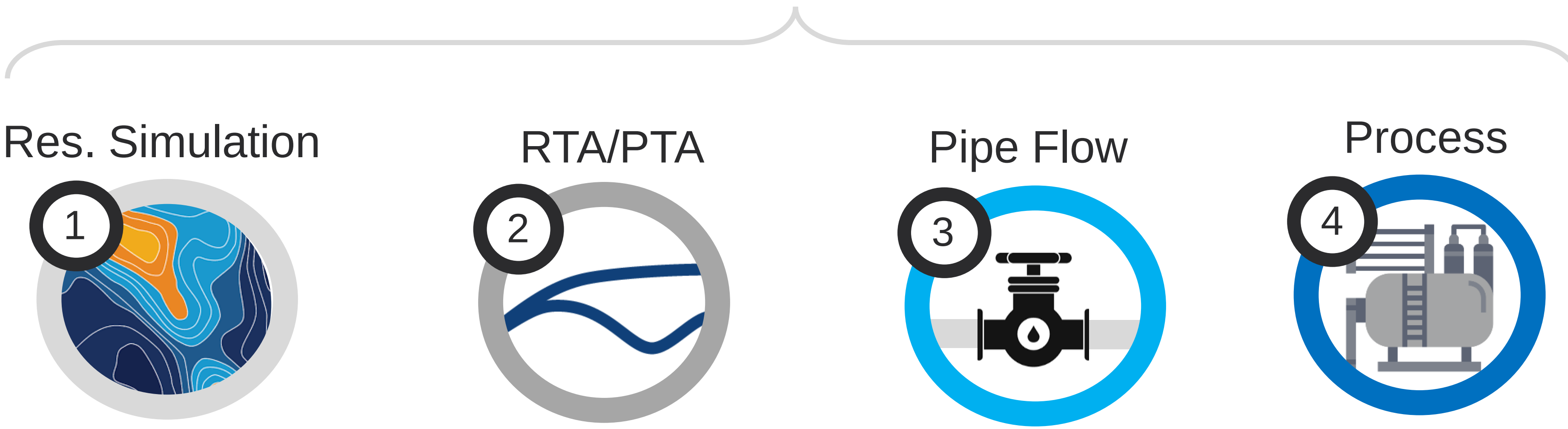
Advanced Topic

Black Oil Table Generation

Black Oil Table (BOT)

@ T = constant

Pressure	Oil			Gas		
p	R_s	B_o	μ_o	r_s	B_{gd}	μ_g
	…	…	…	…	…	…
	…	…	…	…	…	…
	…	…	…	…	…	…



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What is a BOT a function of?

Or what's required to create it?

… That's what we'll learn today!

EOS | Temperature | Composition | Surface Process

Black Oil PVT - Recap

- Two component PVT model: Oil and Gas
- Three properties are defined for each component:
  - Composition (R_s | r_s)
  - Formation volume factor (B_o | B_{gd})
  - Viscosity (μ_o | μ_g)
- Surface oil and gas densities are assumed constant:
  - $\gamma_{\bar{o}o} = \gamma_{\bar{o}g} \neq f(R_s, r_s)$
  - $\overline{\gamma_{\bar{g}o}} = \overline{\gamma_{\bar{g}g}} \neq f(R_s, r_s)$
- PVT properties are process dependent (assumed constant)
- Reservoir temperature is assumed constant

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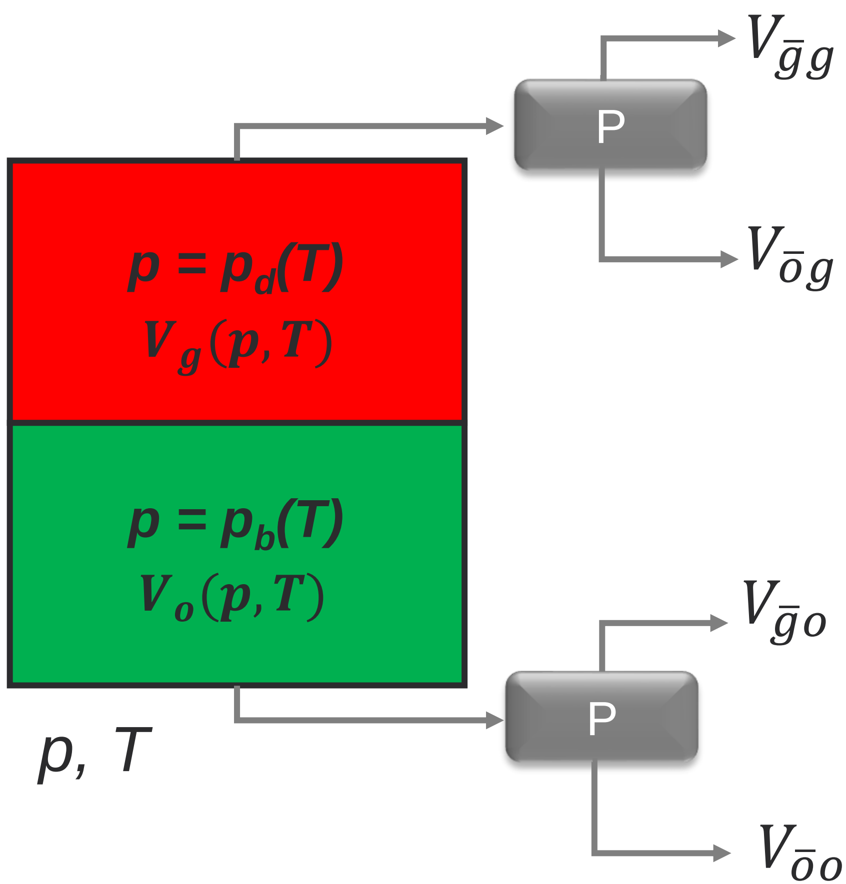
Black Oil PVT - Recap



Process Dependent	*Process Independent*
$B_{gd} = \dfrac{V_g}{V_{\bar{g}g}}$	
$r_s = \dfrac{V_{\bar{o}g}}{V_{\bar{g}g}}$	μ_g
$B_o = \dfrac{V_o}{V_{\bar{o}o}}$	
$R_s = \dfrac{V_{\bar{g}o}}{V_{\bar{o}o}}$	μ_o

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Repeat: Course Summary

1 m^3 is not always 1 m^3

Repeat

Black Oil PVT Properties are a Function of Surface Process

… Not viscosity!

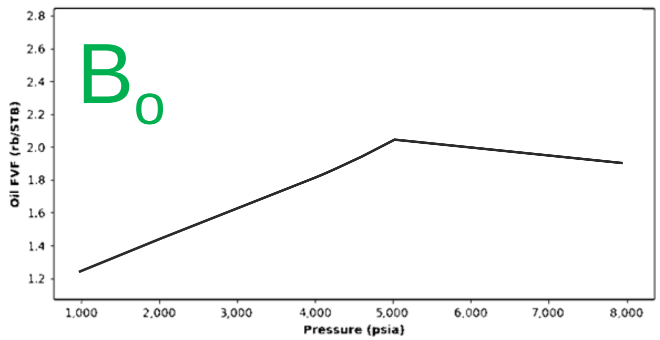
BOT from EOS – Requirements

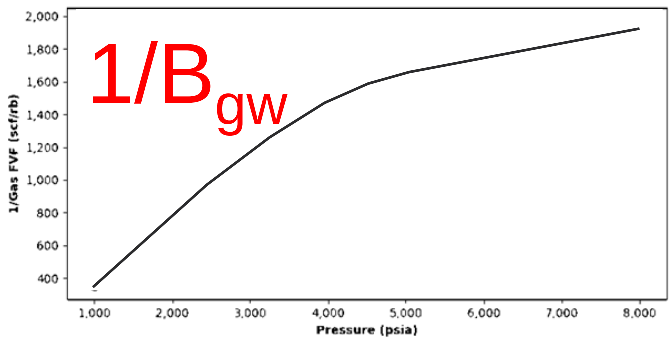
1. ***Equation of State (EOS) Model***
2. ***Temperature***
3. ***Composition (z_{BOi})***
4. ***Surface process***

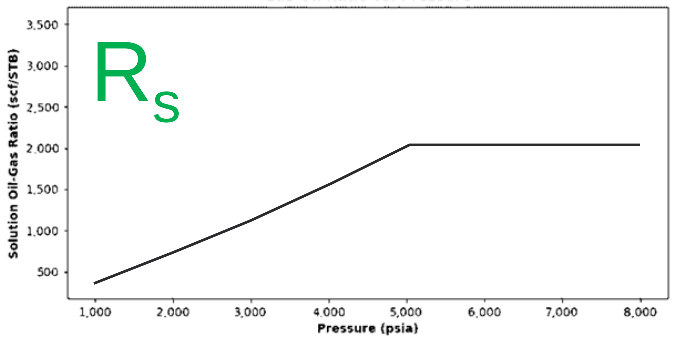
   e.g. Multi-stage separator (p_{sp1}, T_{sp1}, …, p_{sc}, T_{sc}

5. ***Reservoir depletion process***
   - **CCE** | CVD | DLE

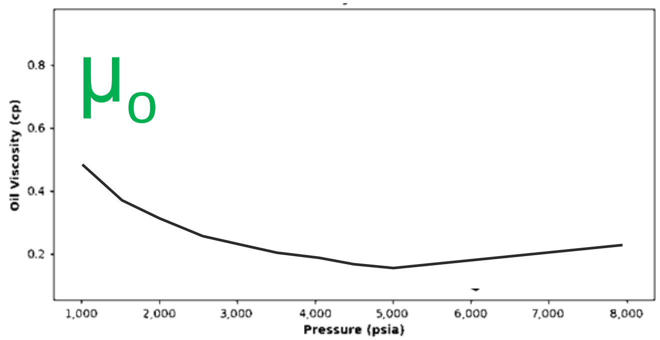
Traditional Black Oil Tables (<1980)

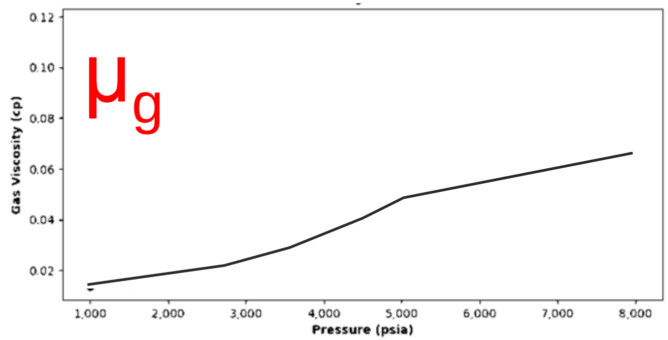






Don’t use!





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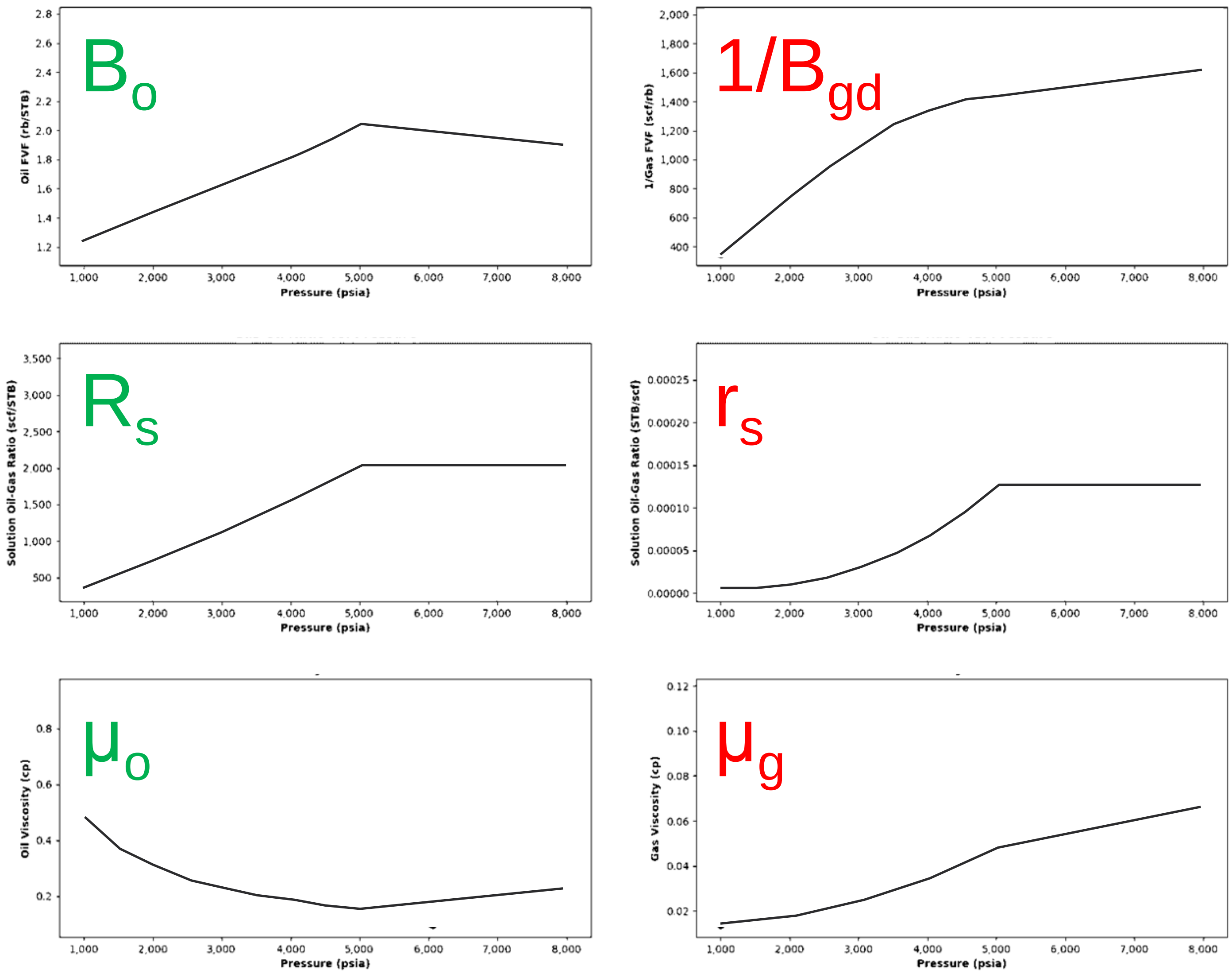
Modified Black Oil Tables (~1980)



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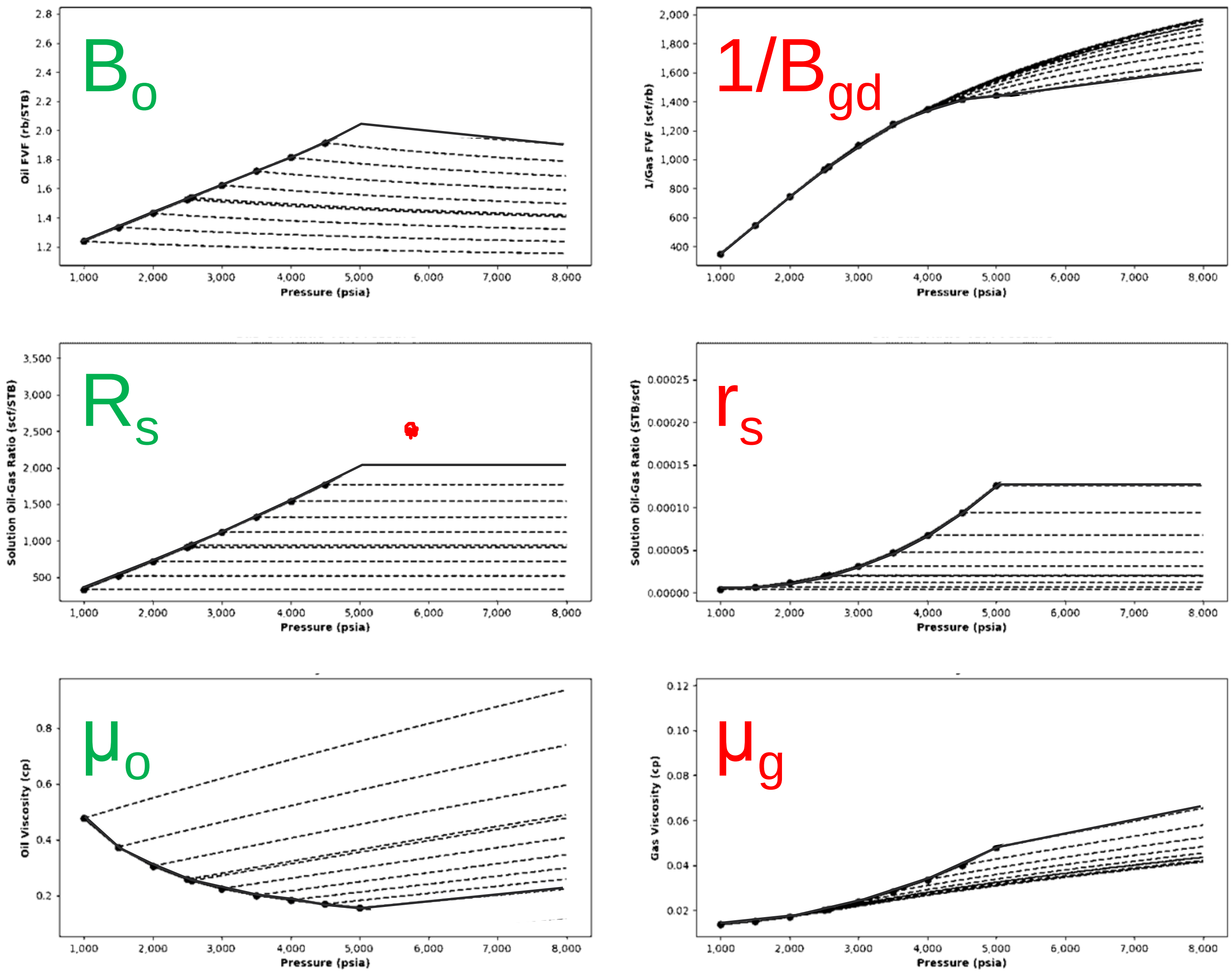
Modified Black Oil Tables (~1980)



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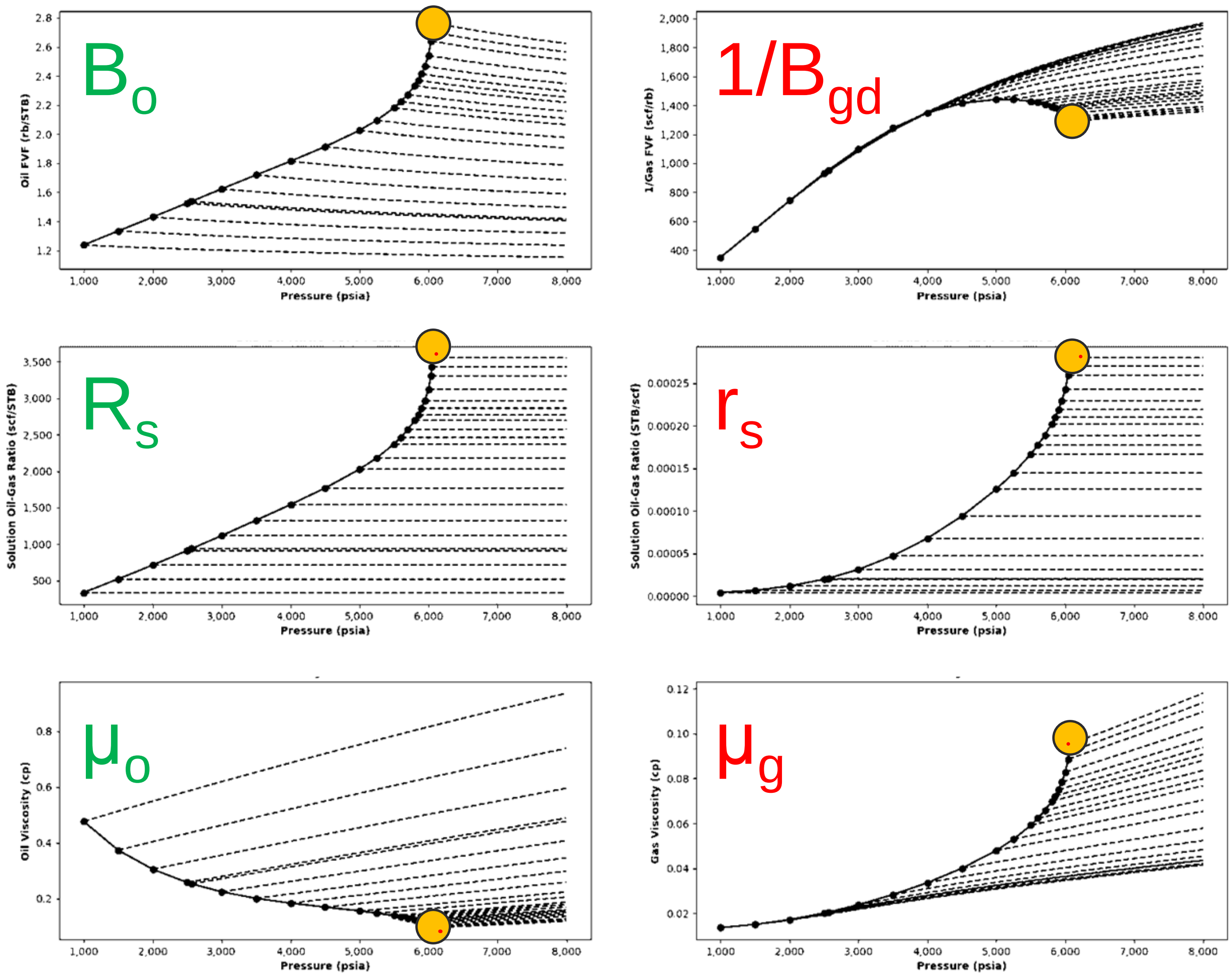
Extrapolated Black Oil Table (~2000)

Critical Point



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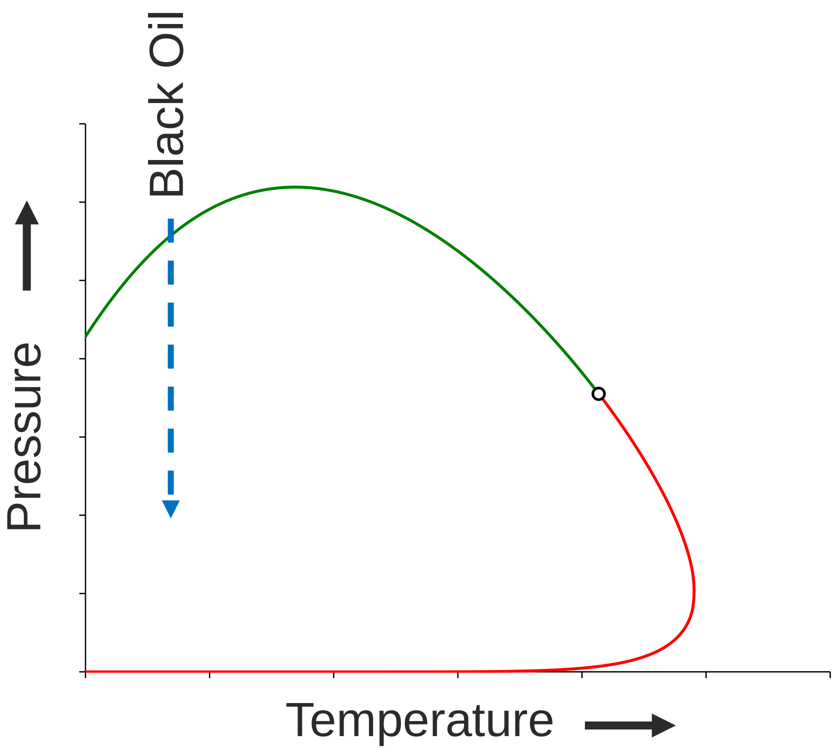
Reservoir Fluid Classification



Fluid type	B_o | B_{gd}/R_v	R_s | $1/R_v$
Unit	(RB/STB)	(scf/STB)
Black Oil	<1.5	<1,000

** These numbers are rules of thumb and should not be interpreted at absolutes.*

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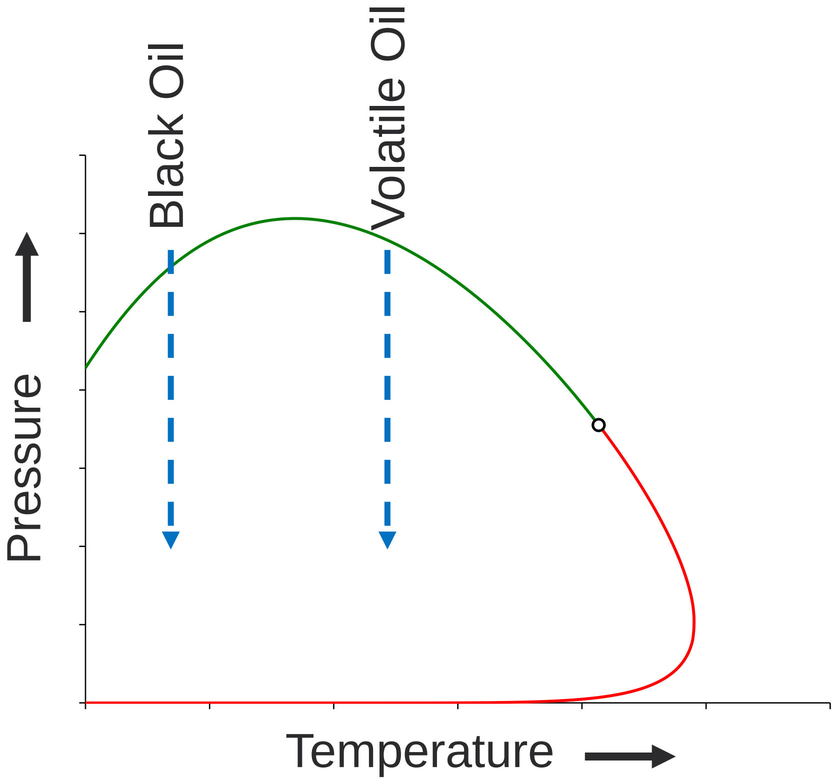
Reservoir Fluid Classification



Fluid type	B_o | B_{gd}/R_v	R_s | $1/R_v$
Unit	(RB/STB)	(scf/STB)
Black Oil	<1.5	<1,000
Volatile Oil	1.5-2.5	1,000-3,000

** These numbers are rules of thumb and should not be interpreted at absolutes.*

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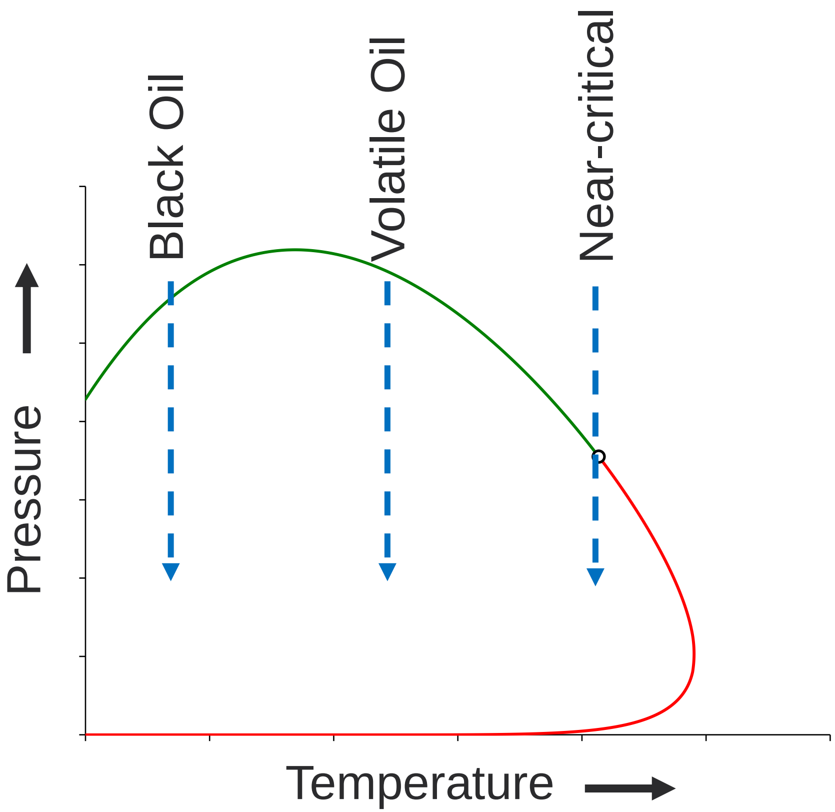
Reservoir Fluid Classification



Fluid type	B_o | B_{gd}/R_v	R_s | $1/R_v$
Unit	(RB/STB)	(scf/STB)
Black Oil	<1.5	<1,000
Volatile Oil	1.5-2.5	1,000-3,000
Near-critical	2.5-4	3,000-4,000

** These numbers are rules of thumb and should not be interpreted at absolutes.*

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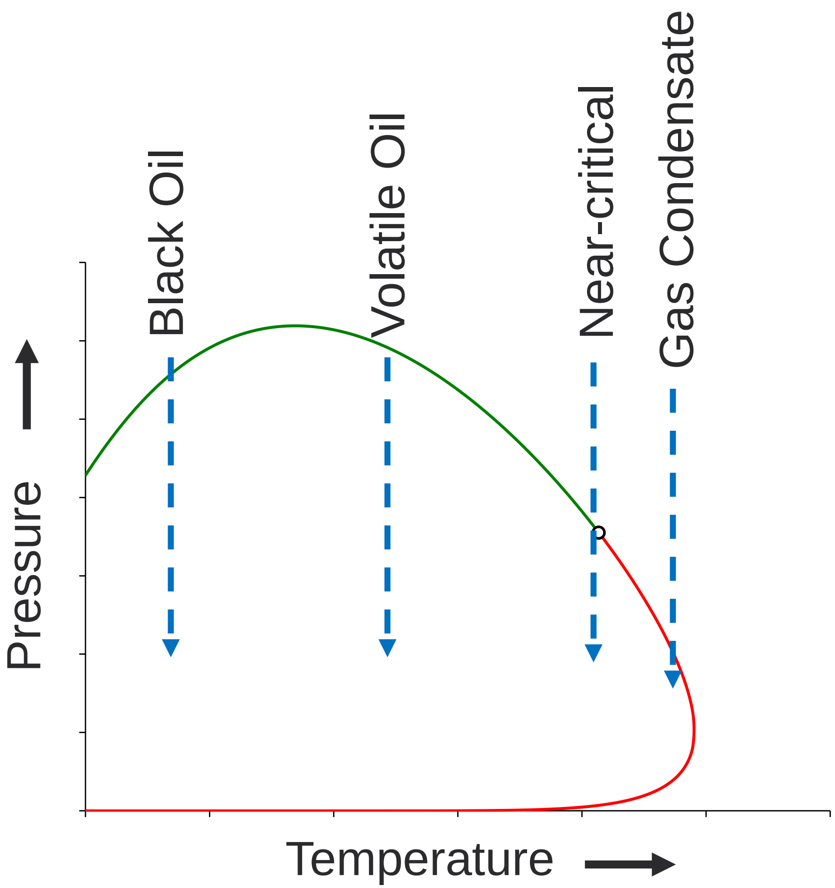
Reservoir Fluid Classification



Fluid type	B_o | B_{gd}/R_v	R_s | $1/R_v$
Unit	(RB/STB)	(scf/STB)
Black Oil	<1.5	<1,000
Volatile Oil	1.5-2.5	1,000-3,000
Near-critical	2.5-4	3,000-4,000
Gas Condensate	4-50	4,000-100,000

** These numbers are rules of thumb and should not be interpreted at absolutes.*

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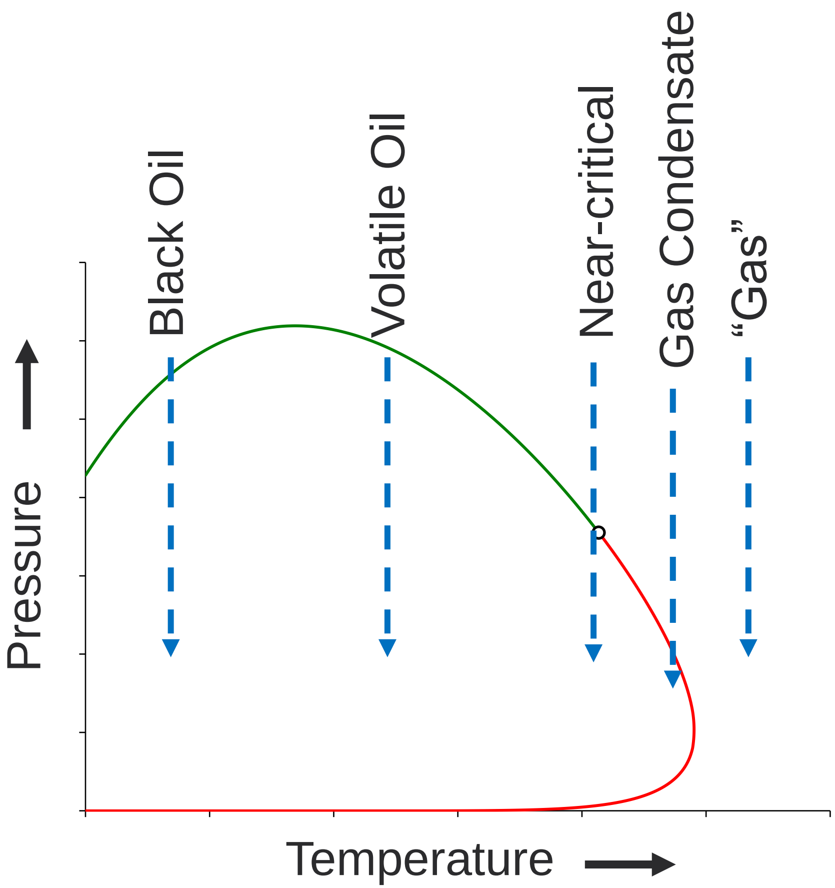
Reservoir Fluid Classification



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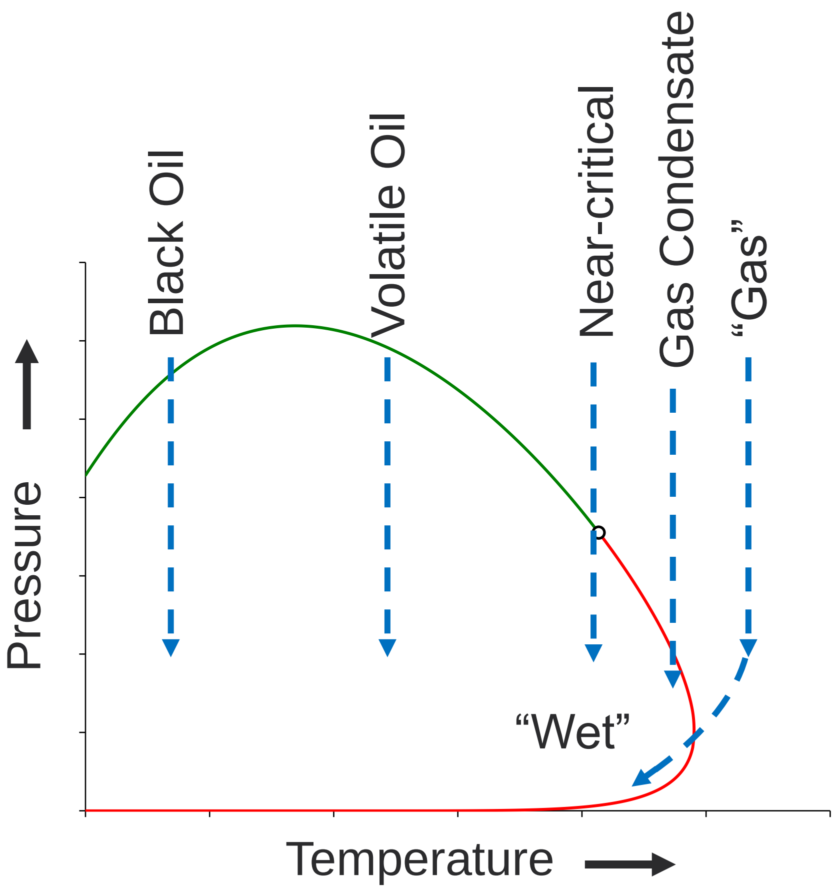
Reservoir Fluid Classification



Fluid type	B_o | B_{gd}/R_v	R_s | $1/R_v$
Unit	(RB/STB)	(scf/STB)
Black Oil	<1.5	<1,000
Volatile Oil	1.5-2.5	1,000-3,000
Near-critical	2.5-4	3,000-4,000
Gas Condensate	4-50	4,000-100,000
«Wet» Gas	>50	>100,000

** These numbers are rules of thumb and should not be interpreted at absolutes.*

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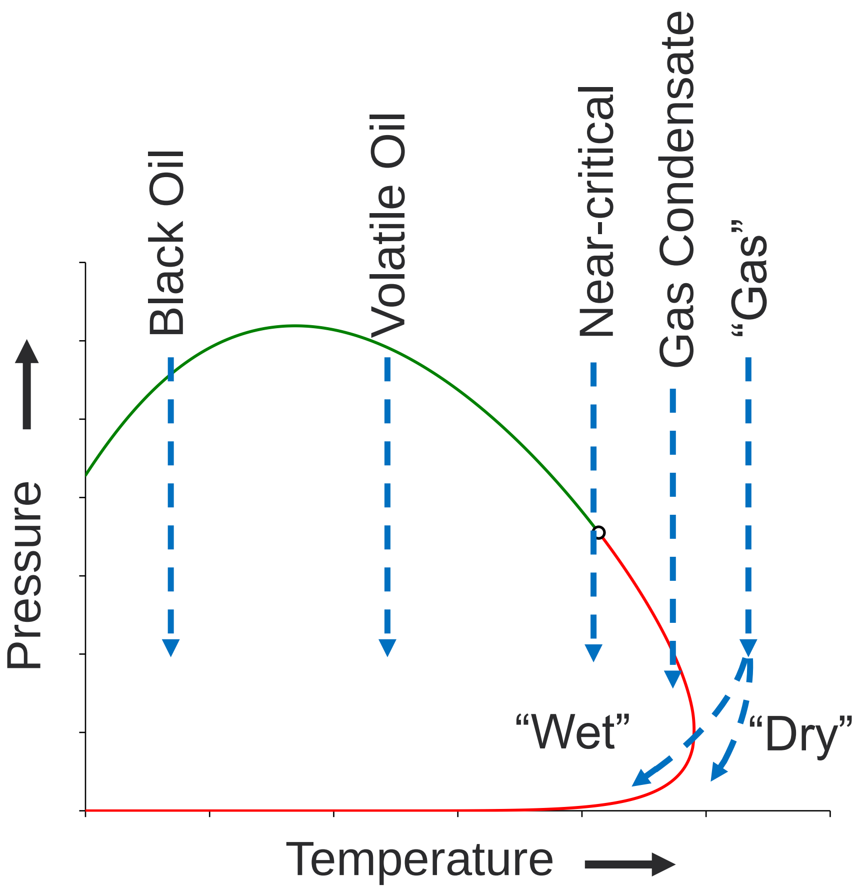
Reservoir Fluid Classification



Fluid type	B_o | B_{gd}/R_v	R_s | $1/R_v$
Unit	(RB/STB)	(scf/STB)
Black Oil	<1.5	<1,000
Volatile Oil	1.5-2.5	1,000-3,000
Near-critical	2.5-4	3,000-4,000
Gas Condensate	4-50	4,000-100,000
«Wet» Gas	>50	>100,000
«Dry» Gas	0	∞

** These numbers are rules of thumb and should not be interpreted at absolutes.*

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Repeat:

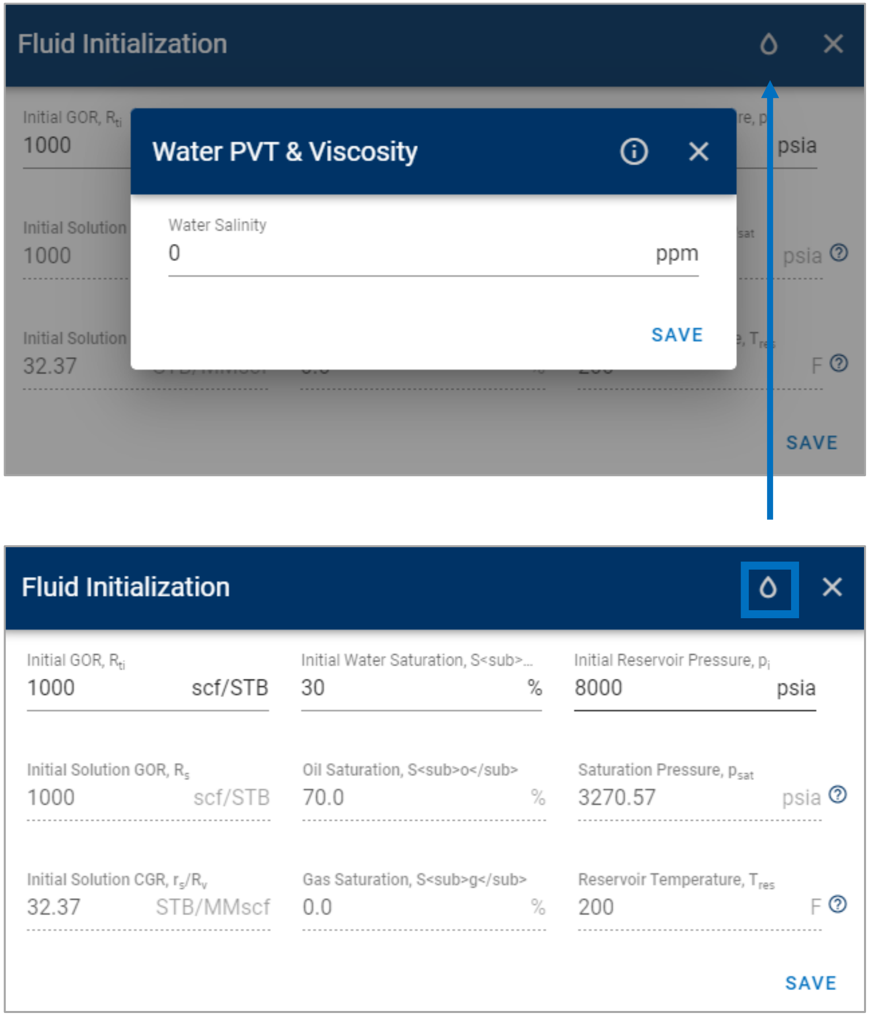
Black Oil Tables

can be used for ALL Reservoir Fluid Systems

… and NOT only for black oil systems !!!

Reservoir Water

Reservoir Water



- Water viscosity (μ_w) ranges 0.3 cp (>250 F) to about 1 cp at ambient temperatures.
- Water compressibility (c_w) ranges 2.5 to 5 x 10^{-6} 1/psi.
- Finally, reservoir brines exhibit only slight shrinkage (<5%) when produced to the surface.
- The brine that is sharing pore space with hydrocarbons always contains limited about of gas in solution (mainly methane), ranging 10-35 scf/STB.

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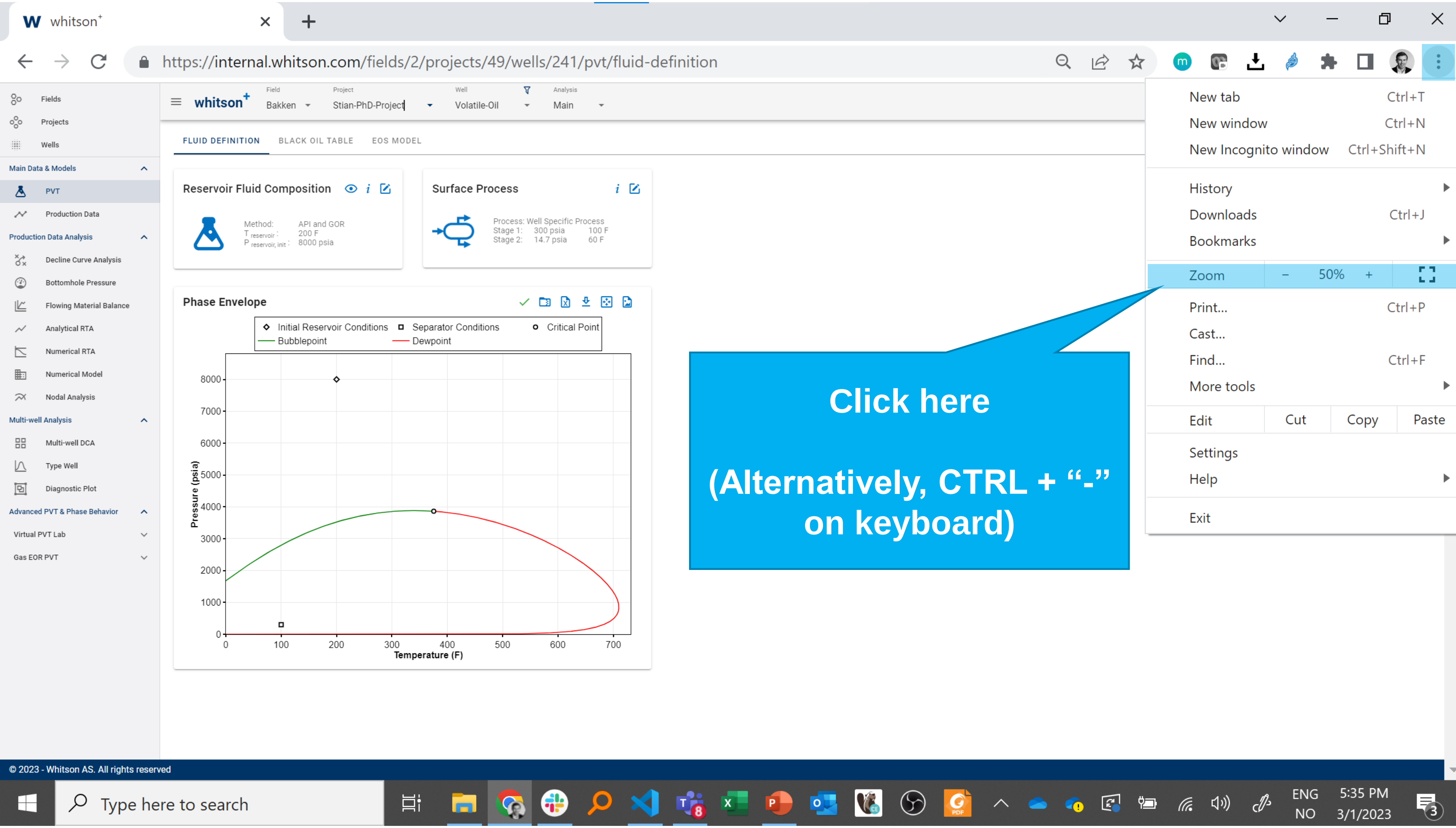
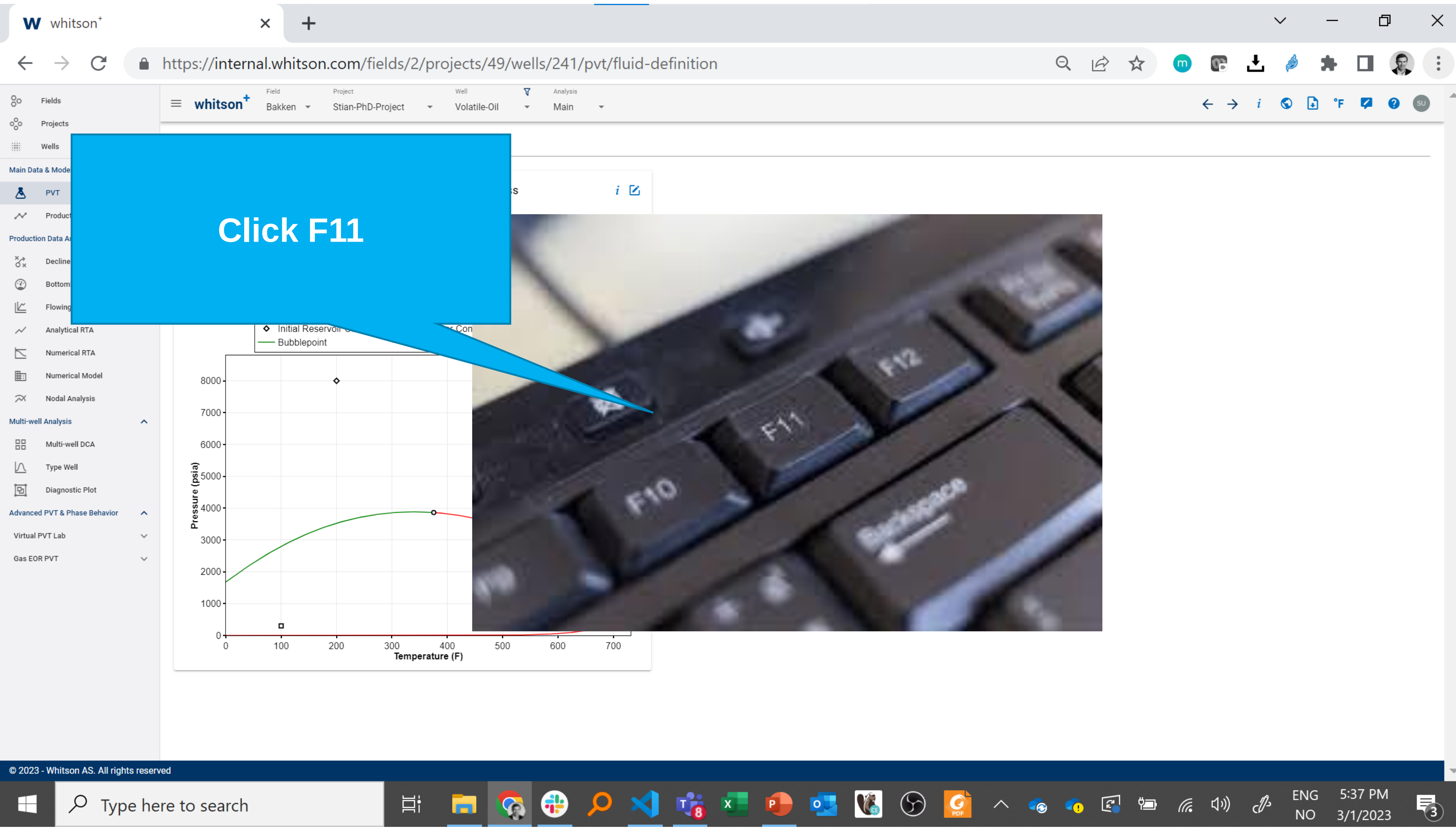
Software

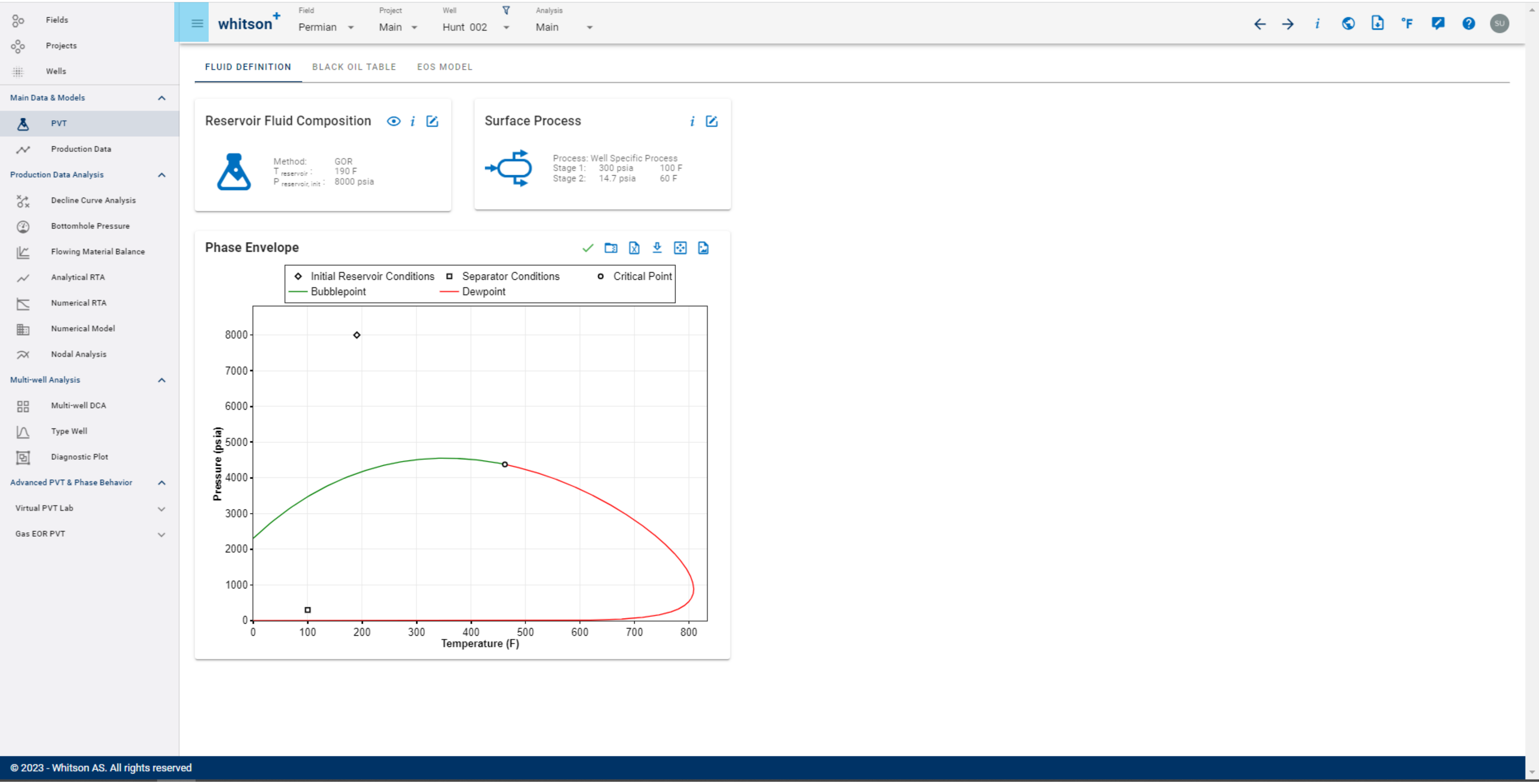
whitson⁺: Set Zoom to 70-80%



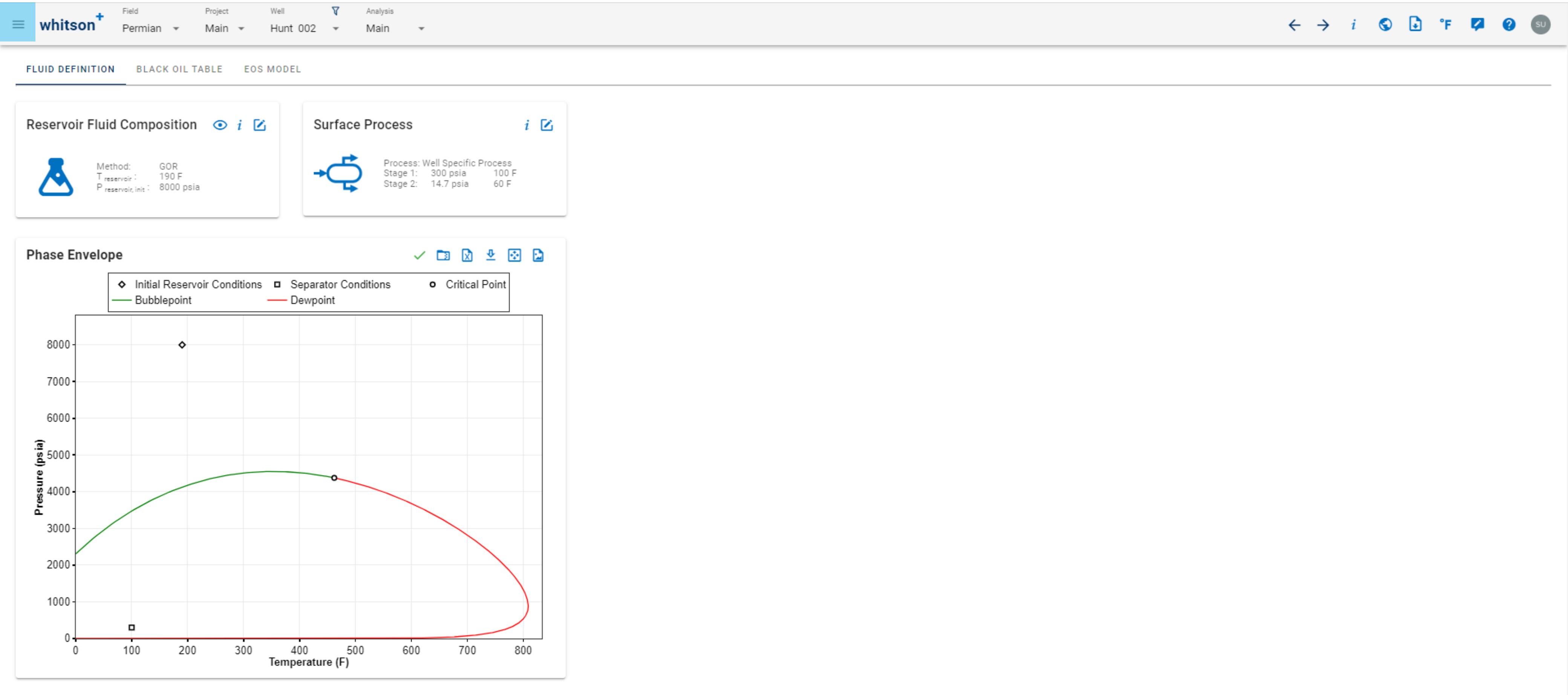
whitson+: Maximize Screen by “F11”



whitson+: More Screen Real Estate



whitson⁺: More Screen Real Estate



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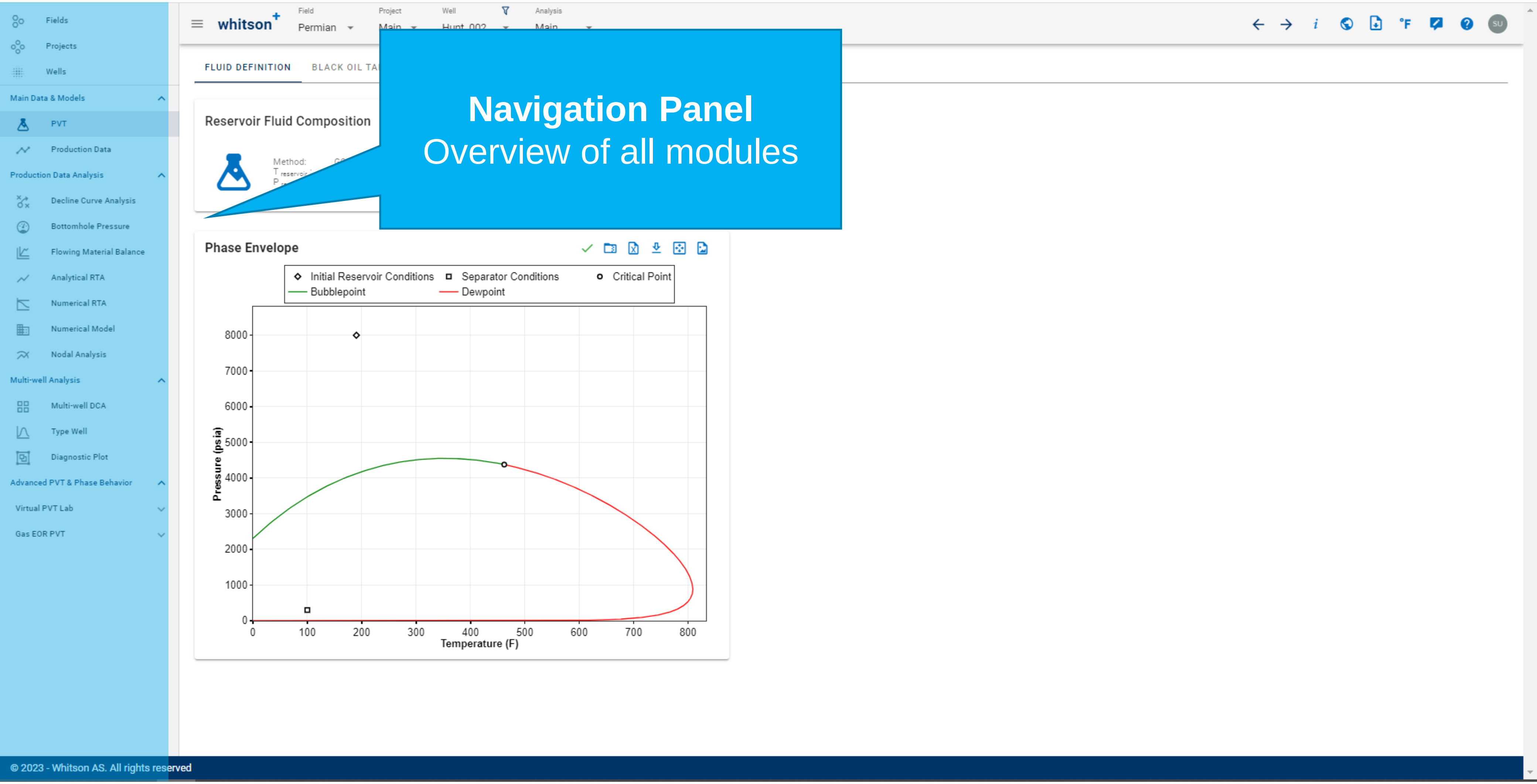
whitson⁺: Navigation Panel



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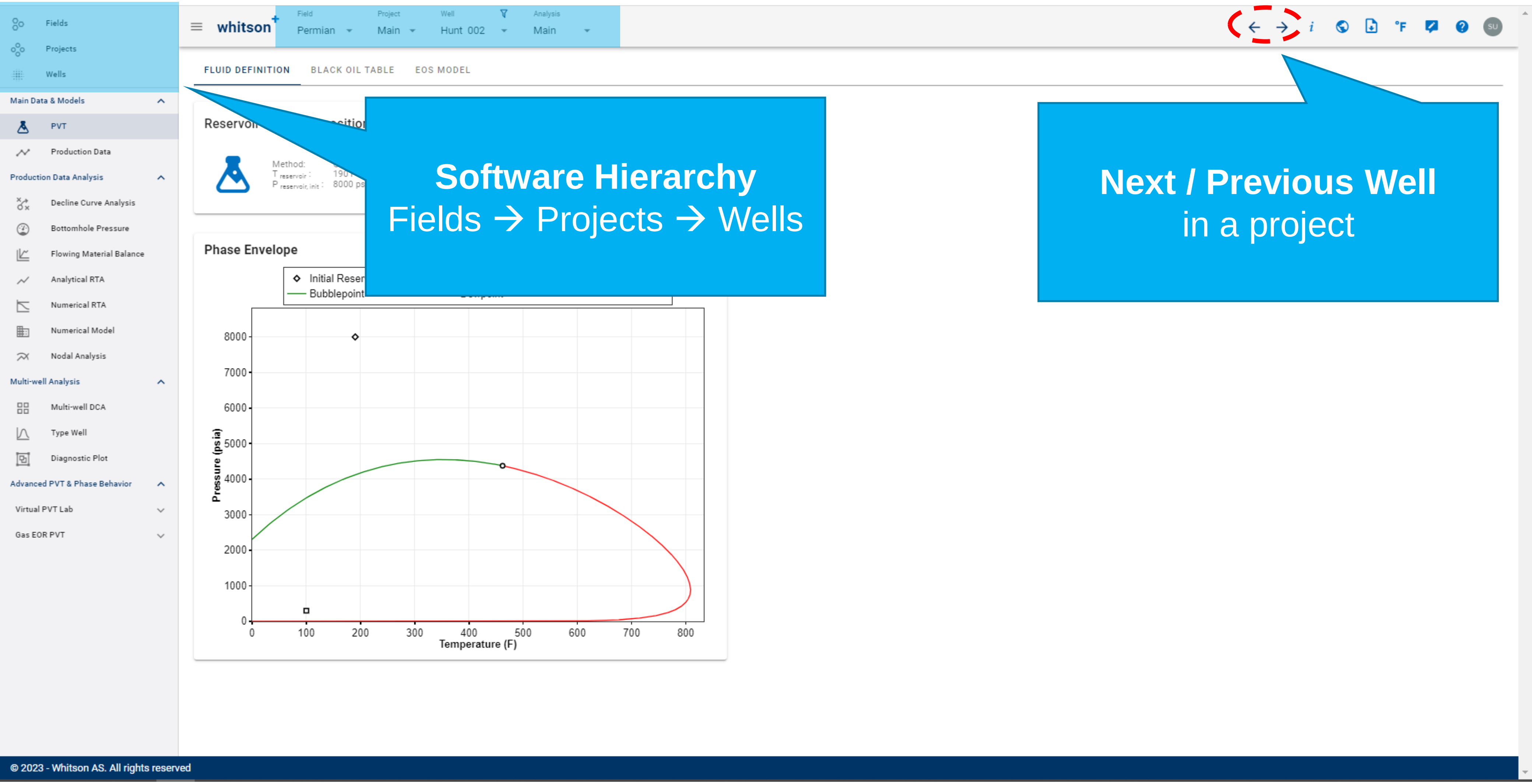
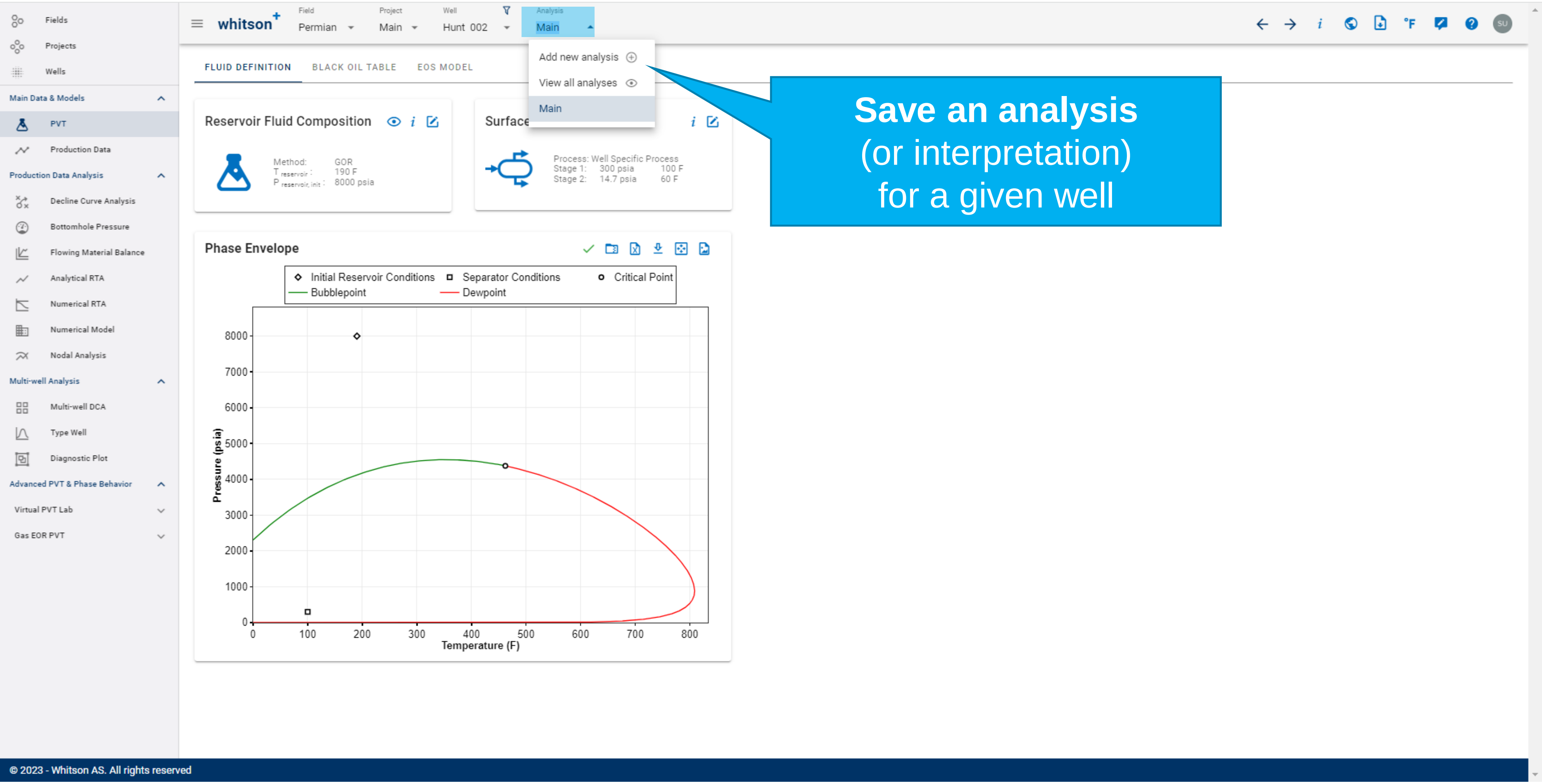
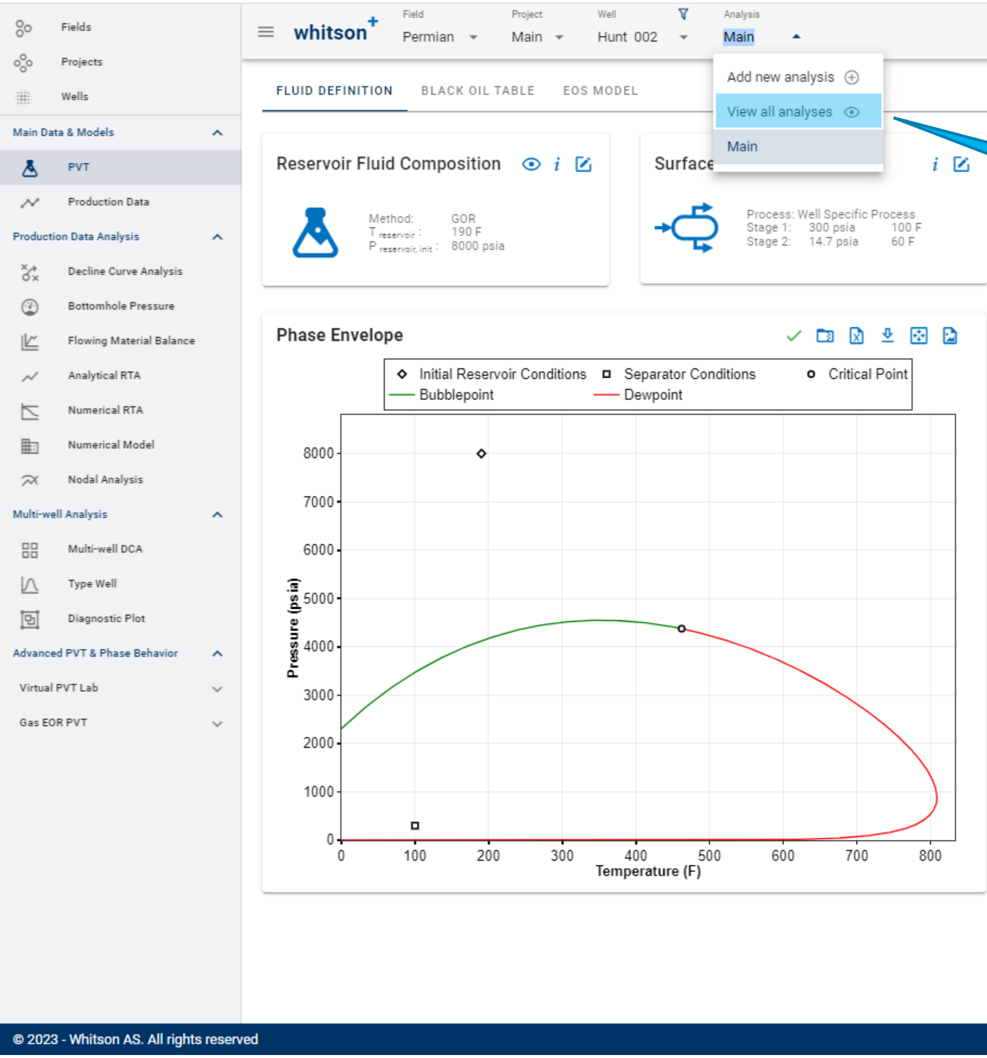
whitson+: Software Hierarchy



whitson⁺: Create Multiple Analyses for a Well

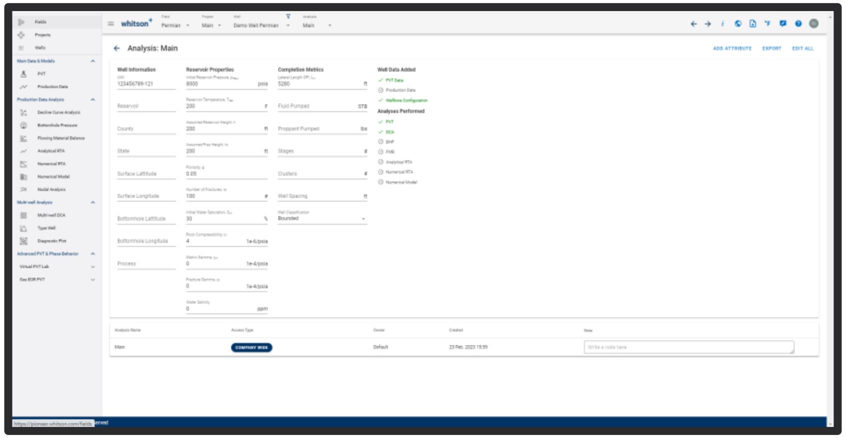


whitson⁺: Create Multiple Analyses for a Well

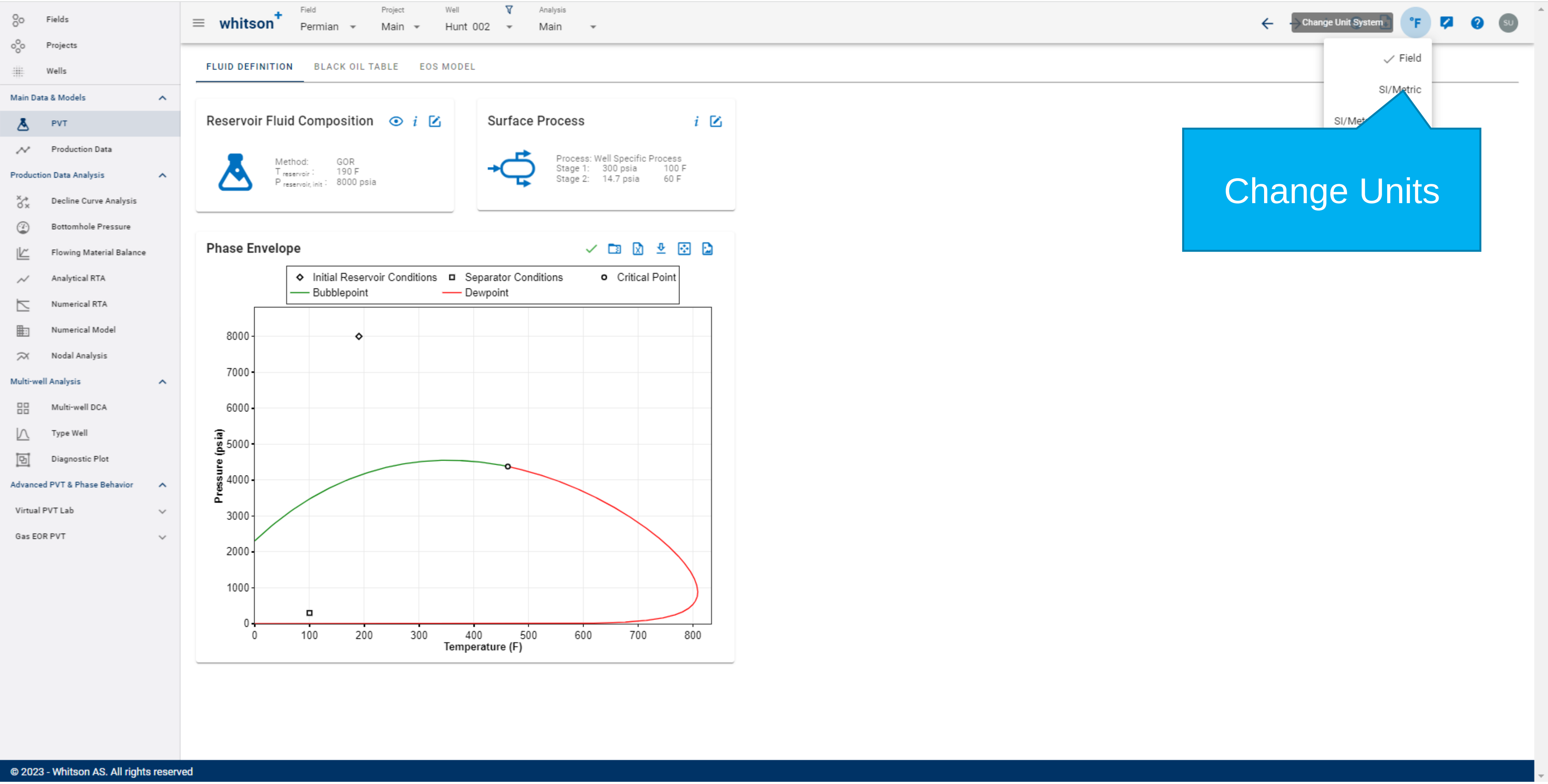


Click here and it will bring you to the well overview page

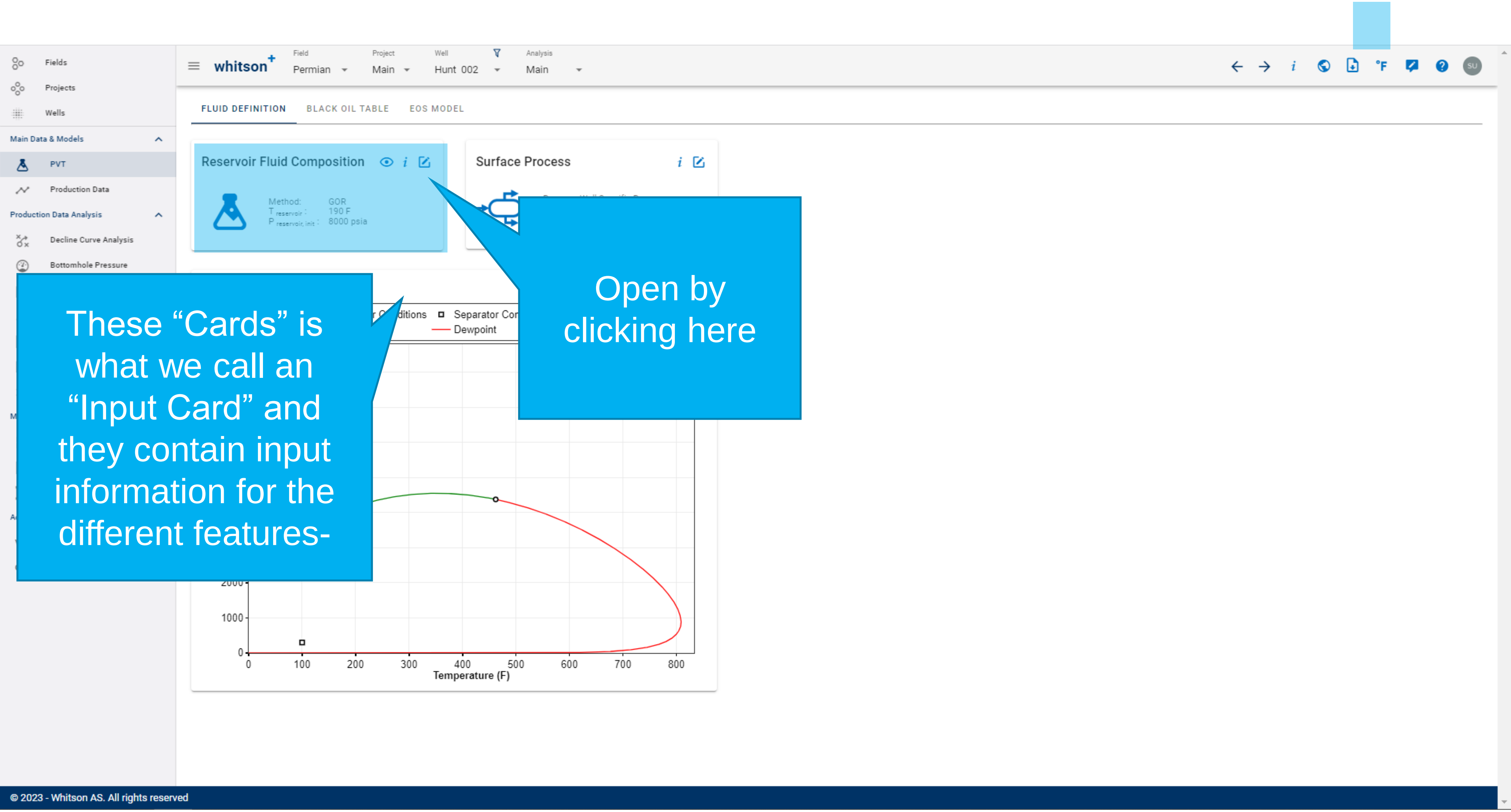
Well Overview page



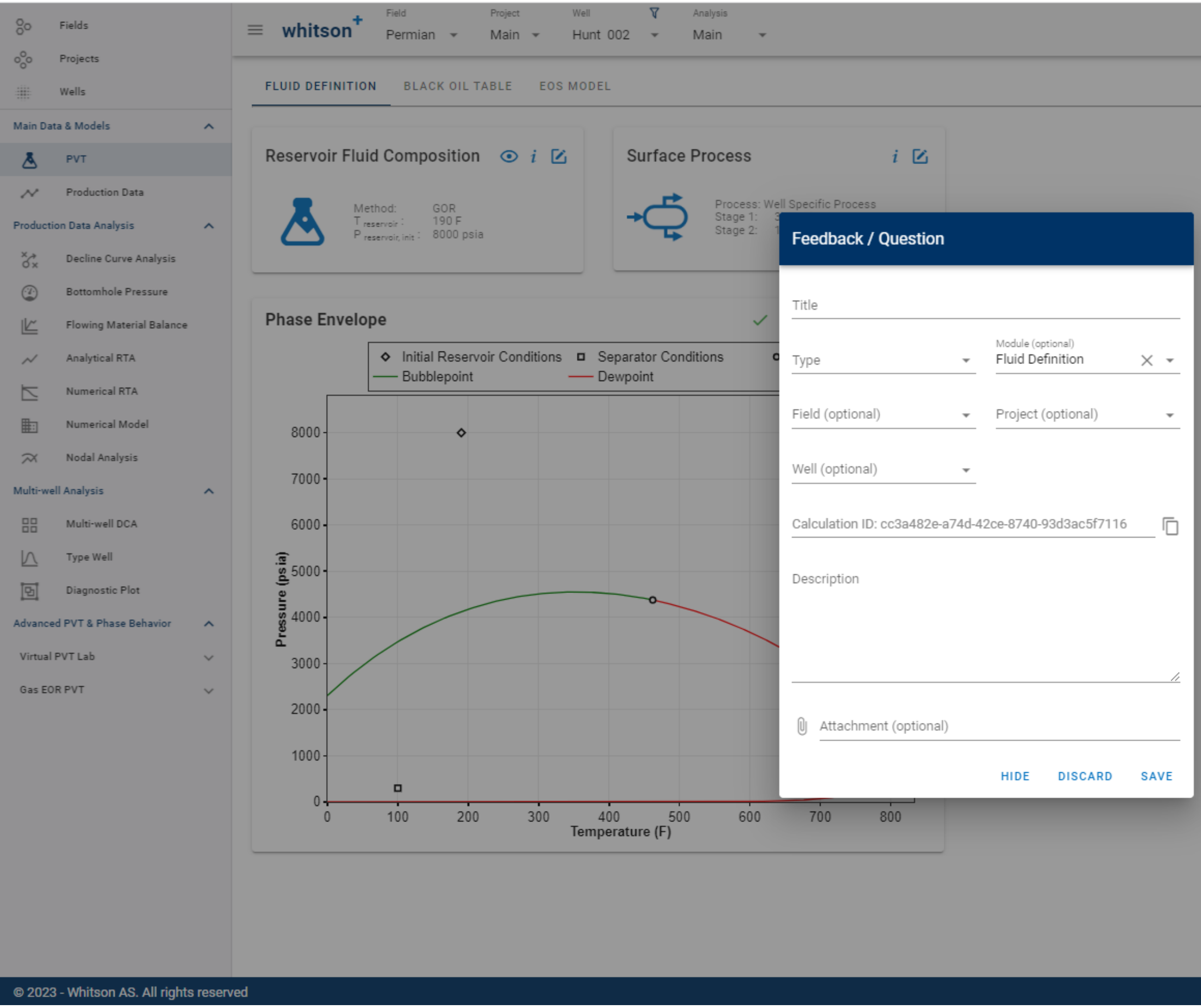
whitson+: Change Units



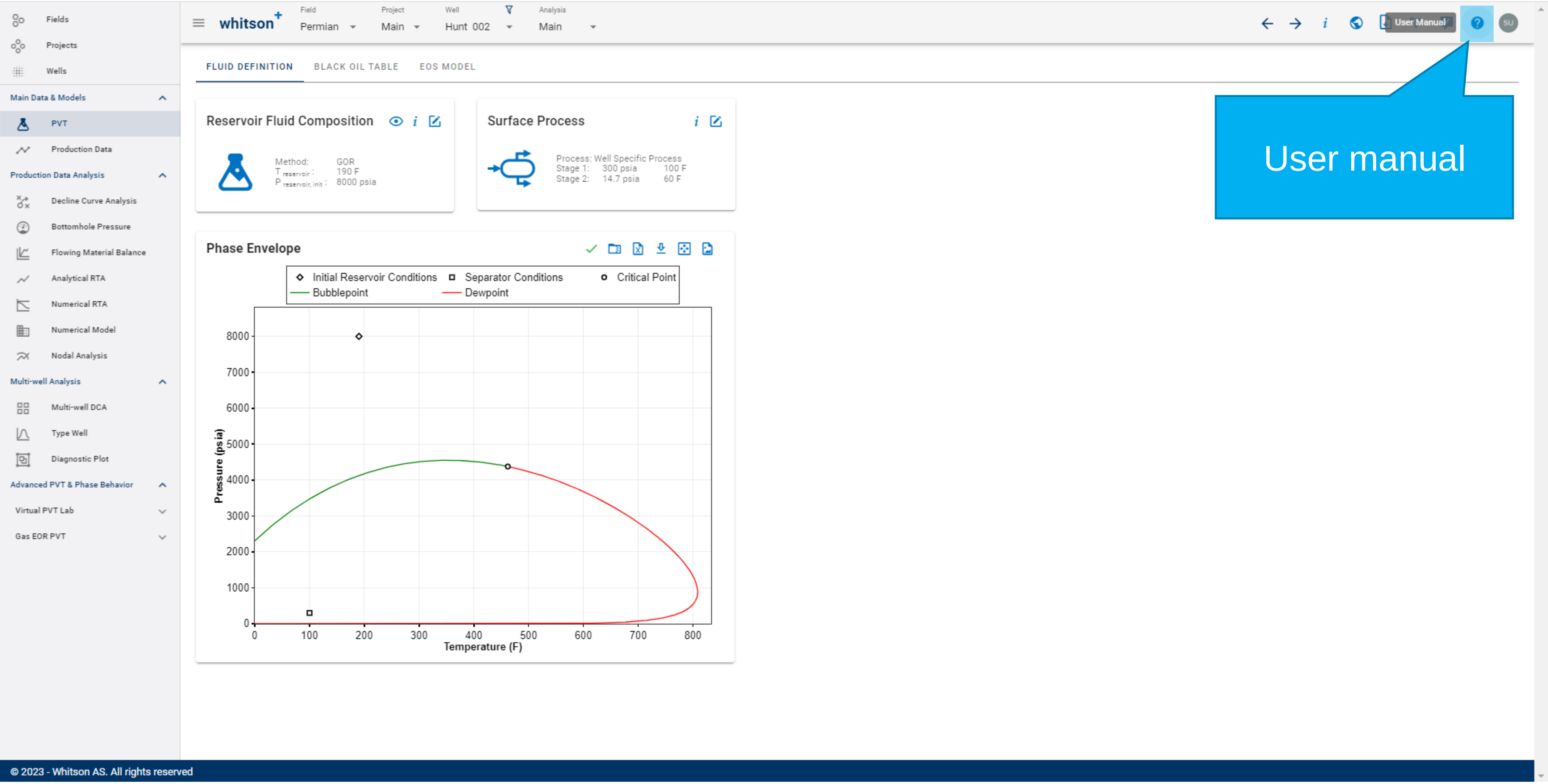
whitson⁺: Input Card



whitson⁺: Support Ticket



You can also e-mail support@whitson.com


Fields
Projects
Wells
Main Data & Models
PVT
Production Data
Production Data Analysis
Decline Curve Analysis
Bottomhole Pressure
Flowing Material Balance
Analytical RTA
Numerical RTA
Numerical Model
Nodal Analysis
Multi-well Analysis
Multi-well DCA
Type Well
Diagnostic Plot
Advanced PVT & Phase Behavior
Virtual PVT Lab
Gas EOR PVT
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Field Permian
Project Main
Well Hunt 002
Analysis Main
User Manual
FLUID DEFINITION
BLACK OIL TABLE
EOS MODEL
Reservoir Fluid Composition
Method: GOR
T reservoir : 190 F
P reservoir, init : 8000 psia
Surface Process
Process: Well Specific Process
Stage 1: 300 psia 100 F
Stage 2: 14.7 psia 60 F
Phase Envelope
Initial Reservoir Conditions
Separator Conditions
Critical Point
Bubblepoint
Dewpoint
Pressure (psia)
Temperature (F)
User manual
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Important Shortcut: Refresh

- Refresh shortcut: “CTRL + R”

- Use if you experience
  - Bad connection
  - The browser is “stuck”

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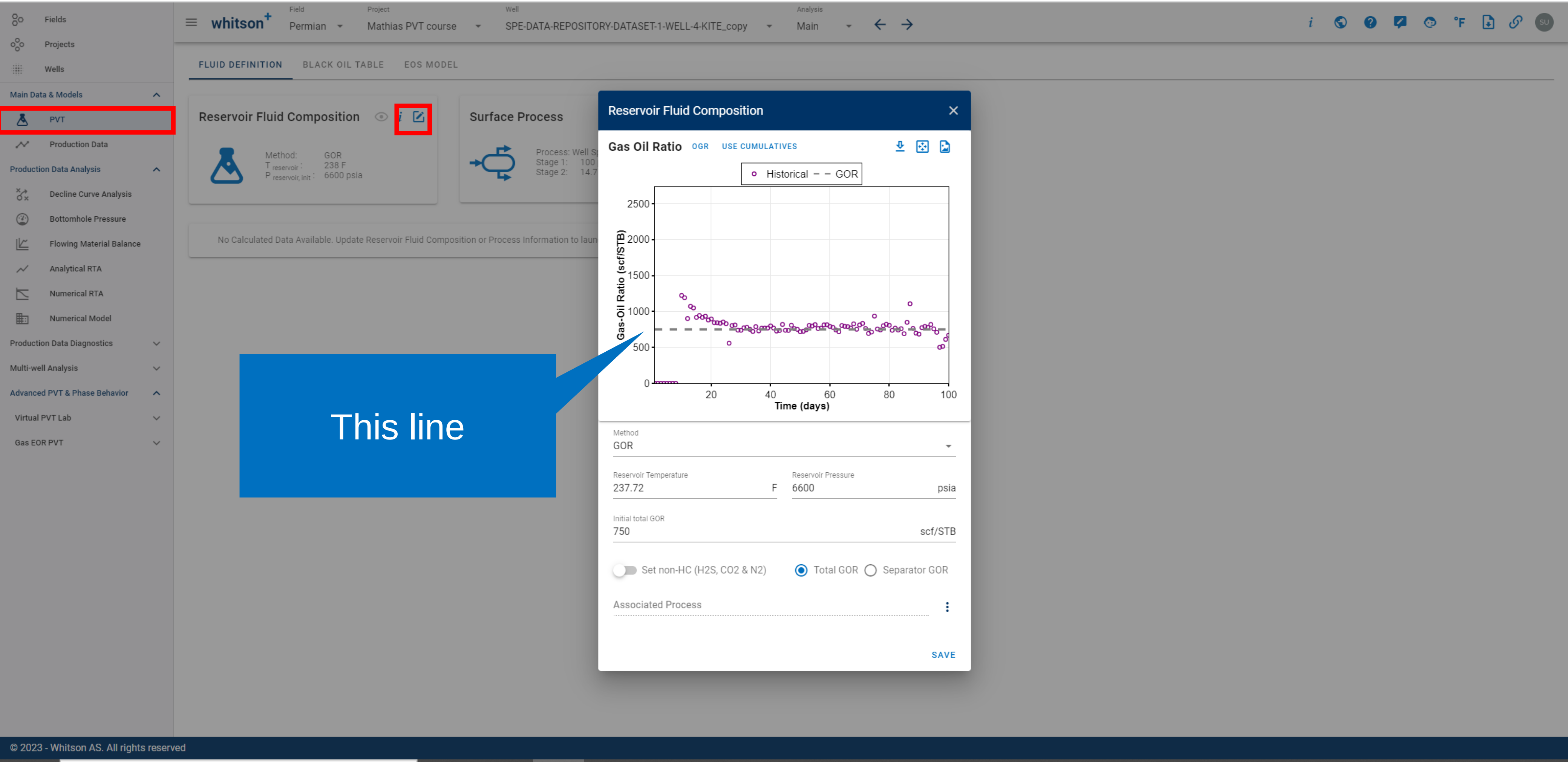
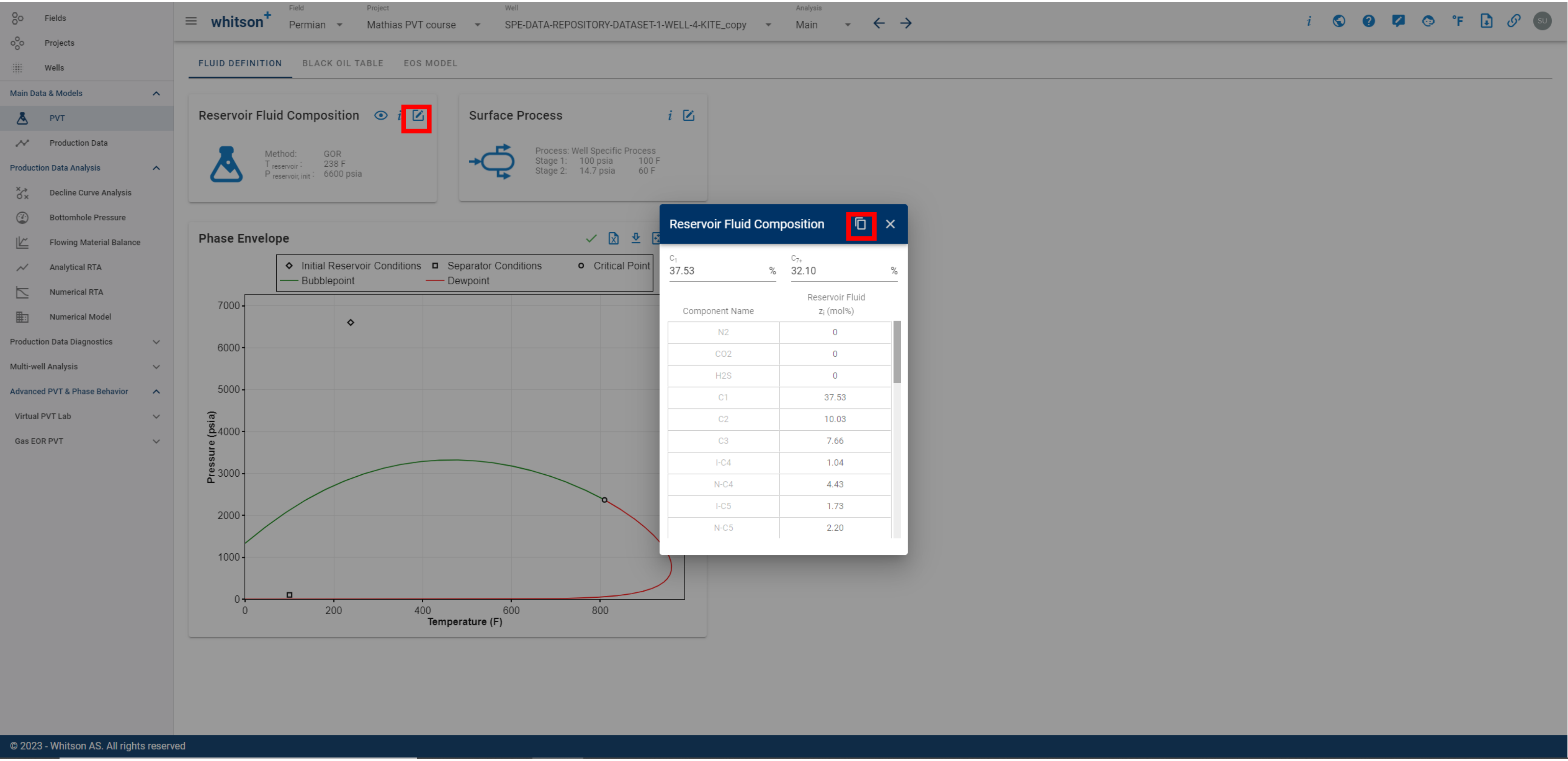
Exercise

1. Drag and drop GOR to match initial data

What is the insitu representative GOR?

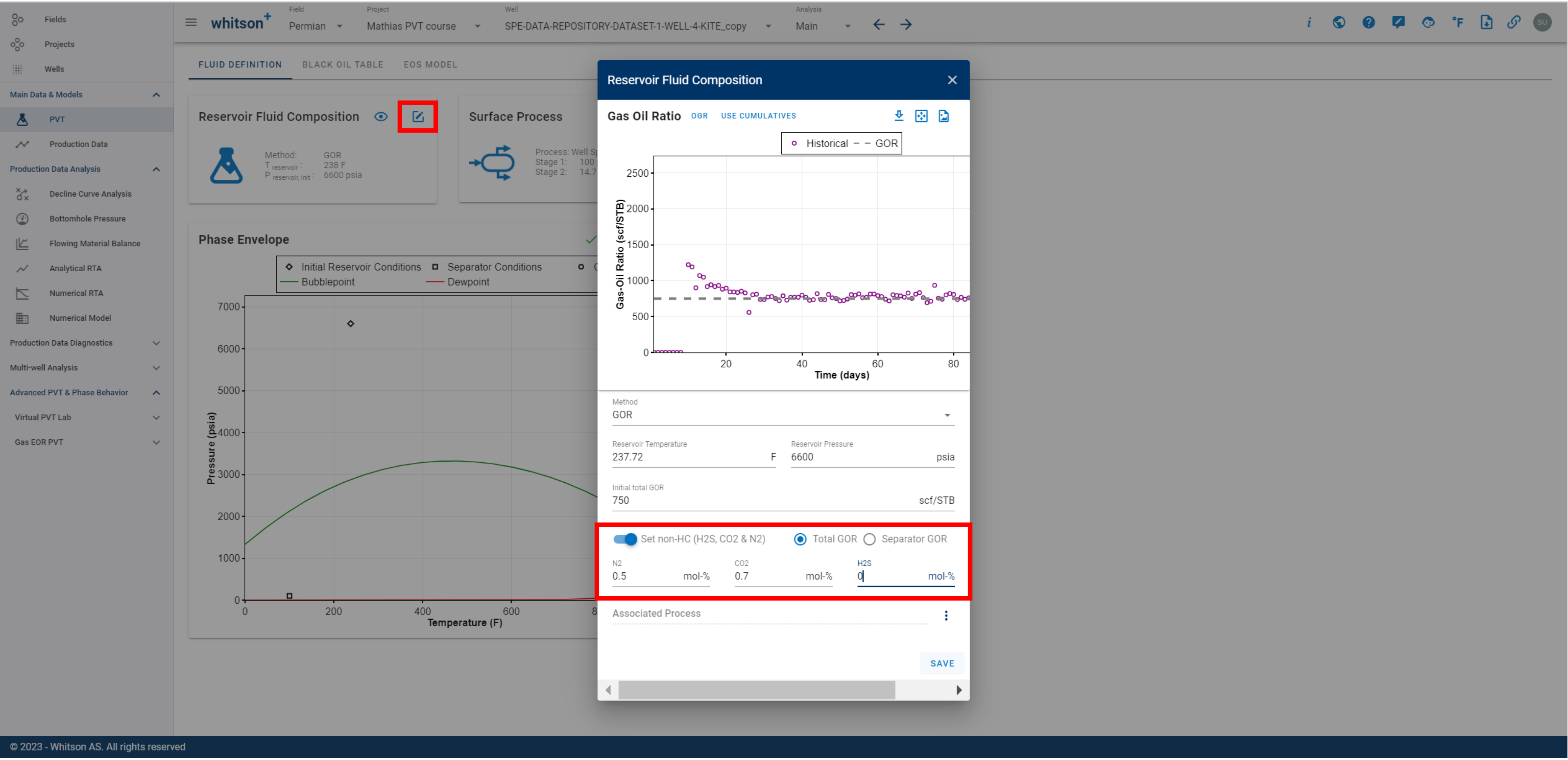


2. Copy your composition into excel

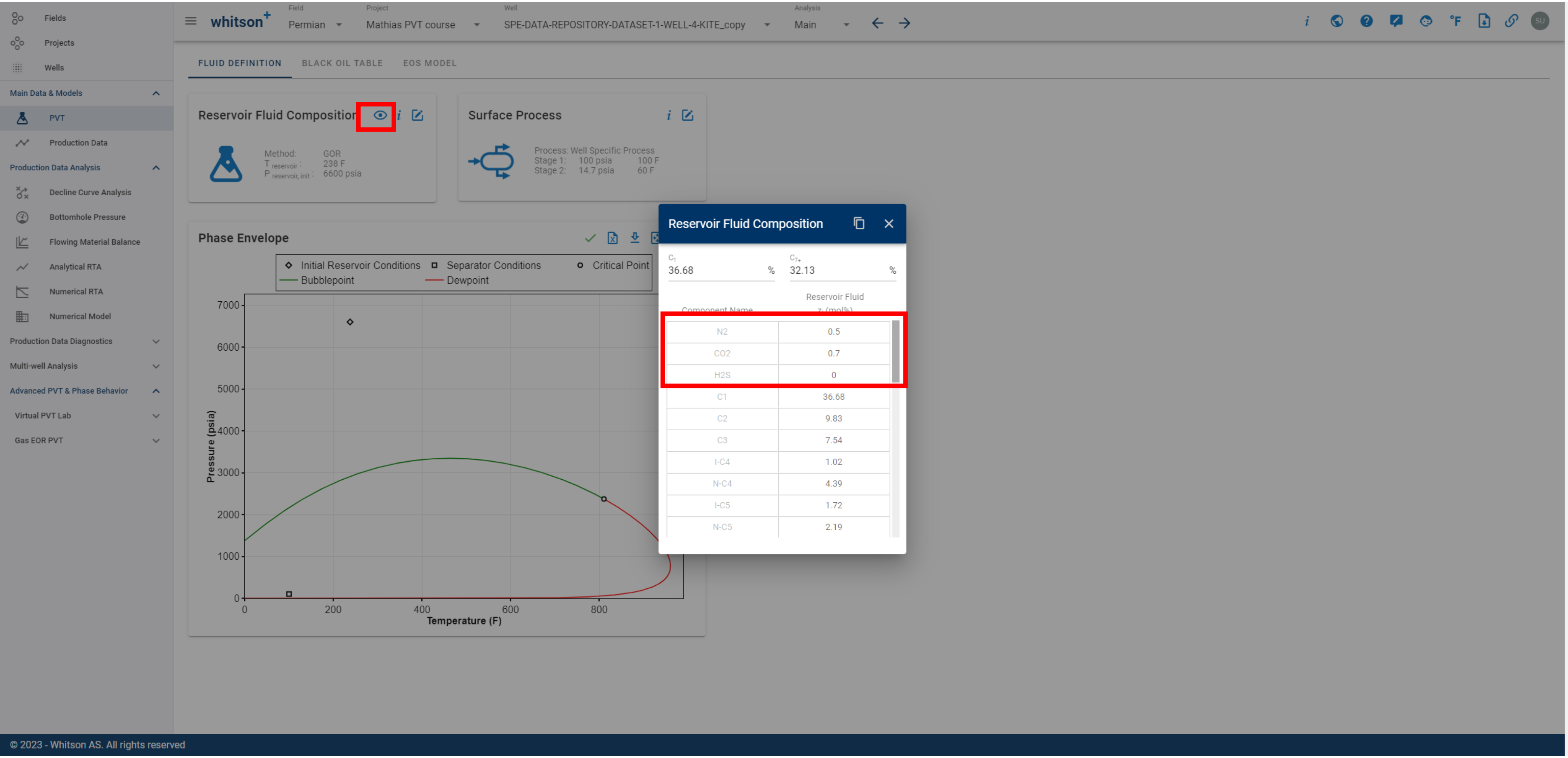


3. Specify the non-hydrocarbons

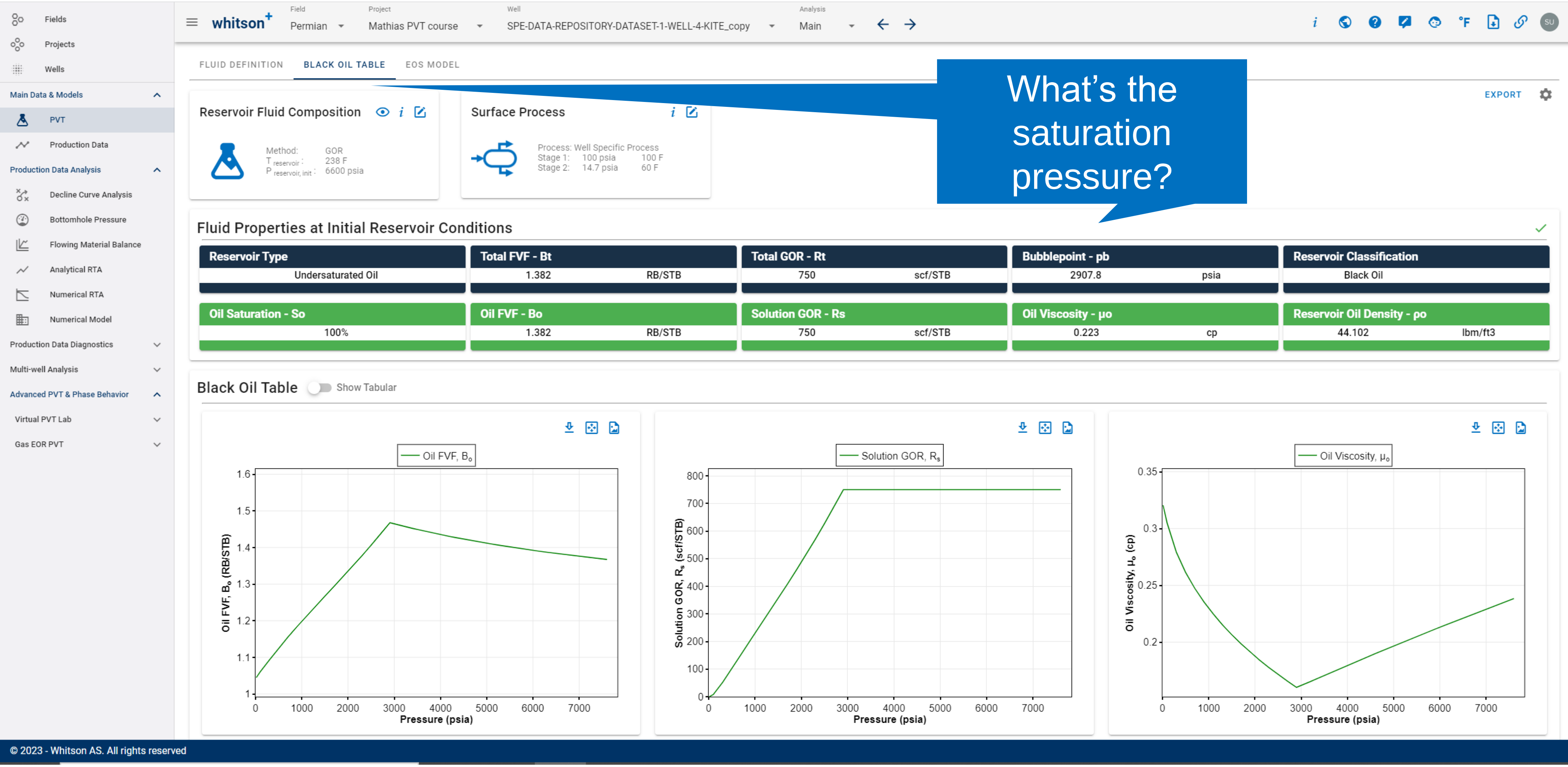
N_2 = 0.5%, CO_2 = 0.7%, H_2S = 0%



4. Check your compositions

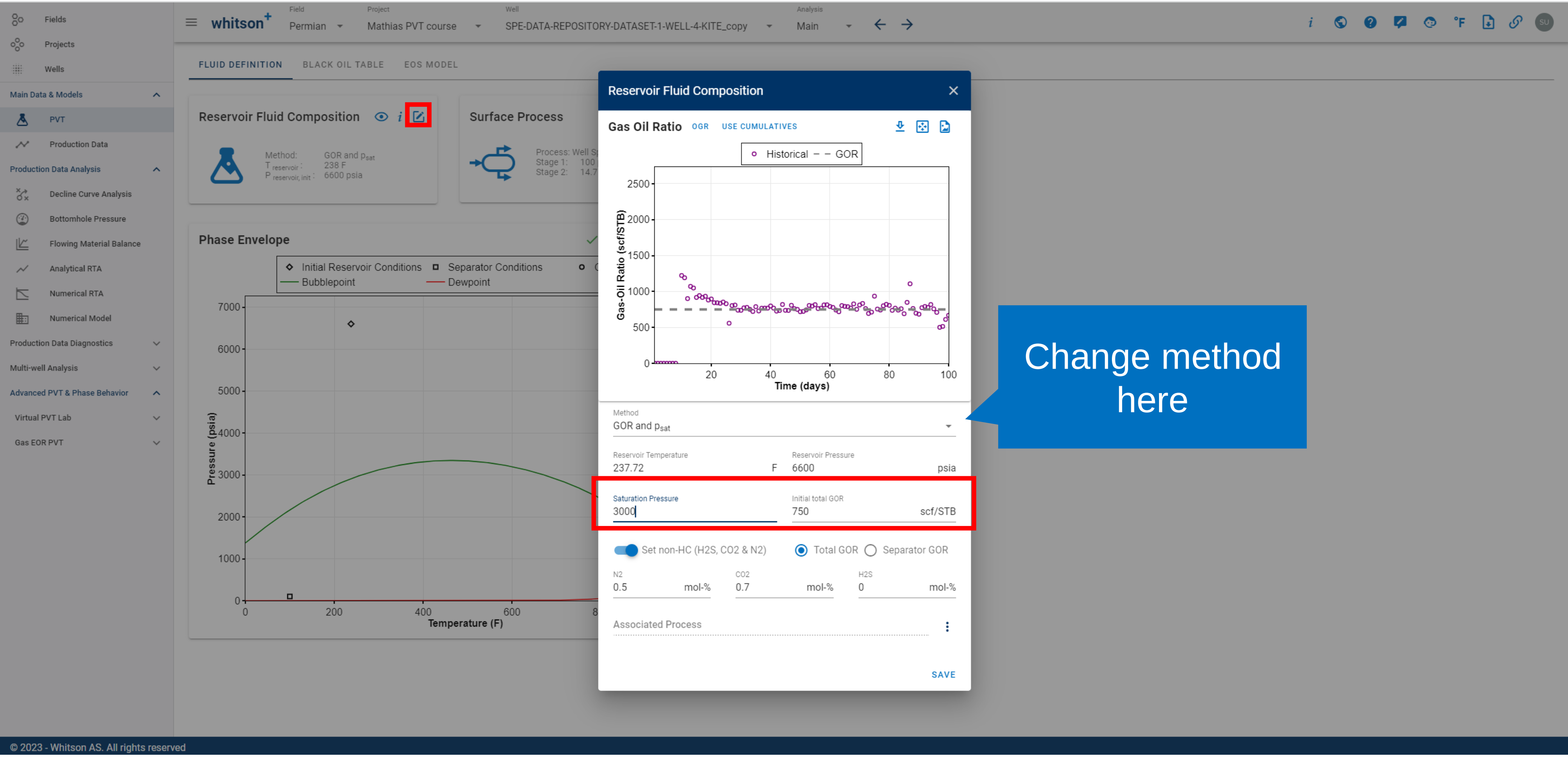


5. What’s the saturation pressure?



6. Change to GOR + psat method

GOR = 750 scf/STB, Saturation pressure = 3000 psia (somewhat computationally expensive method)



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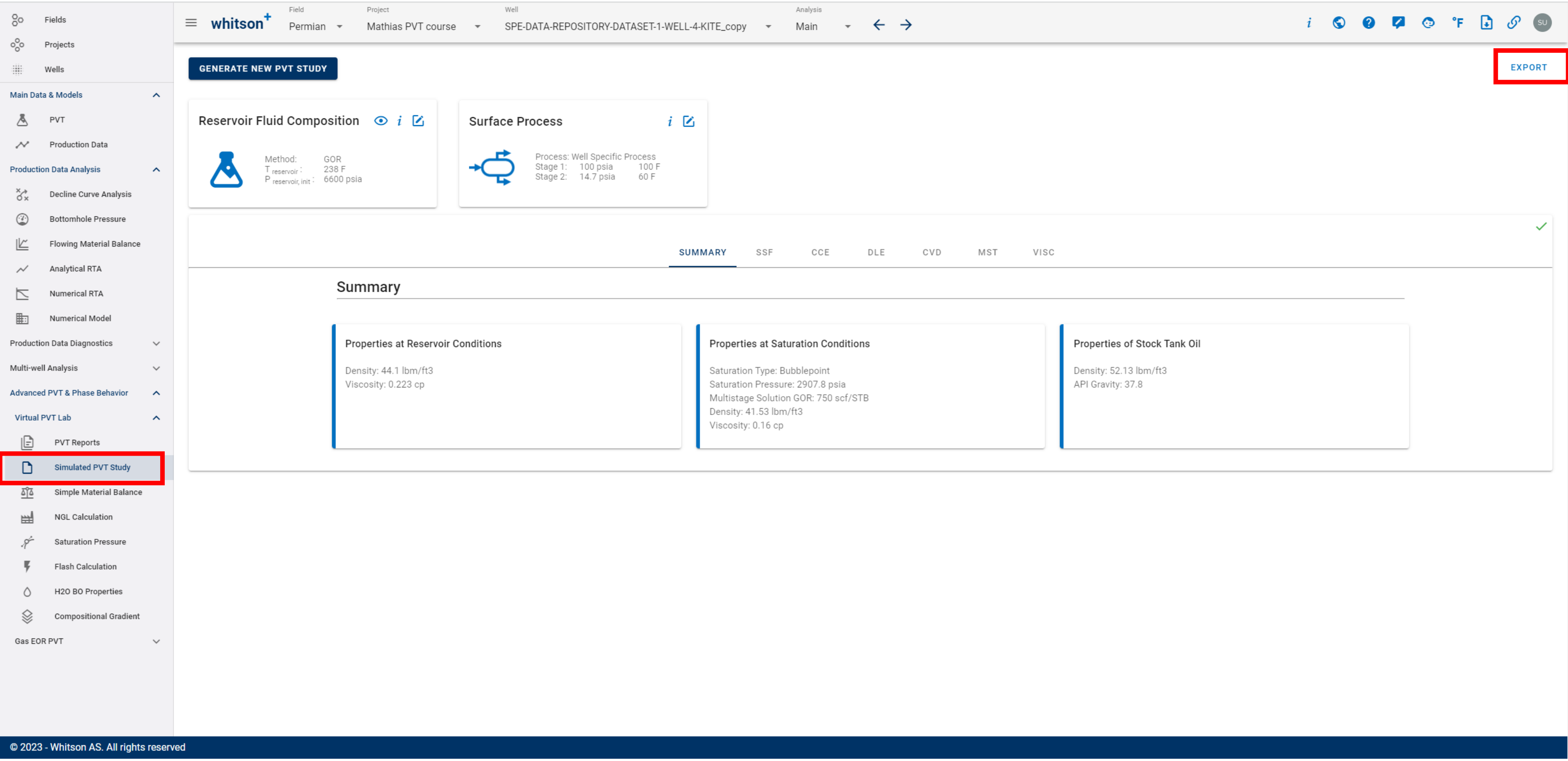
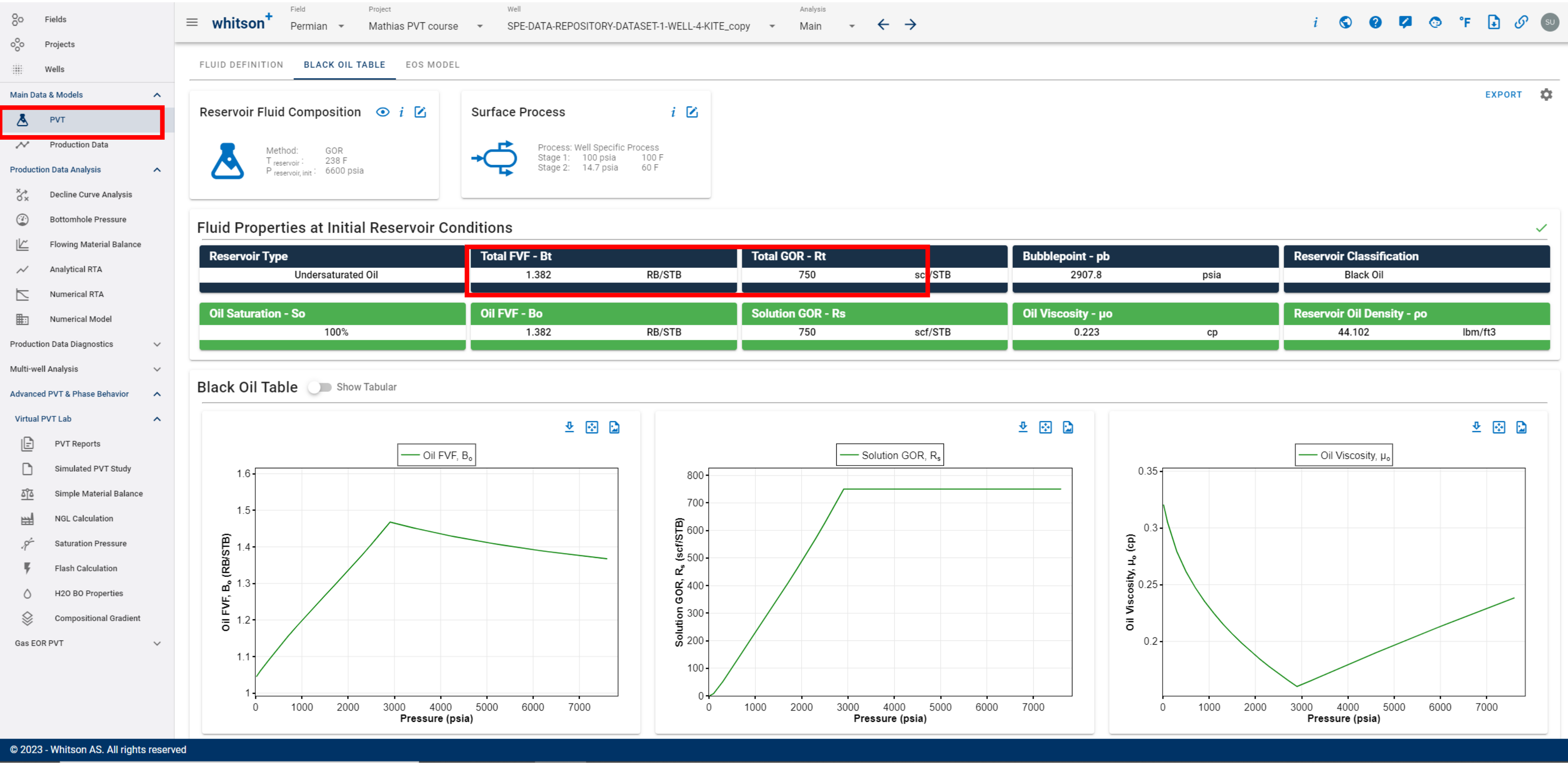
7. Create a synthetic PVT Report



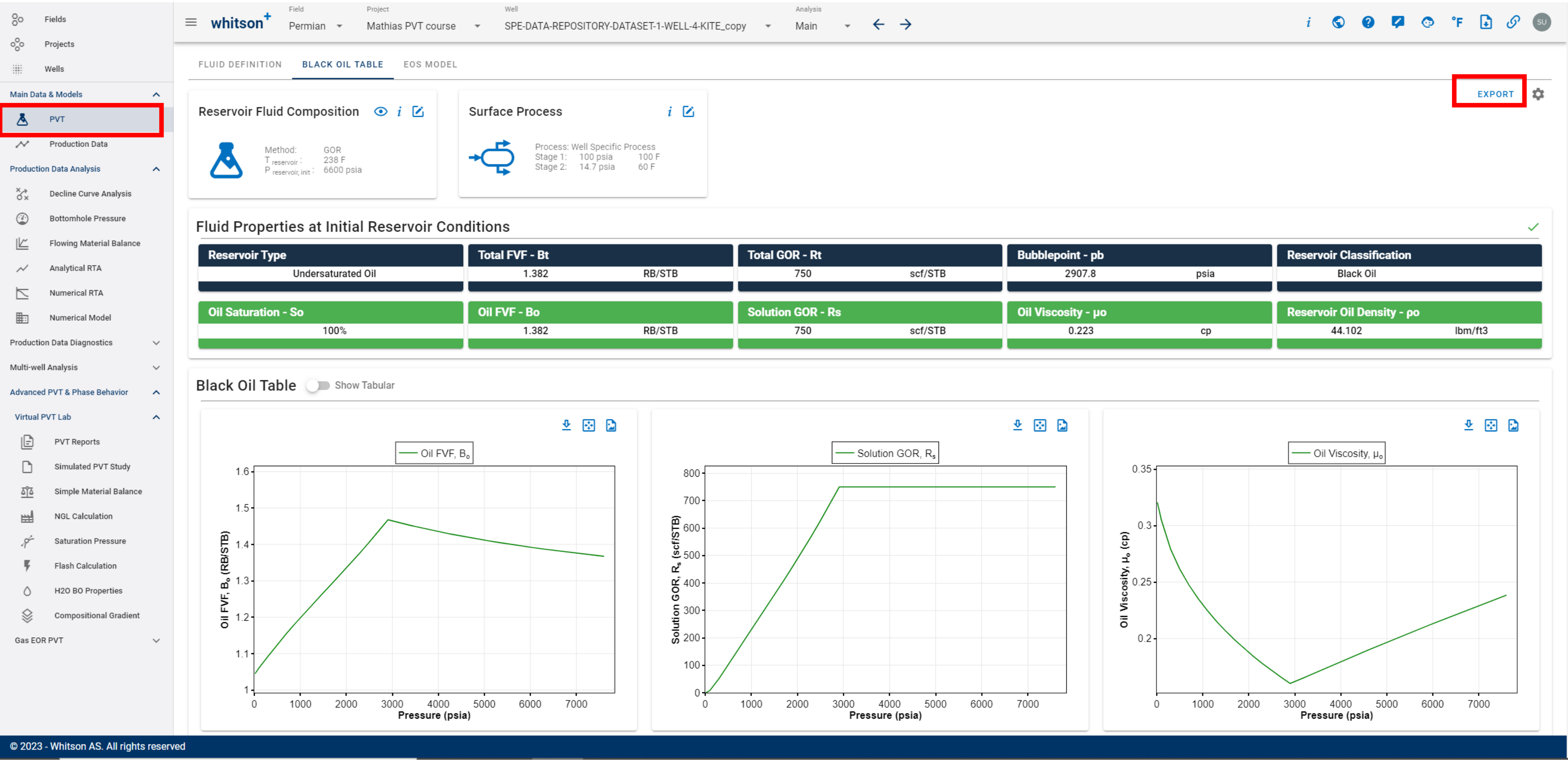
What type of reservoir fluid is this?

8. What is the OOIP and OGIP?

HCPV = 10 000 RB

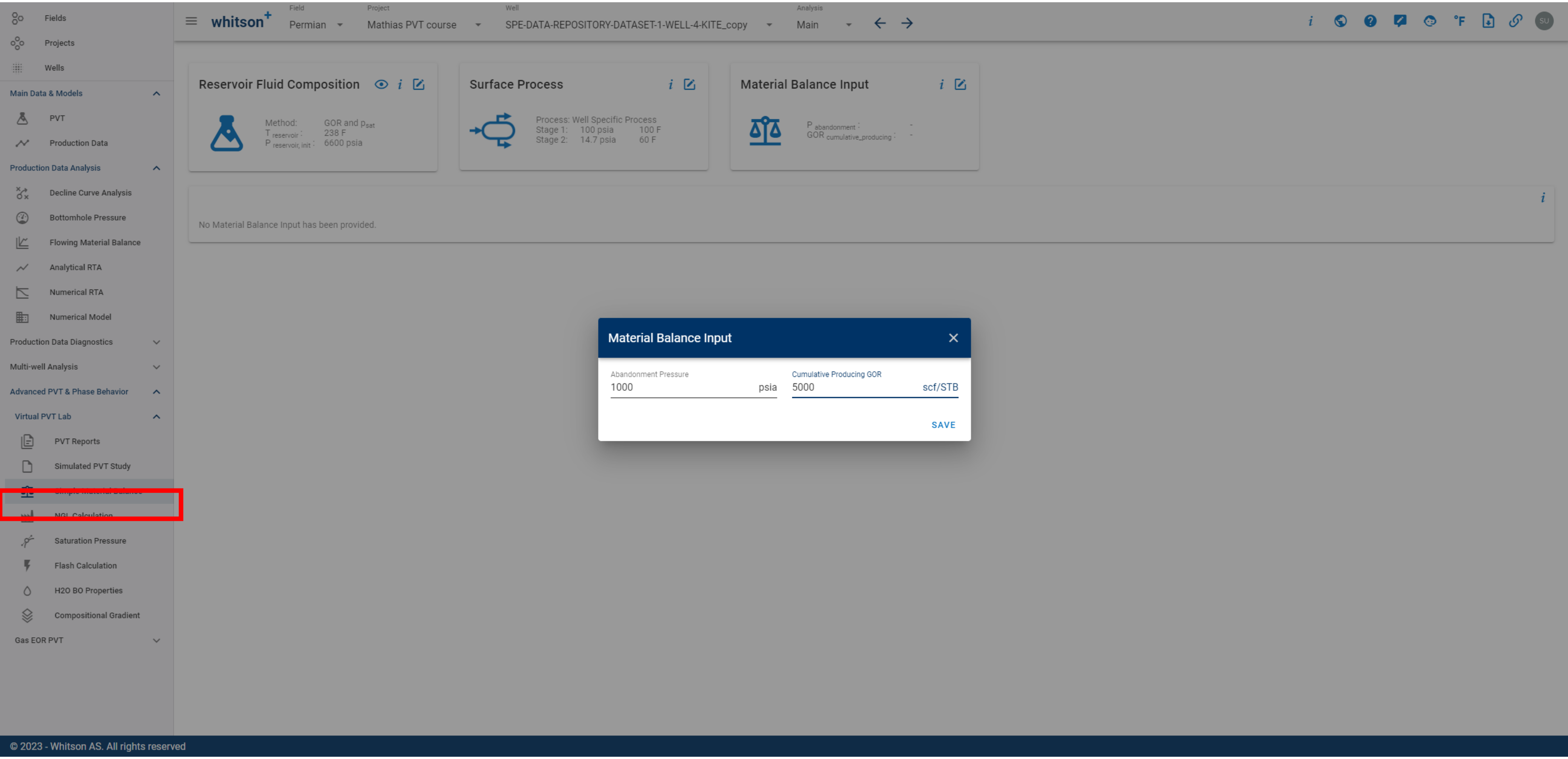


8. Export the Black Oil Table to Excel

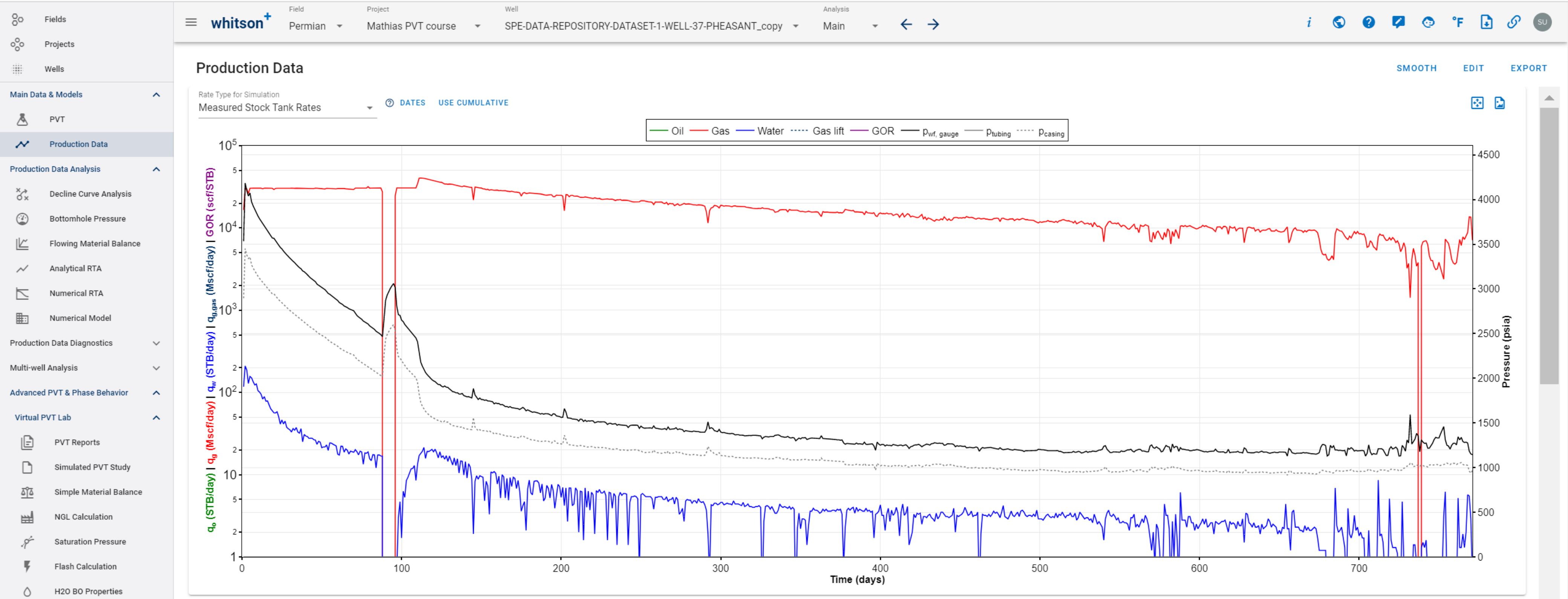


9. Calculate Recovery Factors

pa = 1000 psia | Cum GOR = 5000 scf/STB



10. Dry gas data



Time		Stock Tank Rates				Separator Rates & Conditions						Measured Pressure and Gas-Lift Rates				
Date	Day #	$GOR_{stock\ tank}$ [scf/STB]	q_o [STB/d]	q_g [Mscf/d]	q_w [STB/d]	GOR_{sep} [scf/sep-bbl]	q_o [sep-bbl/d]	q_g [Mscf/d]	q_w [sep-bbl/d]	p_{sep} [psia]	T_{sep} [F]	$p_{wf,\ gauge}$ [psia]	p_{tubing} [psia]	p_{casing} [psia]	$q_{g,\ gas\ lift}$ [Mscf/d]	Liquid level (MD) [ft]
1 Jan. 2019 00:00	1	NaN	0	16548.9	117.4	NaN	0	0	0	0	NaN	3532.9	0	2894.9	0	0
2 Jan. 2019 00:00	2	NaN	0	30067.4	210.3	NaN	0	0	0	0	NaN	4183.9	0	3450.4	0	0
3 Jan. 2019 00:00	3	NaN	0	29839.3	187.3	NaN	0	0	0	0	NaN	4100.4	0	3378.7	0	0
4 Jan. 2019 00:00	4	NaN	0	26233.2	128.5	NaN	0	0	0	0	NaN	4039	0	3339.7	0	0
5 Jan. 2019 00:00	5	NaN	0	30357.3	156.6	NaN	0	0	0	0	NaN	4073.1	0	3357.5	0	0

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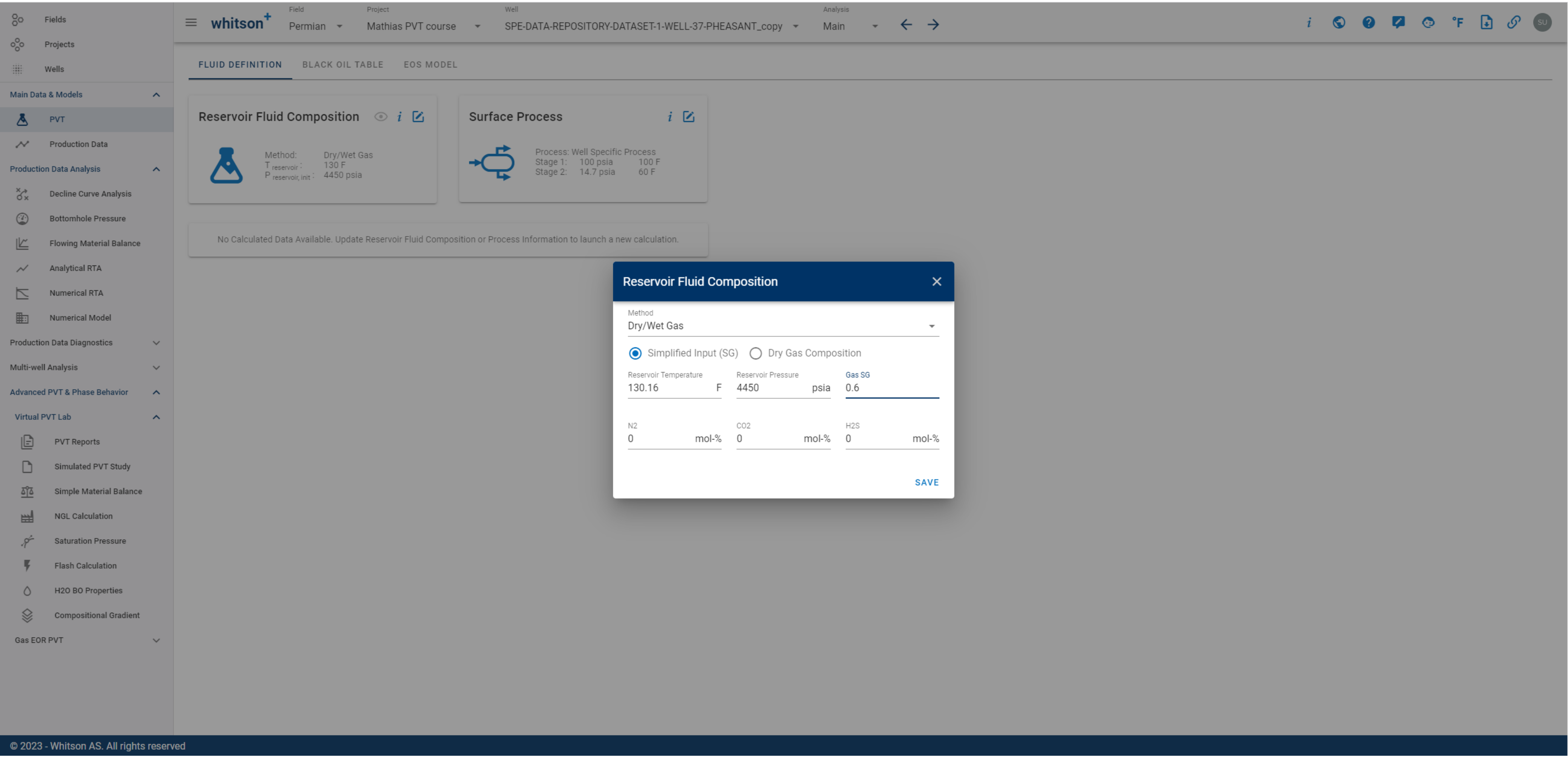
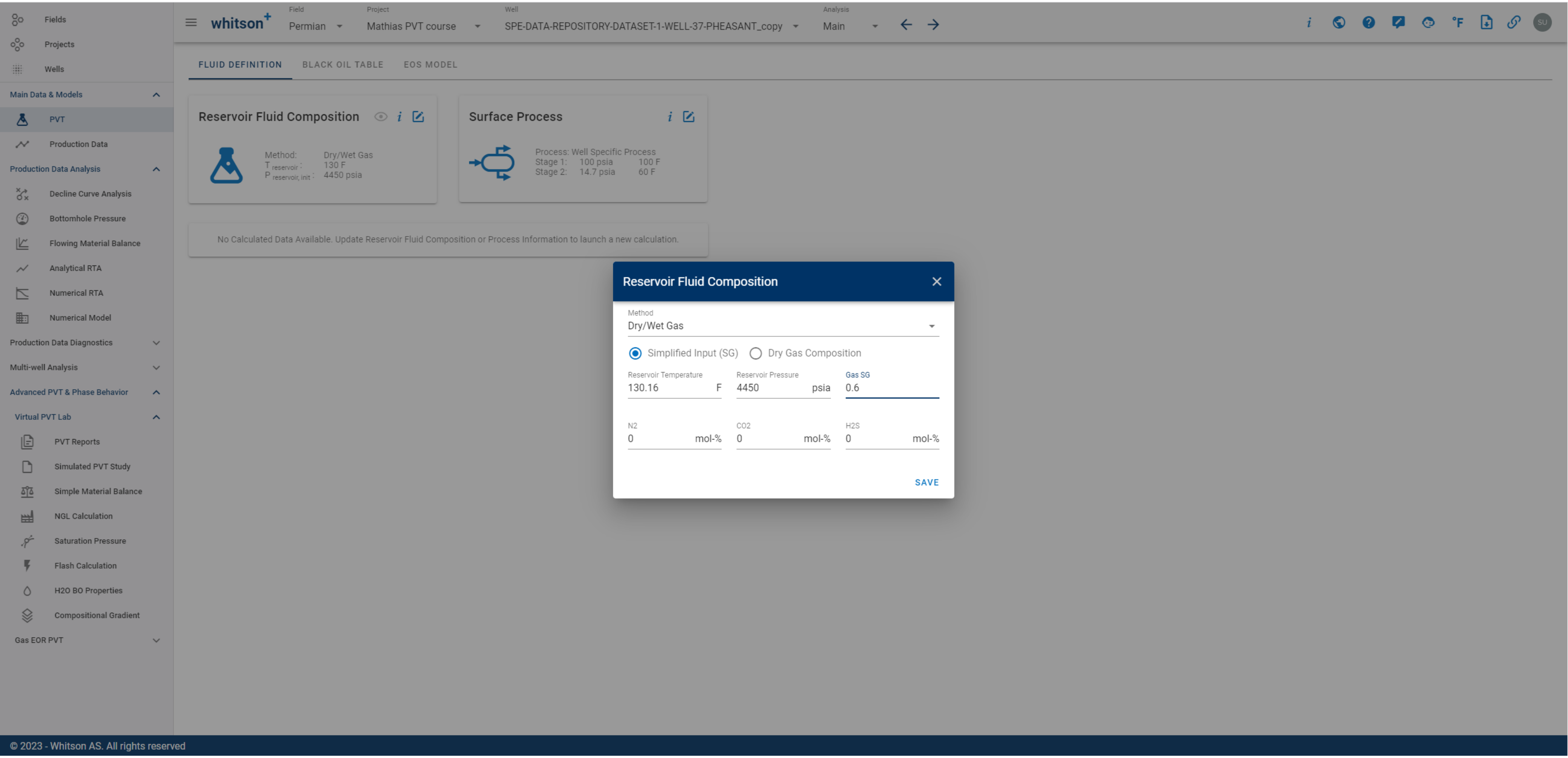
10. Use a specific gravity of 0.6

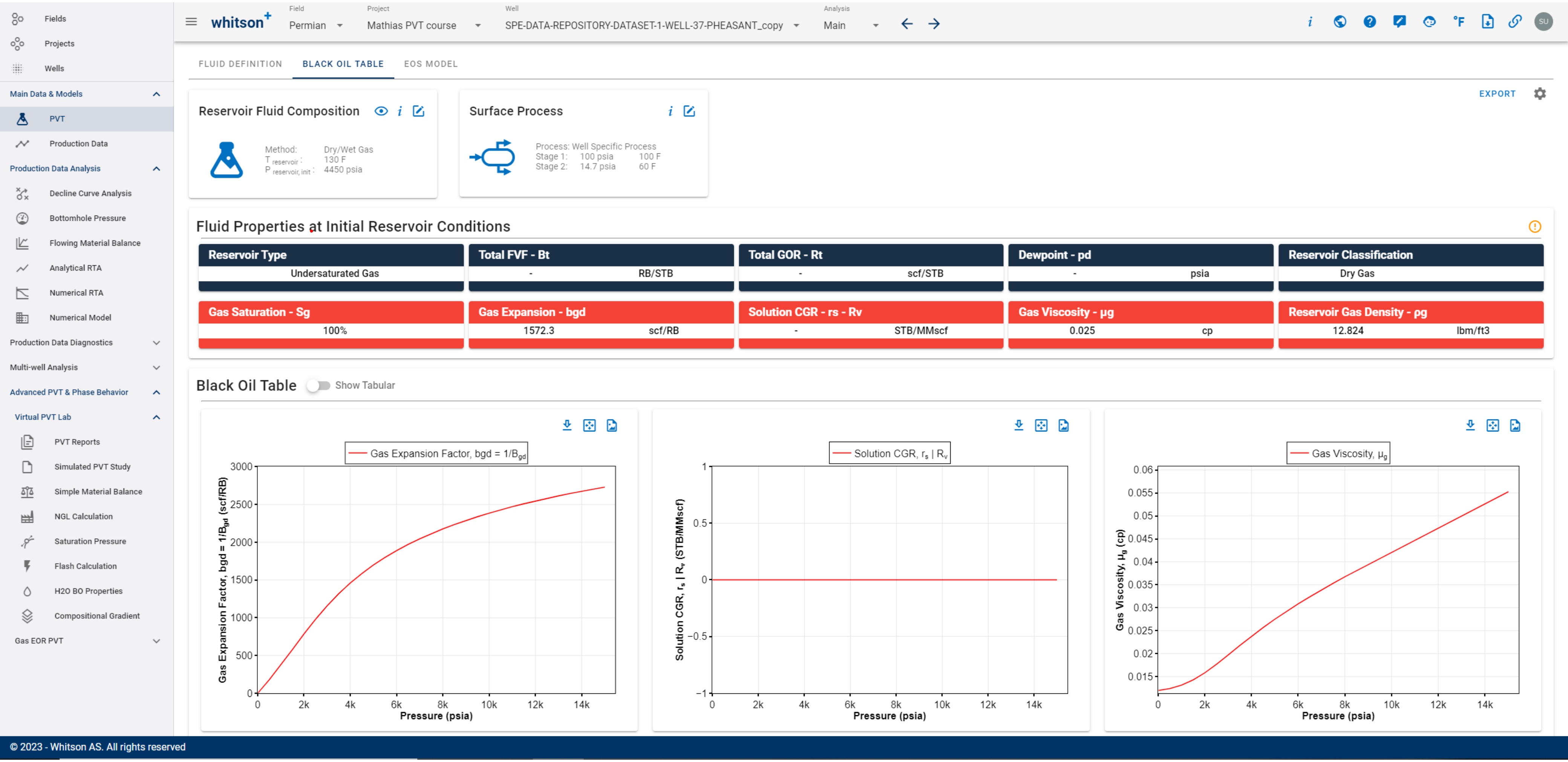


11. Specify the non-hydrocarbons

N_2 = 0.5%, CO_2 = 0.7%, H_2S = 0%



12. Take a look at the PVT table



We support energy companies, oil services companies, investors and government organizations with expertise and expansive analysis within PVT, gas condensate reservoirs and gas-based EOR. Our coverage ranges from R&D based industry studies to detailed due diligence, transaction or court case projects.

We help our clients find best possible answers to complex questions and assist them in the successful decision-making on technical challenges. We do this through a continuous, transparent dialog with our clients - before, during and after our engagement.

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Advanced Topic

Quantifying Separator Shrinkage

Practical Observations

Rates are measured at separator conditions and seldom reach “stock tank” conditions on a single well basis

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Rates are measured at separator conditions and seldom reach “stock tank” conditions on a single well basis

- Albeit not correct, **separator measured rates** are frequently used directly in well analysis

  → overestimate the profitability

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Practical Observations

Rates are measured at separator conditions and seldom reach "stock tank" conditions on a single well basis

- Albeit not correct, **separator measured rates** are frequently used directly in well analysis

  → overestimate the profitability

- If separator shrinkage is accounted for, common to apply one **constant** shrinkage factor for well and/or field

  → shrinkage factors change with time

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Topics to Investigate …

- **Under what circumstances is …**

  … separator oil shrinkage important?

  … expected to change considerably with time?

- **How use an EOS model to estimate daily**

  … separator oil shrinkage factors (STB/sep.bbl)

  … separator oil flash factors (scf/STB)

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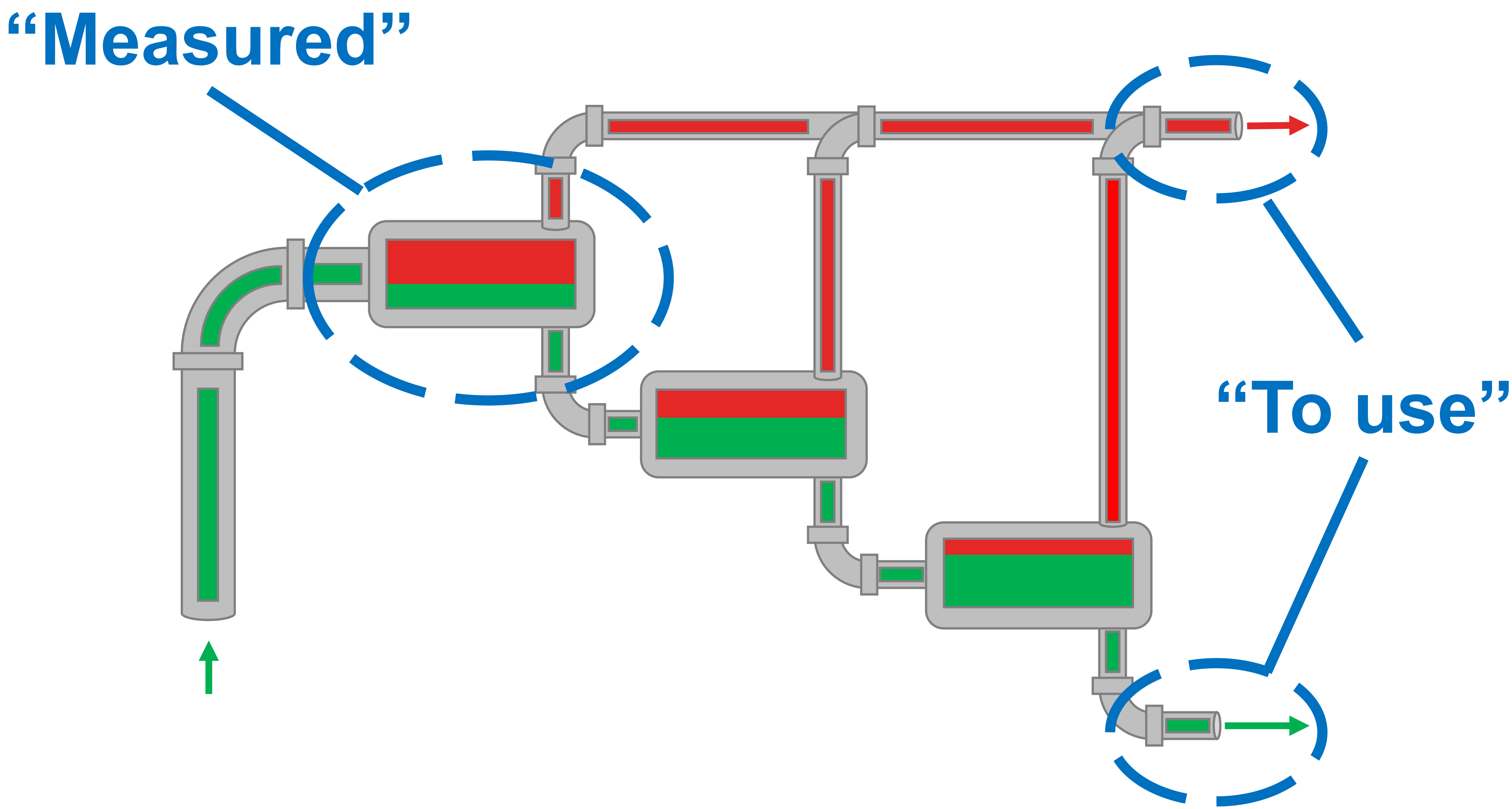
Separator Oil Shrinkage

A Recap

Separator Rates vs. Stock Tank Rates



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Separator Rates vs. Stock Tank Rates

"Measured"

$$GOR_{tot} = \frac{GOR_{sep}}{SF} + FF$$

"Must be Calculated"

GOR_{tot}: total stock tank gas oil ratio
GOR_{sep}: separator gas oil ratio
SF: separator oil shrinkage factor
FF: separator oil flash factor

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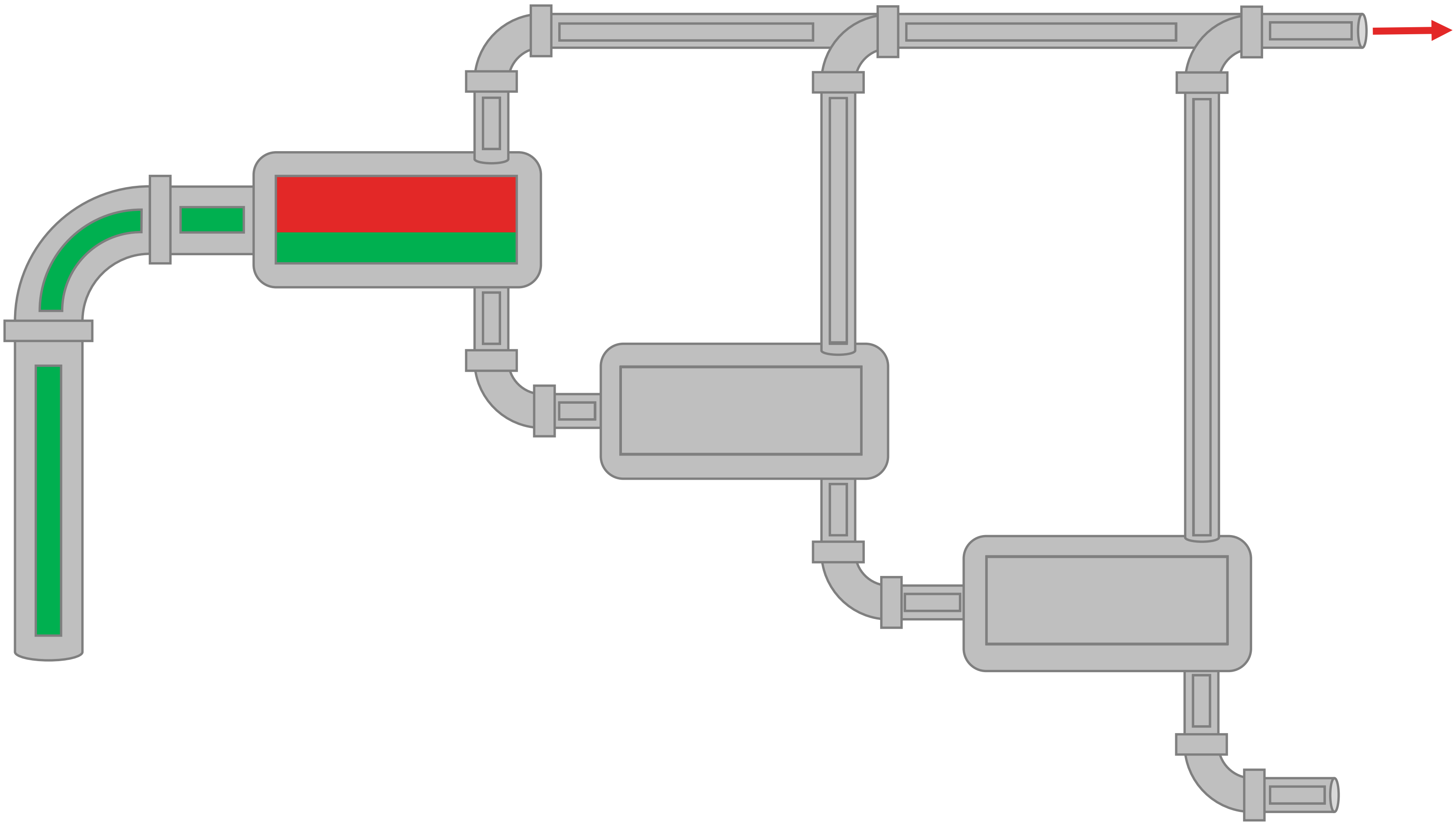
Separator Oil Shrinkage … A Recap



*This is a cartoon not to scale

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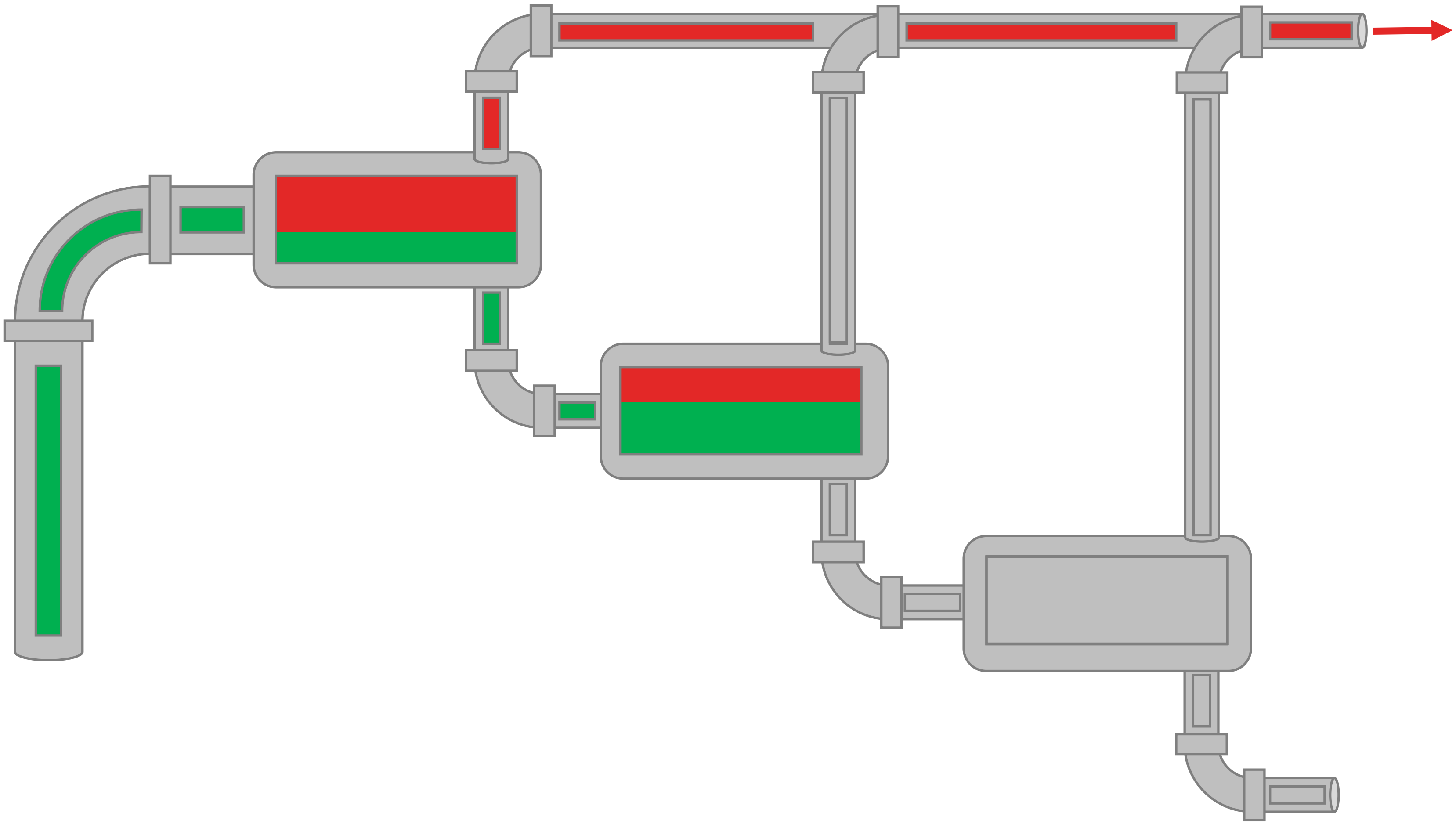
Separator Oil Shrinkage … A Recap



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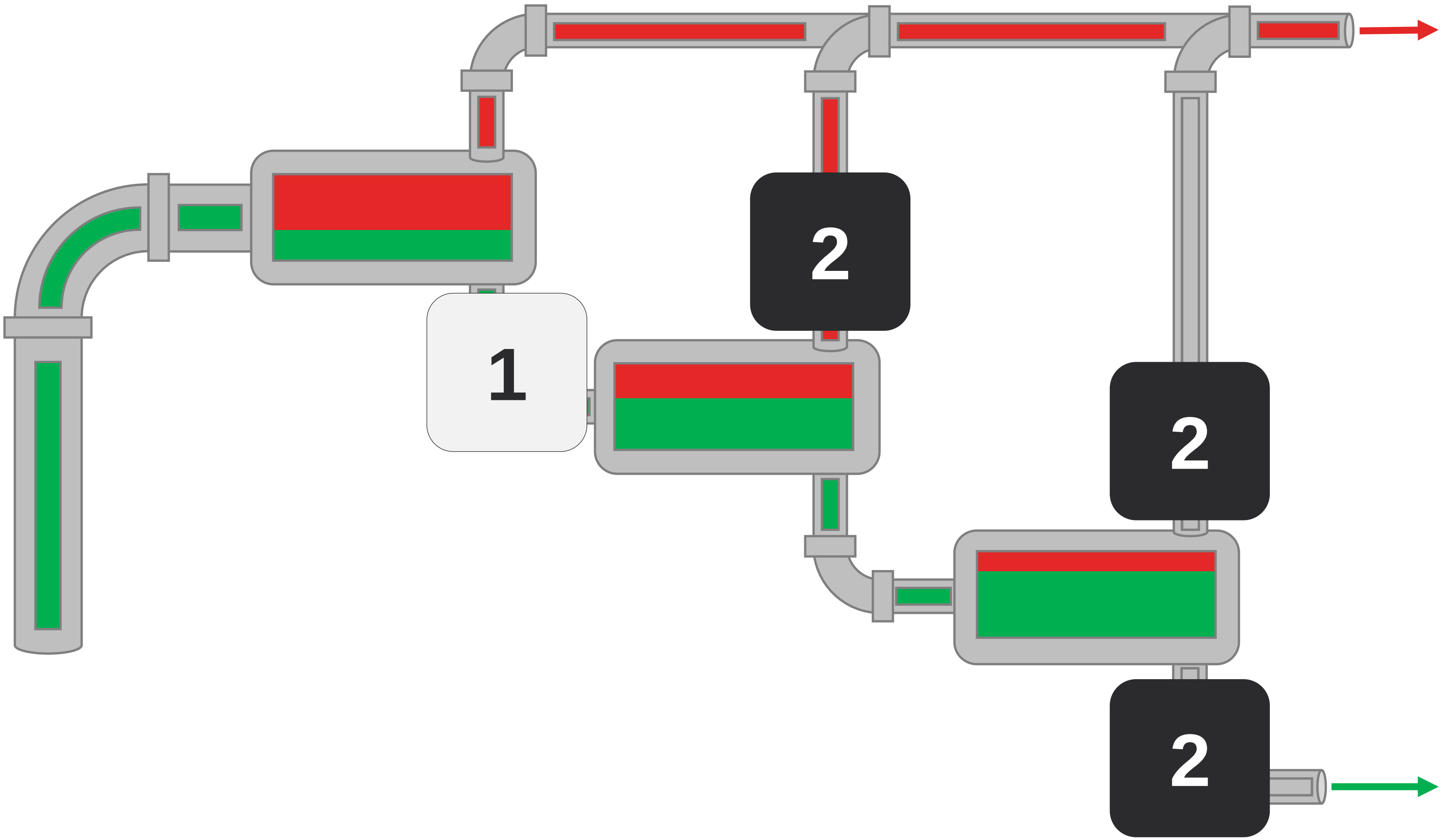
Separator Oil Shrinkage … A Recap



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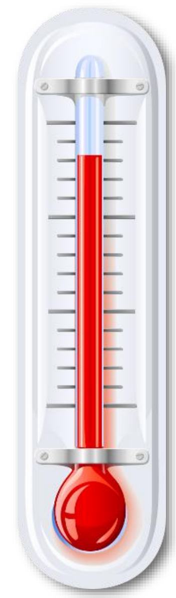
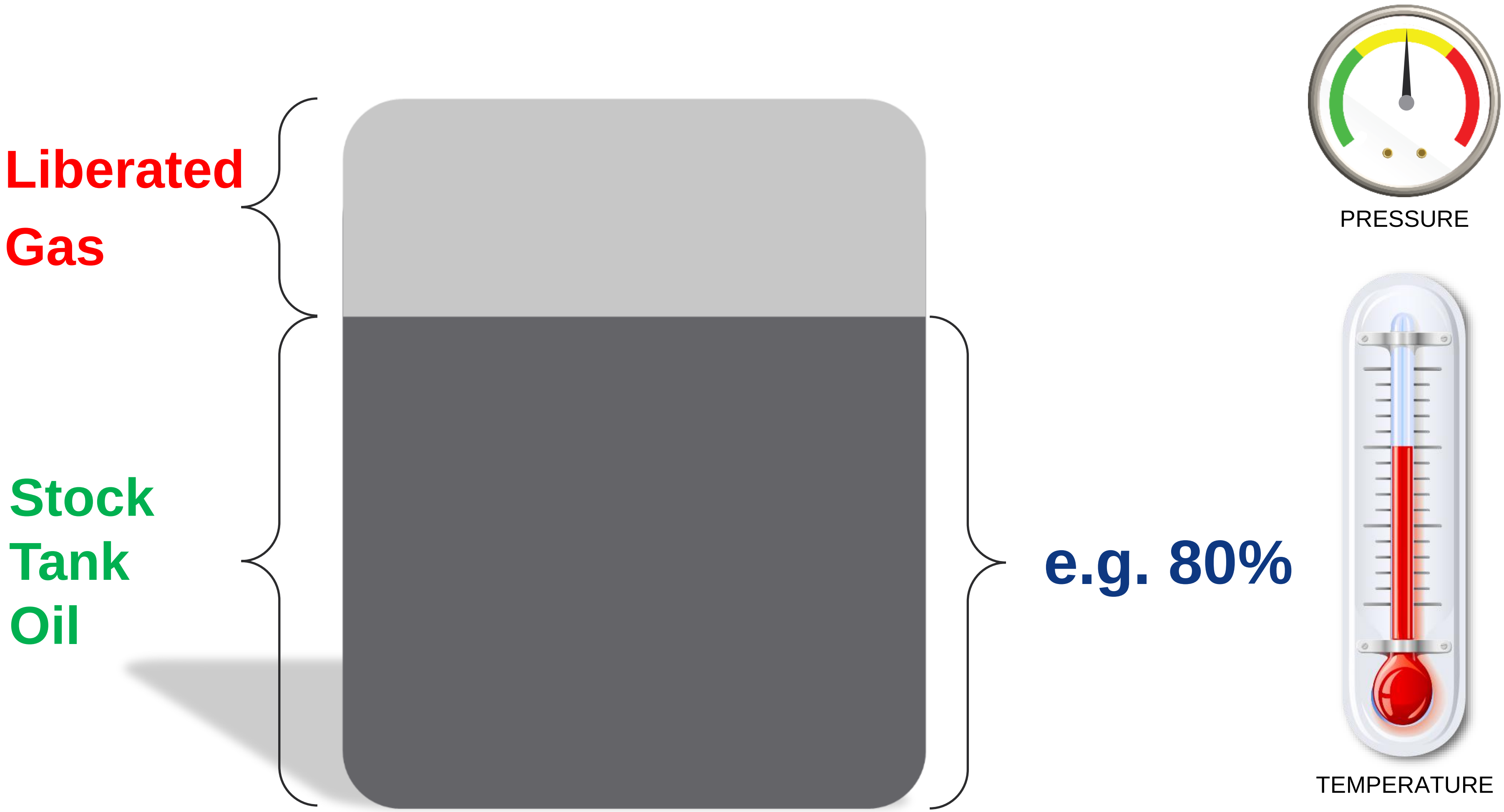
Separator Oil

PRESSURE



TEMPERATURE

Shrinkage of Oil and Additional Gas "Flashed Off"



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Separator Oil Shrinkage Factor (SF)

$$SF\left(\frac{STB}{sep.bbl}\right)$$

<0.6 - 1

Separator Oil Flash Factor (FF)

$$FF\left(\frac{scf}{STB}\right)$$

Essentially solution GOR of separator oil

1. Under what circumstances is …

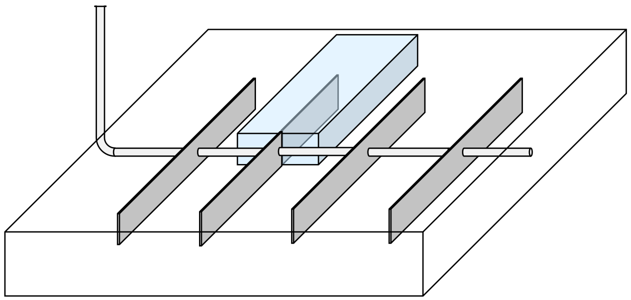
…separator oil shrinkage important?

…expected to change with time?

To Understand When It is Important, we …

… a wide range of in-situ fluids (reservoir oils | reservoir gas)

… with a **compositional** reservoir simulator

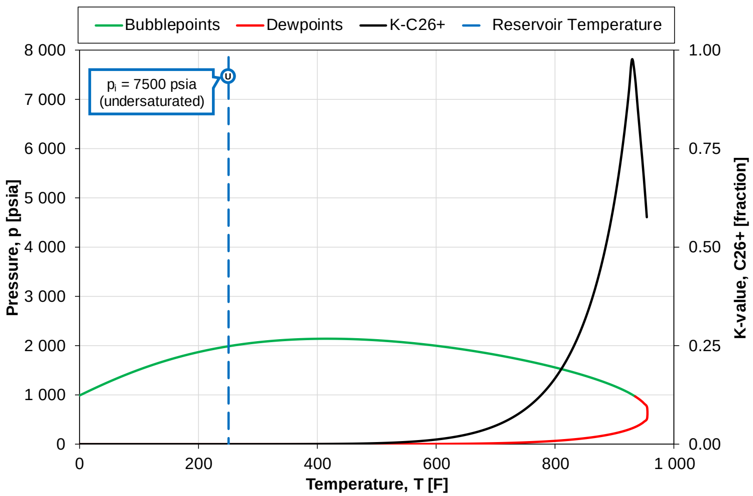


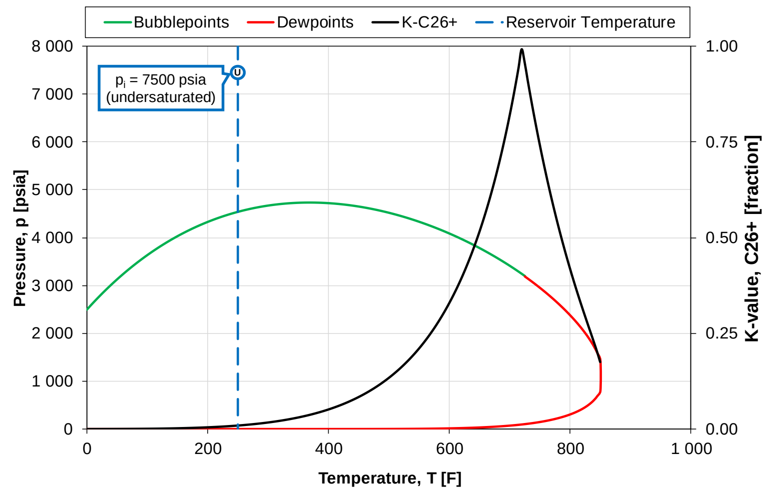
… controlled on a **constant BHP** profile

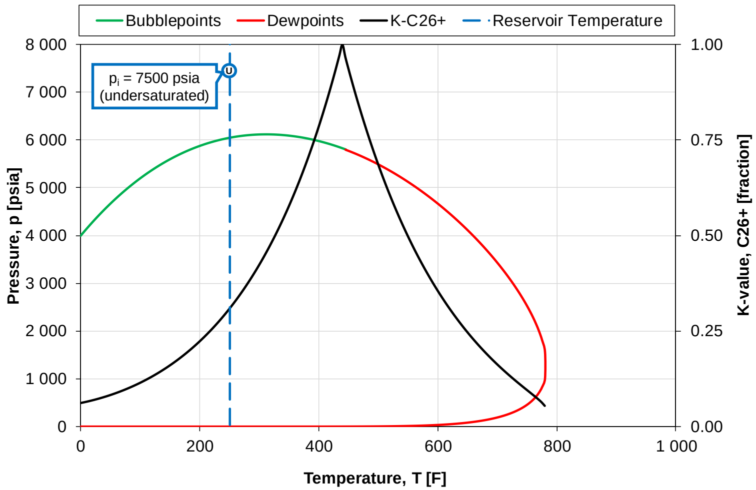
… i) fluids produced at **constant** separator conditions

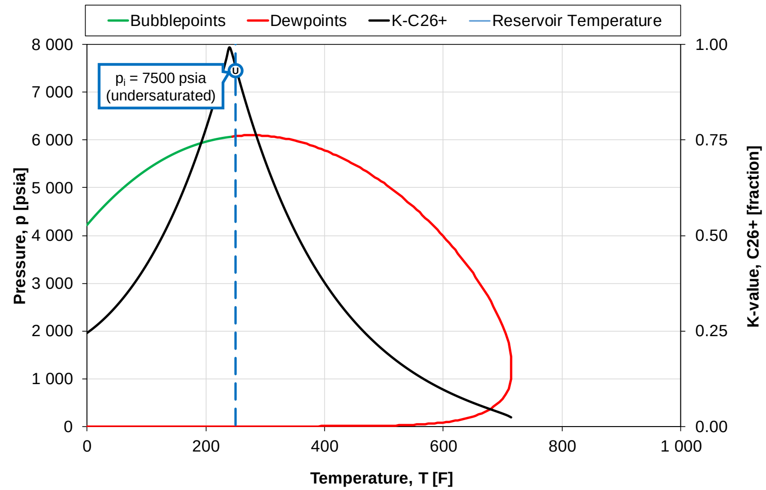
… ii) fluids produced at **changing** separator conditions

A Wide Range of Fluid Systems Studied (p_{Ri} = 7500 psia)









A Wide Range of Fluid Systems Studied (p_{Ri} = 7500 psia)

Black Oil

Volatile Oil

Near Critical Volatile Oil

Near Critical Gas Condensate

What is Separator Oil Shrinkage a Function of?

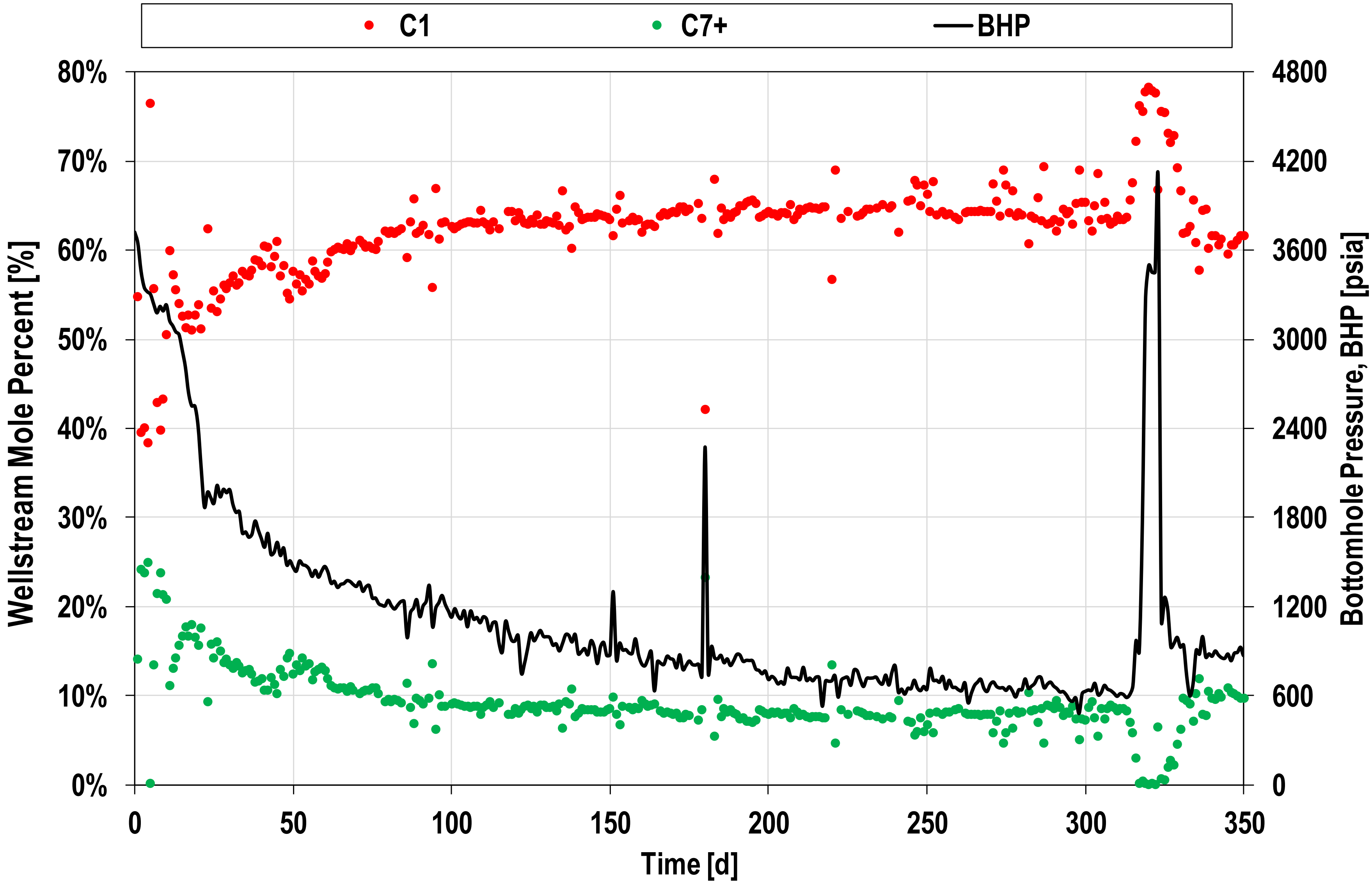
Surface Process

- Separator Stages - fixed
- Separator Pressure (p_{sep}) – f(time)
- Separator Temperature (T_{sep}) – f(time)

Wellstream composition (z_i) – f(time)

- Amount of different components (C_1 | C_{7+})

Wellstream Compositions Might Change Substantially with Time



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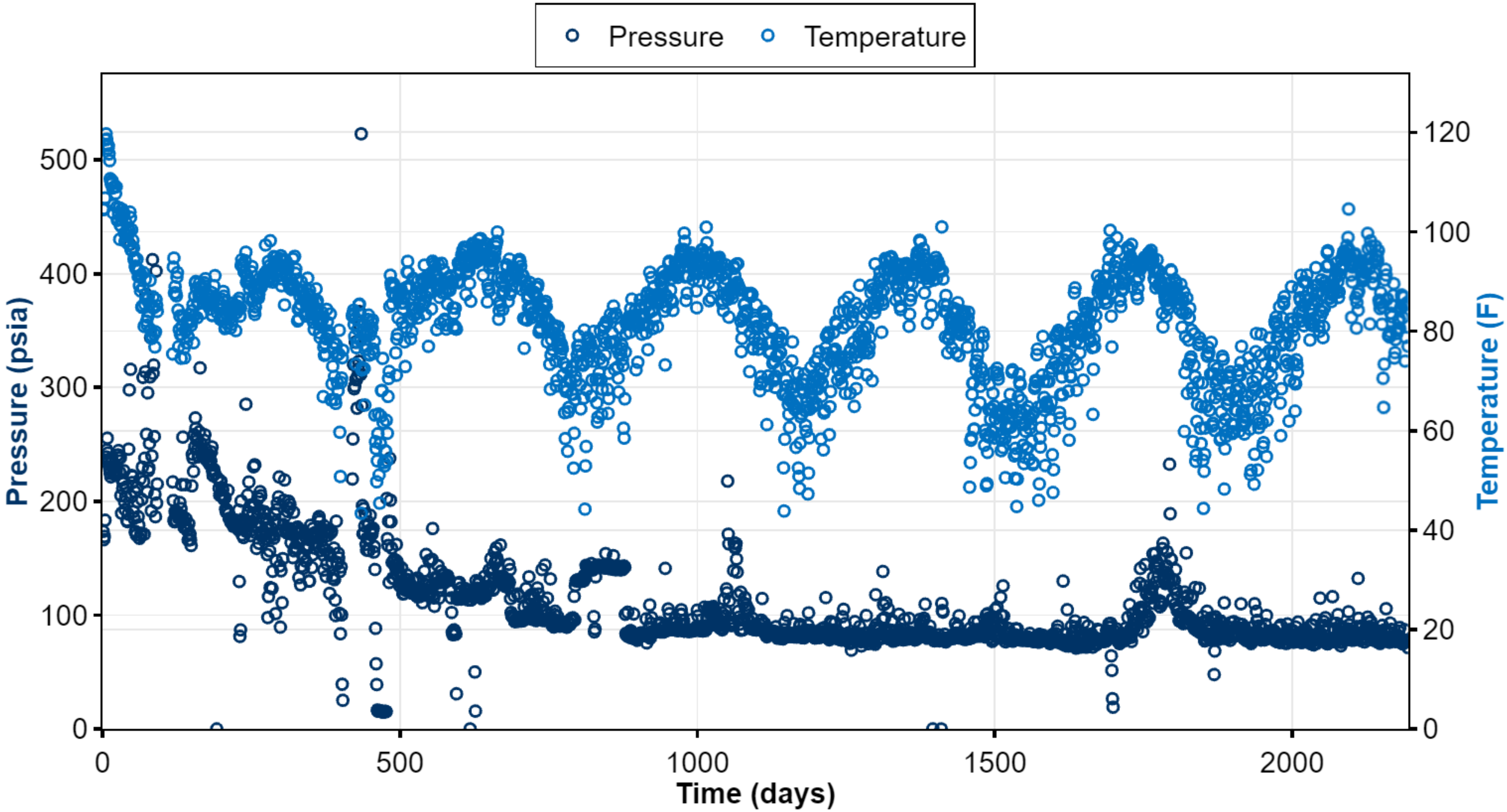
Separator Conditions Changes Substantially with Time



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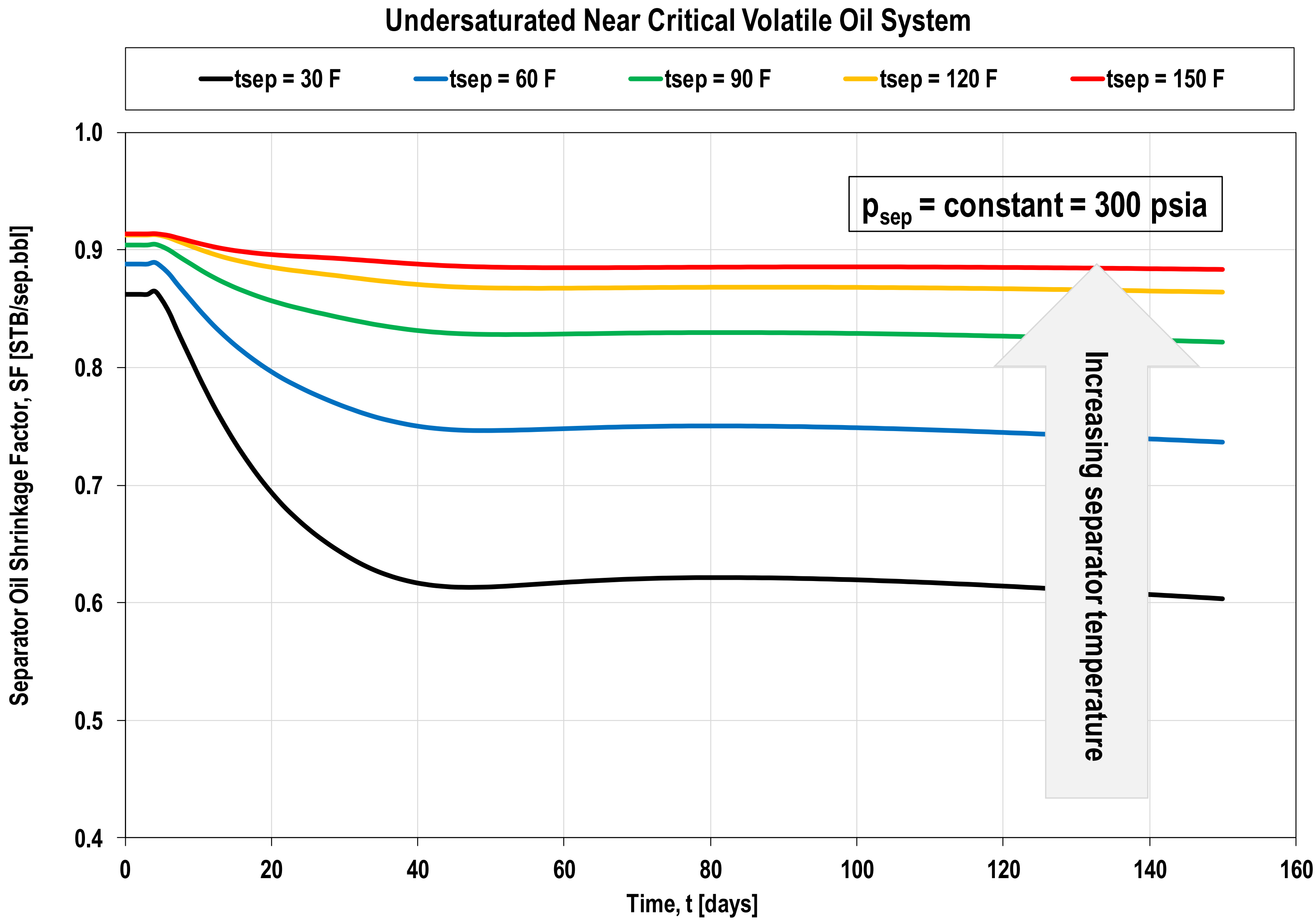
Lower Sep. Temperature, Lower Shrinkage Factor!



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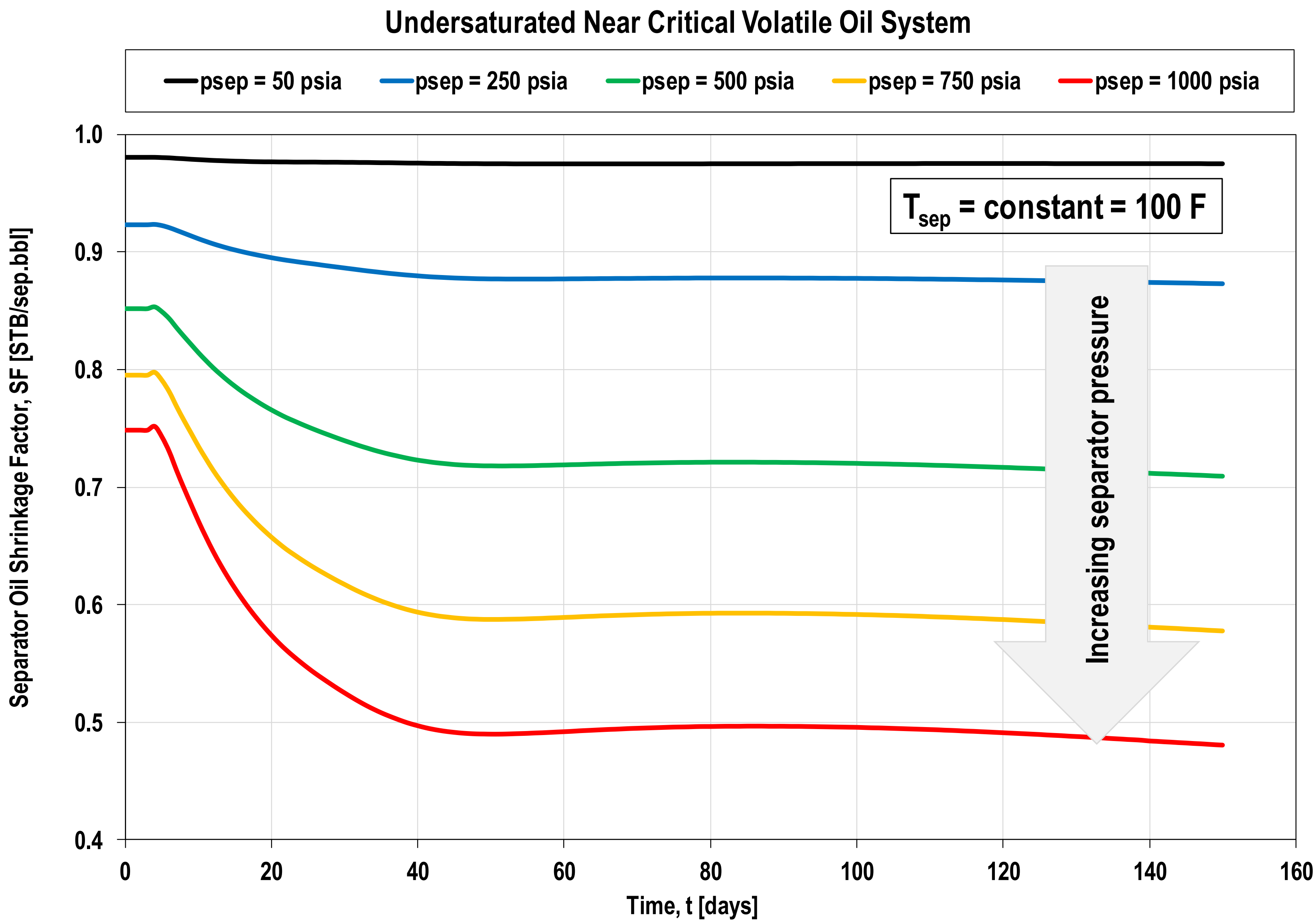
Higher Sep. Pressure, Lower Shrinkage Factor!



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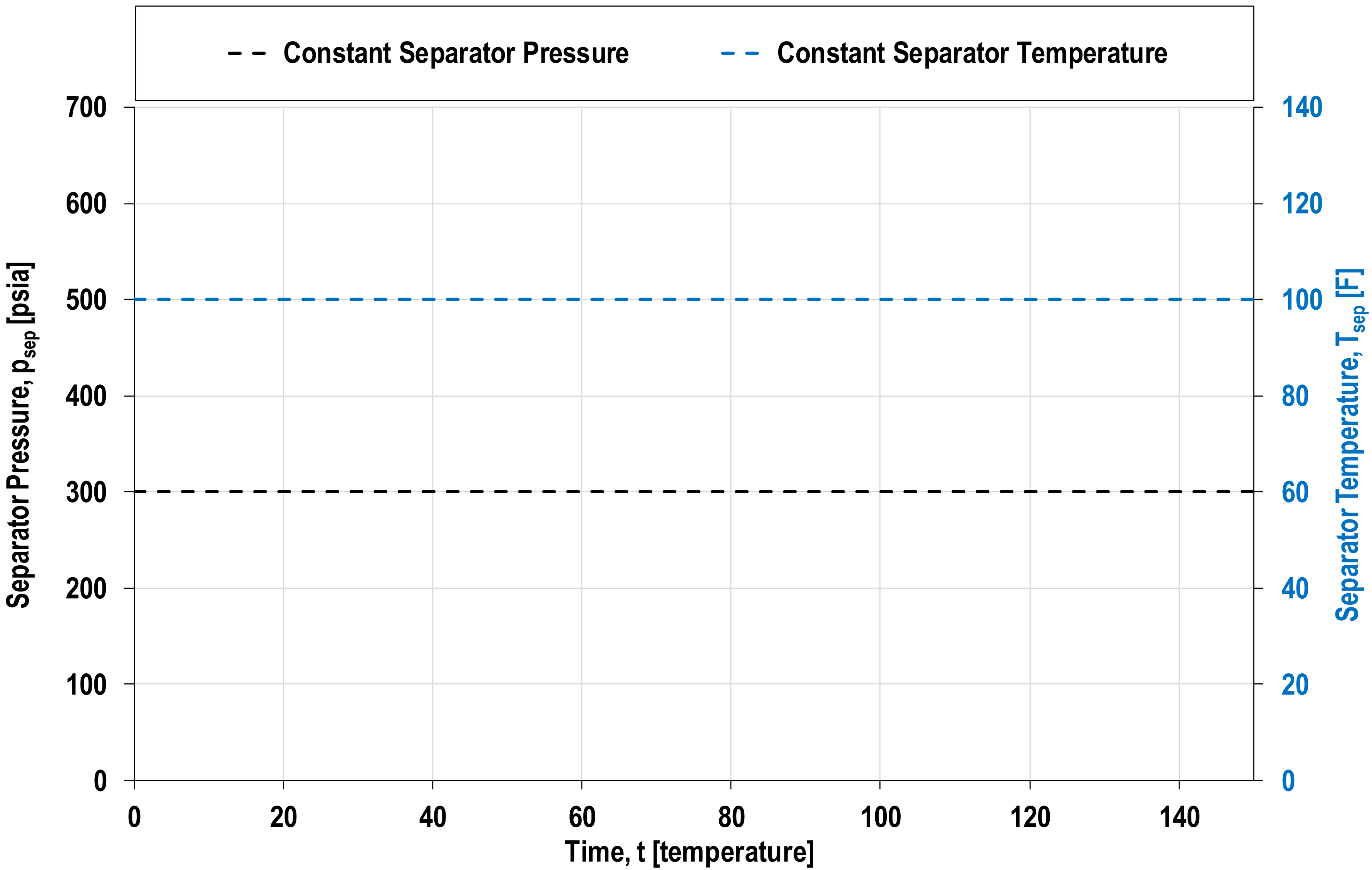
Constant Separator Conditions



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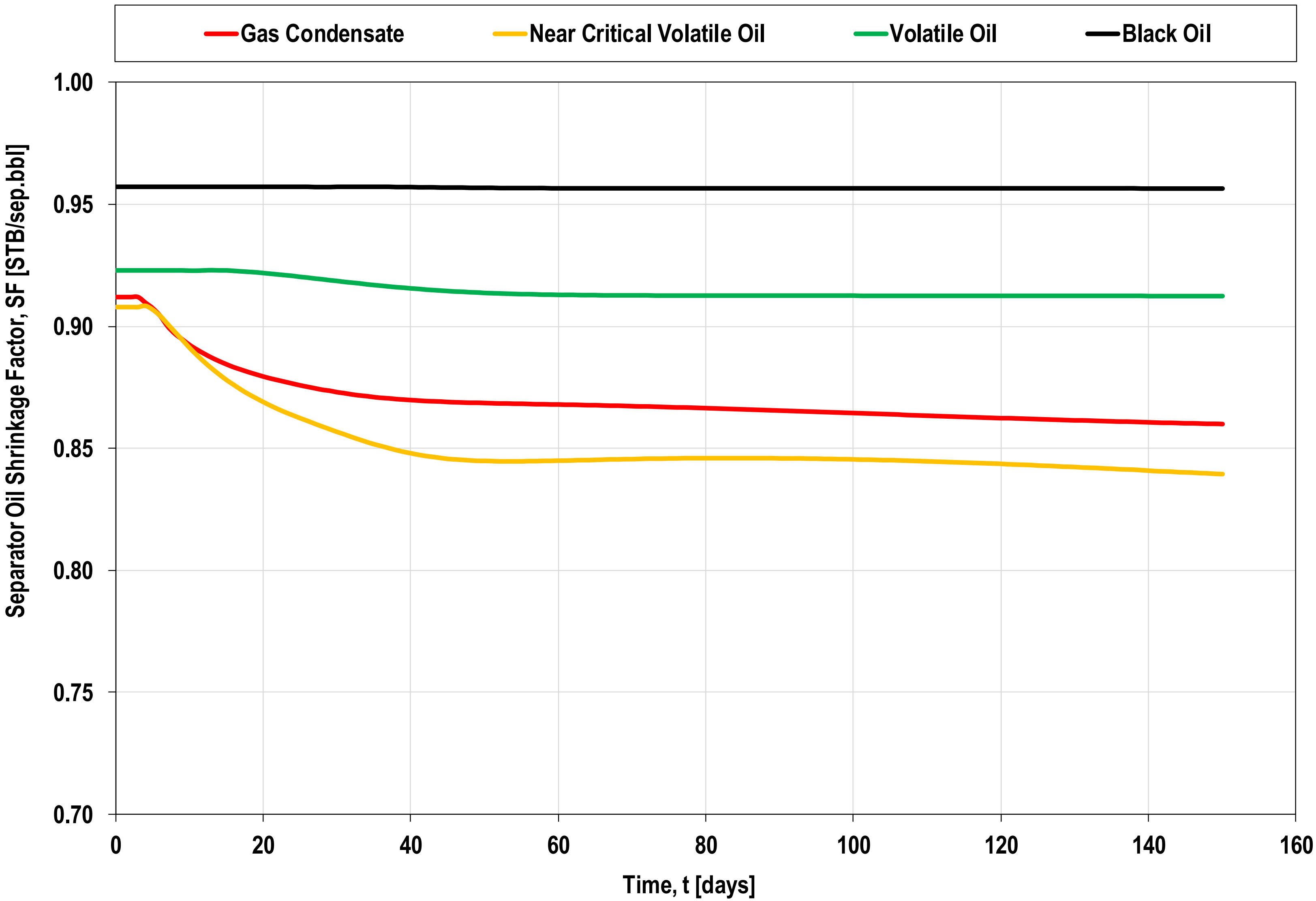
Lower Shrinkage Factors at Higher GORs



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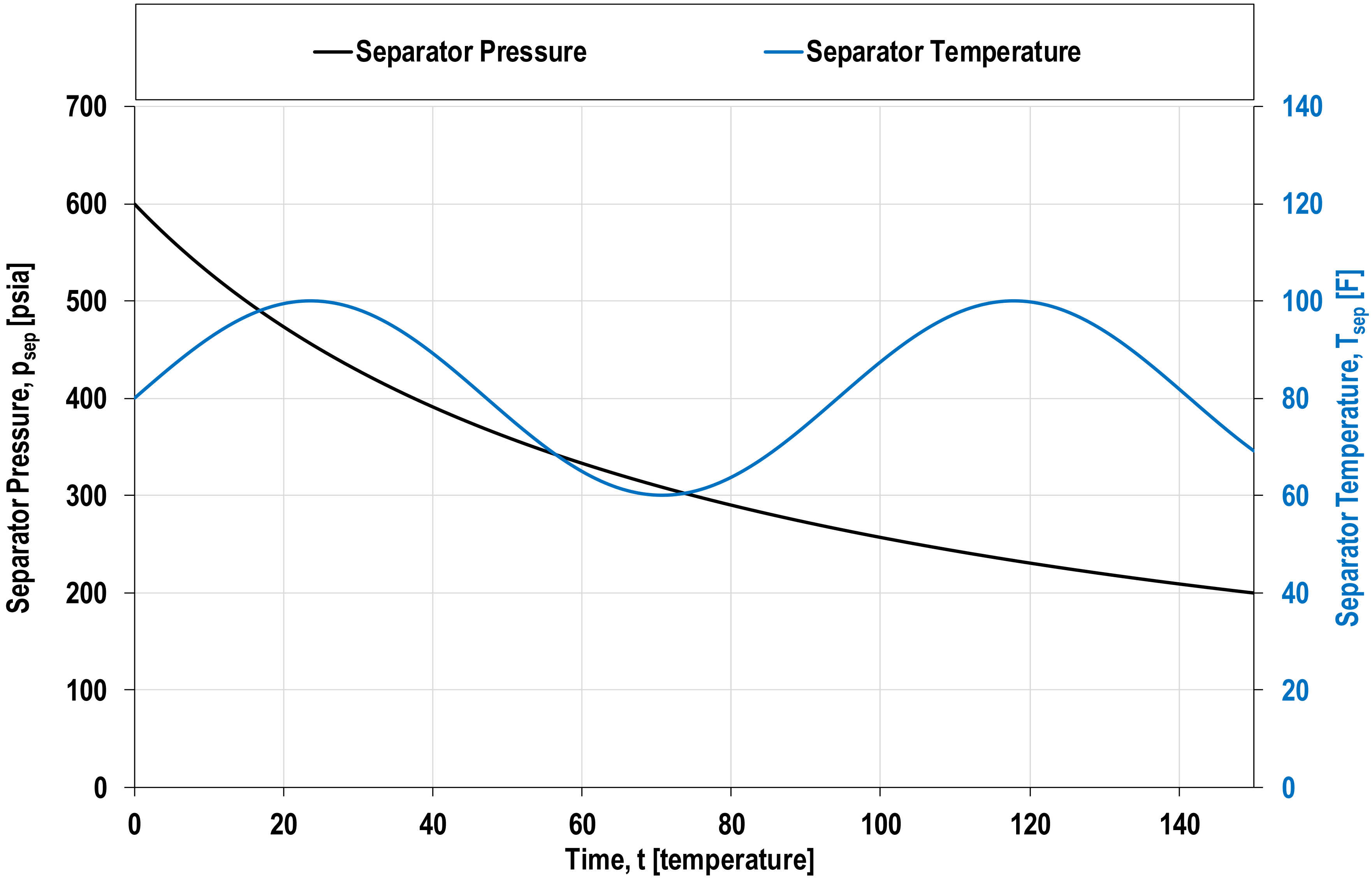
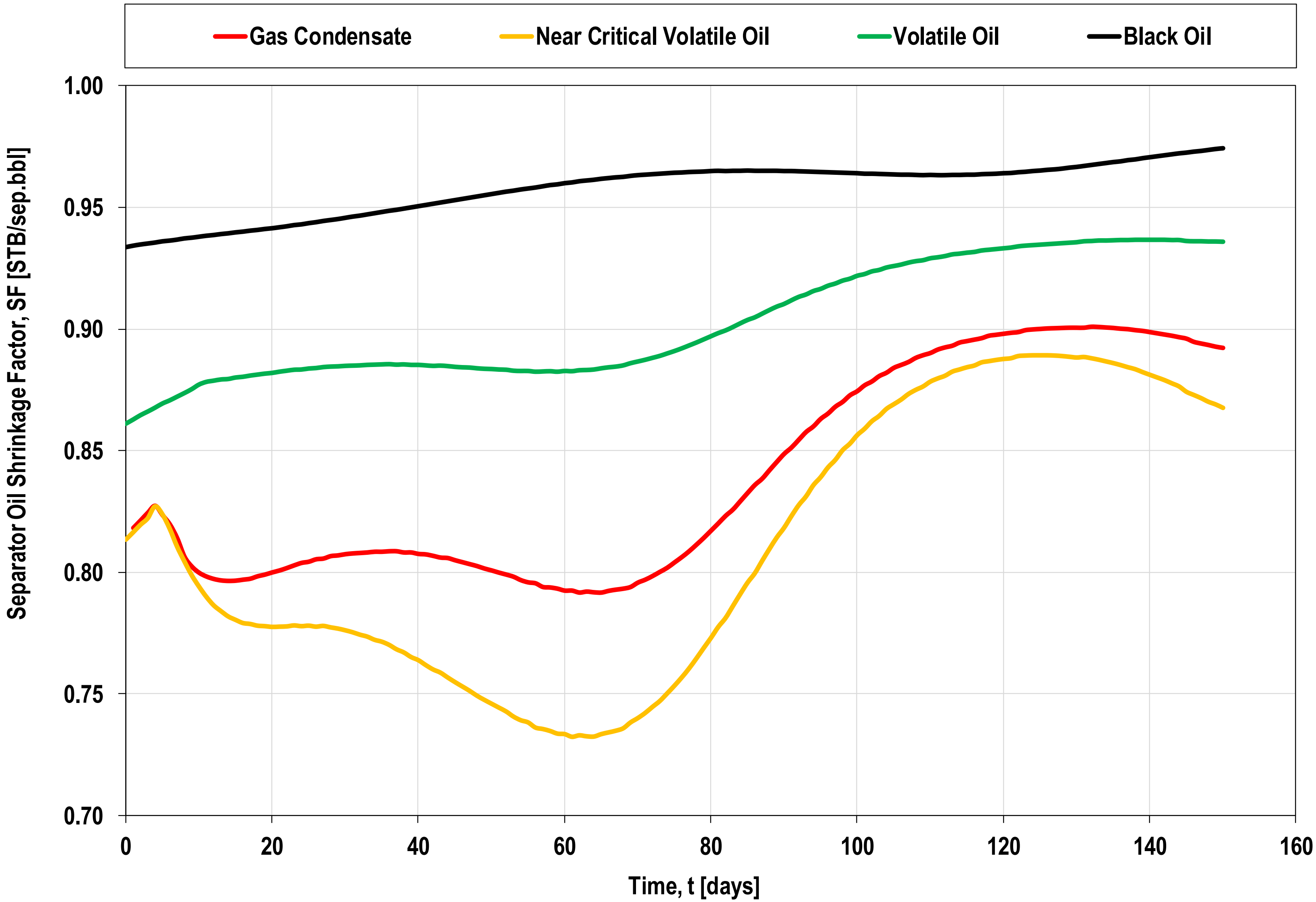
Changing Separator Conditions



Changing Separator Conditions has a Big Impact!



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Summary

Shrinkage factors **and flash factors should be updated daily if one or more of these criteria are met:**

- In-situ solution GOR (R_s) > 1000 scf/STB
- Separator conditions changing with time
- Wellstream compositions changing with time

… Large changes in producing GOR with time

… Rapid decline in bottomhole pressure

… Frequent shut-ins (“CGR kicks”)

… Wells subject to gas EOR

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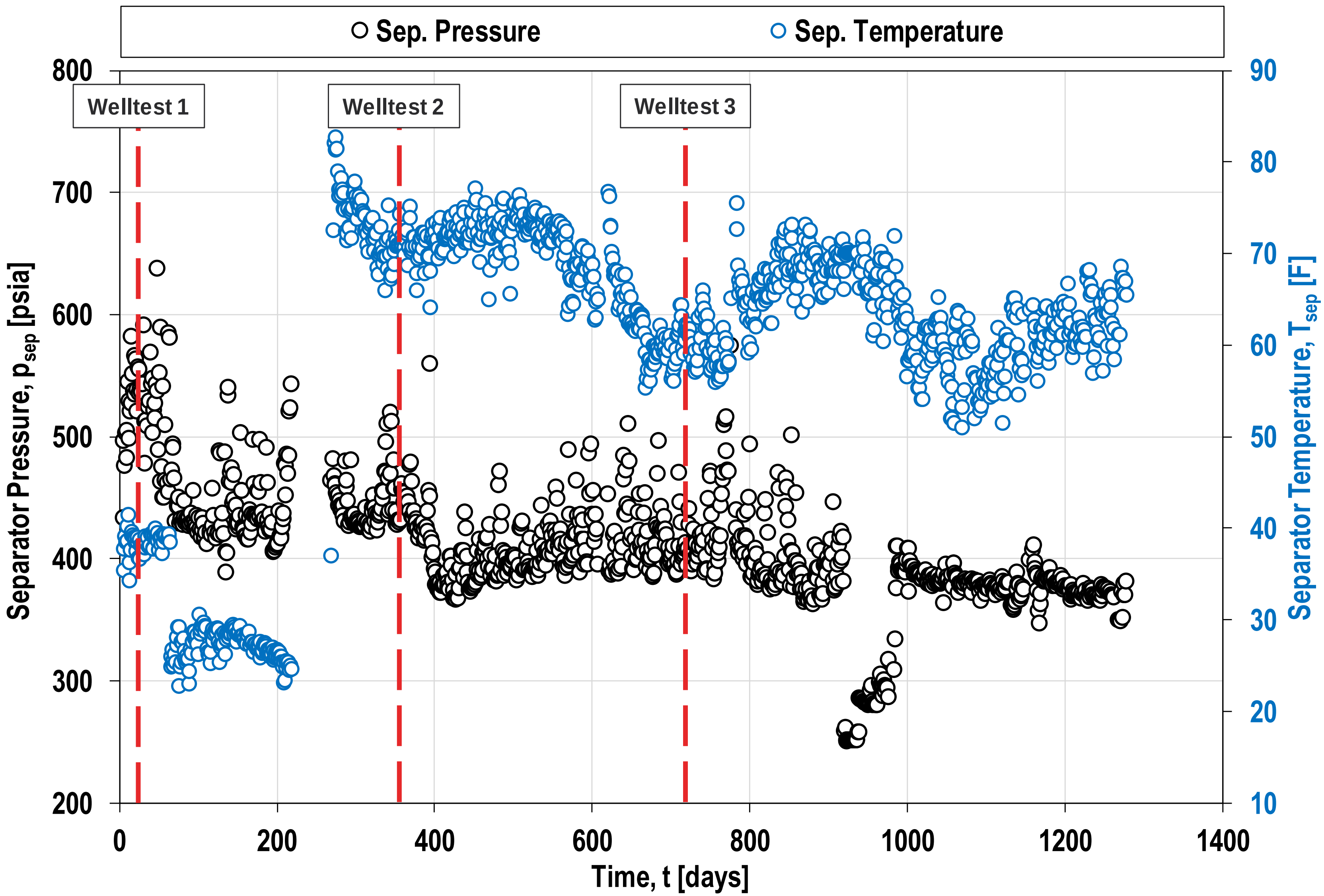
2. EOS model to estimate daily

… separator oil shrinkage factors

… separator oil flash factors

… Daily Separator Conditions



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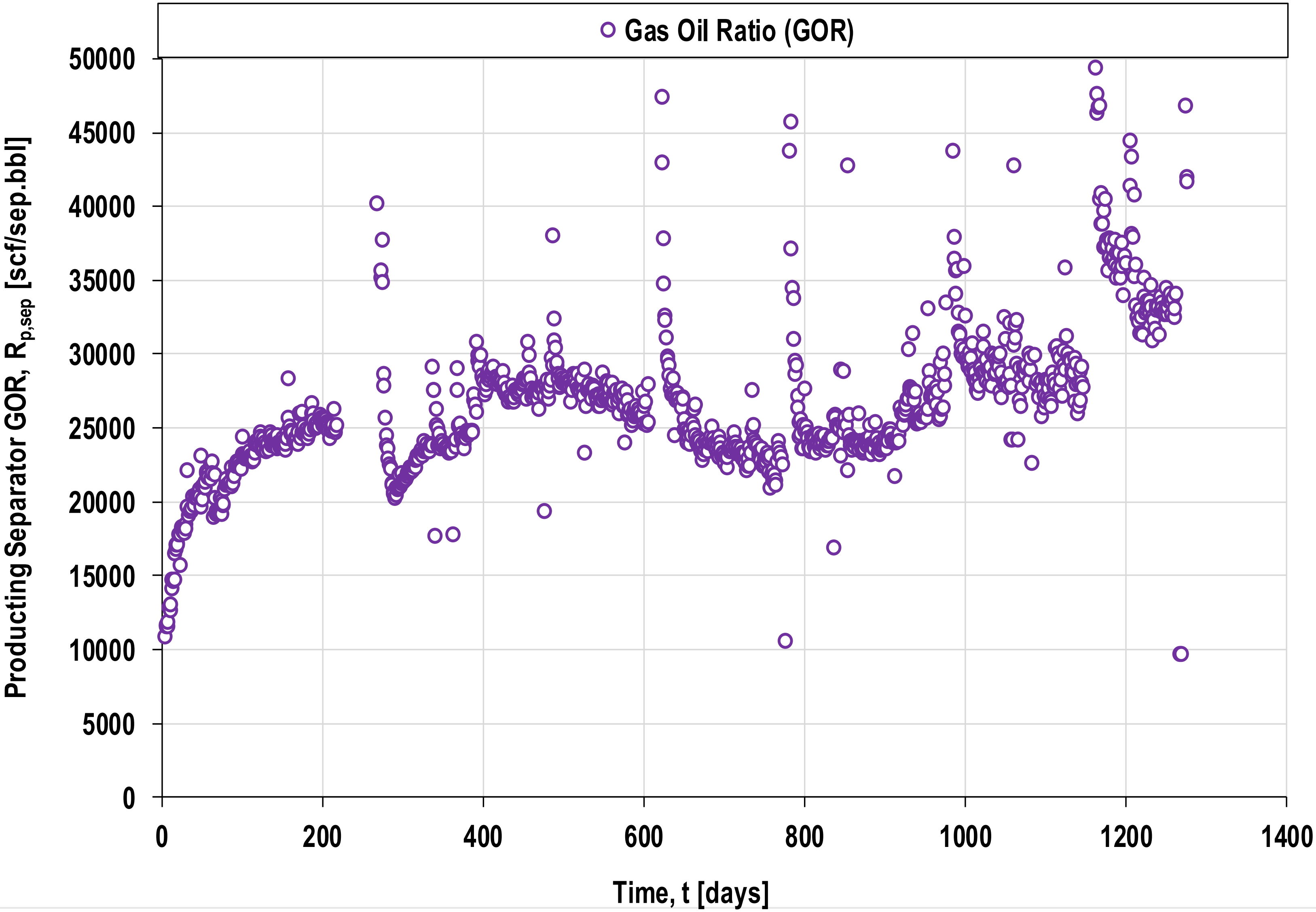
… plus Daily Separator Volumetric Rates …



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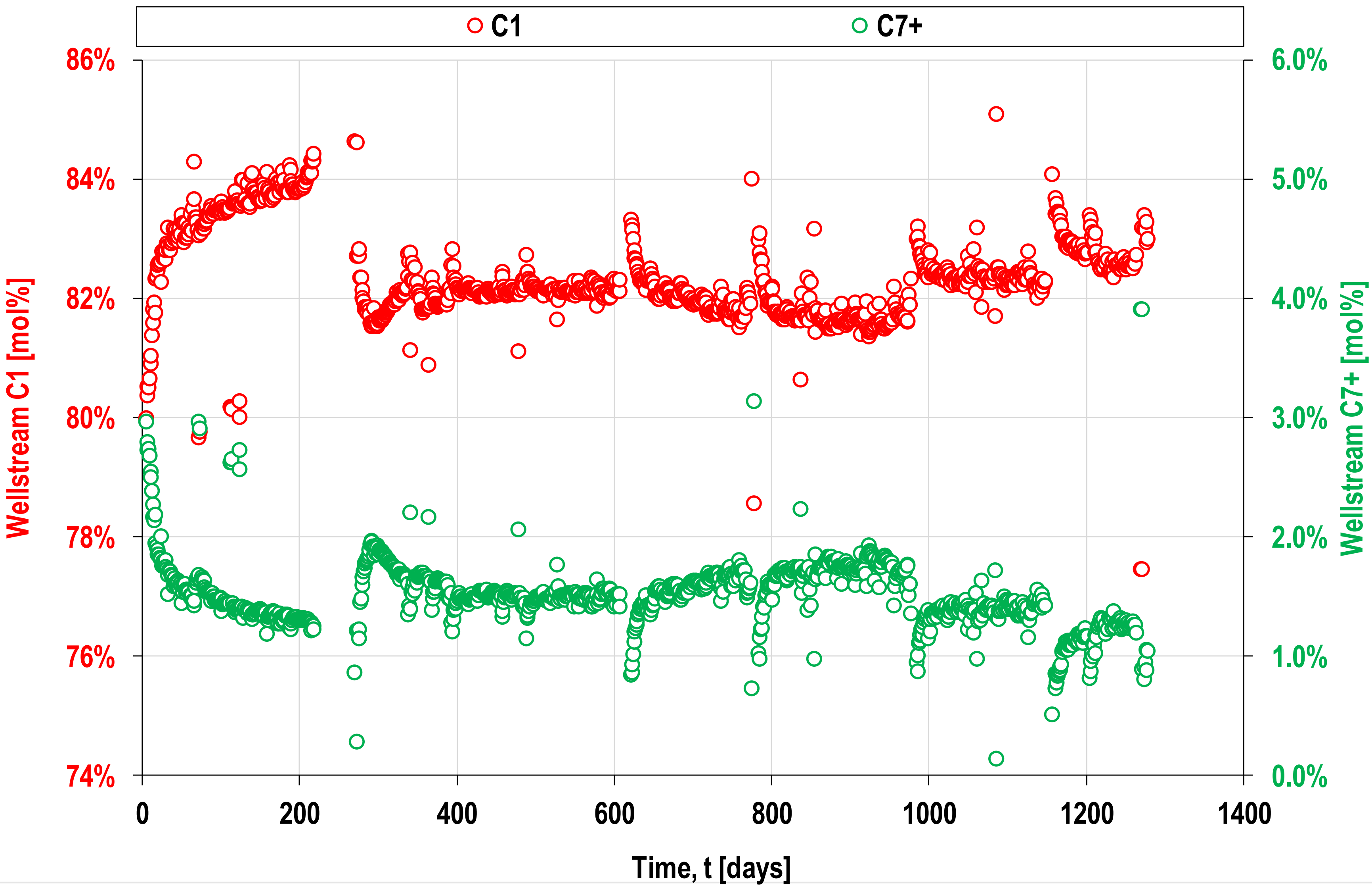
… used to Estimate Daily Wellstream Composition



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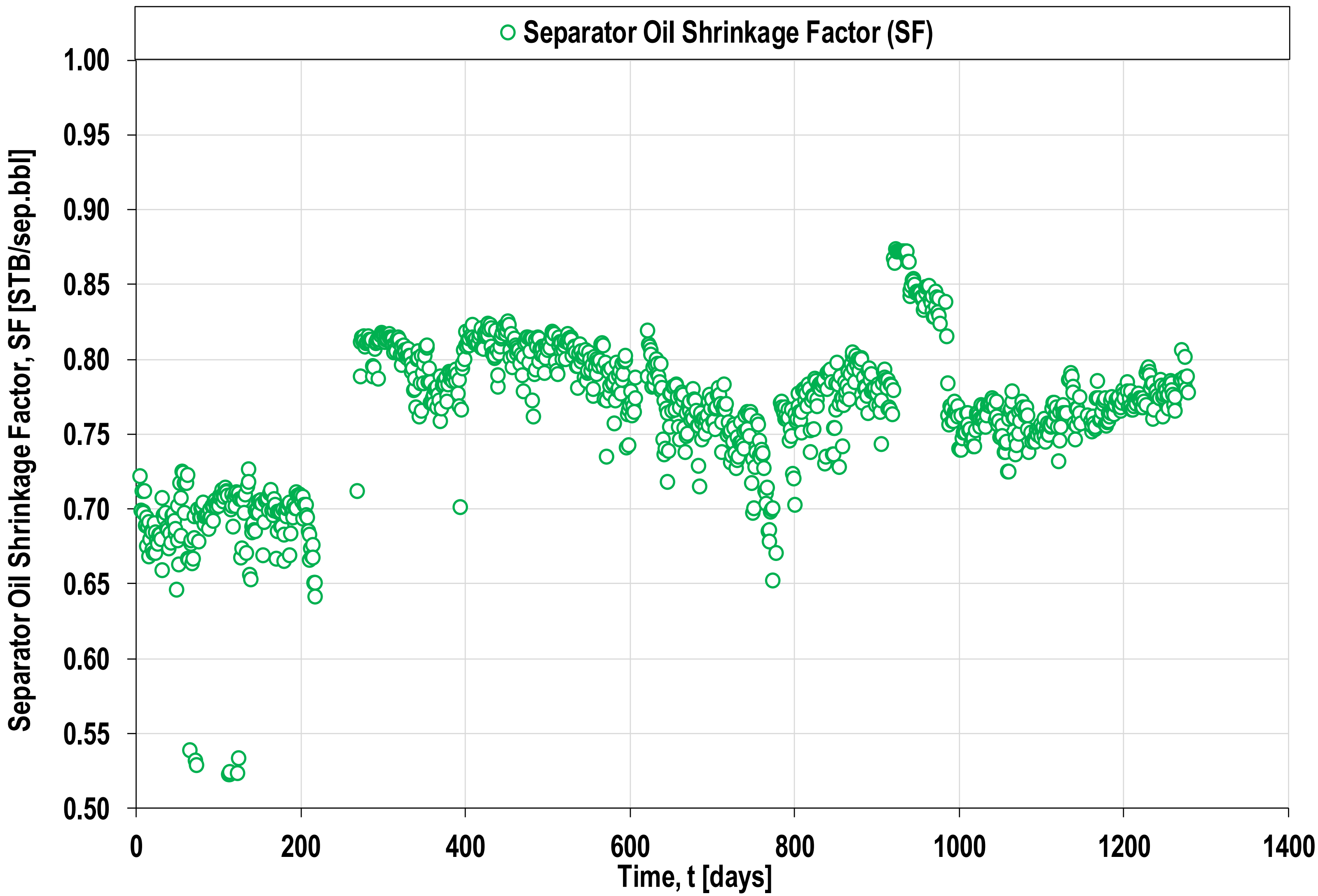
… that's used to Calculate Daily Shrinkage Factors



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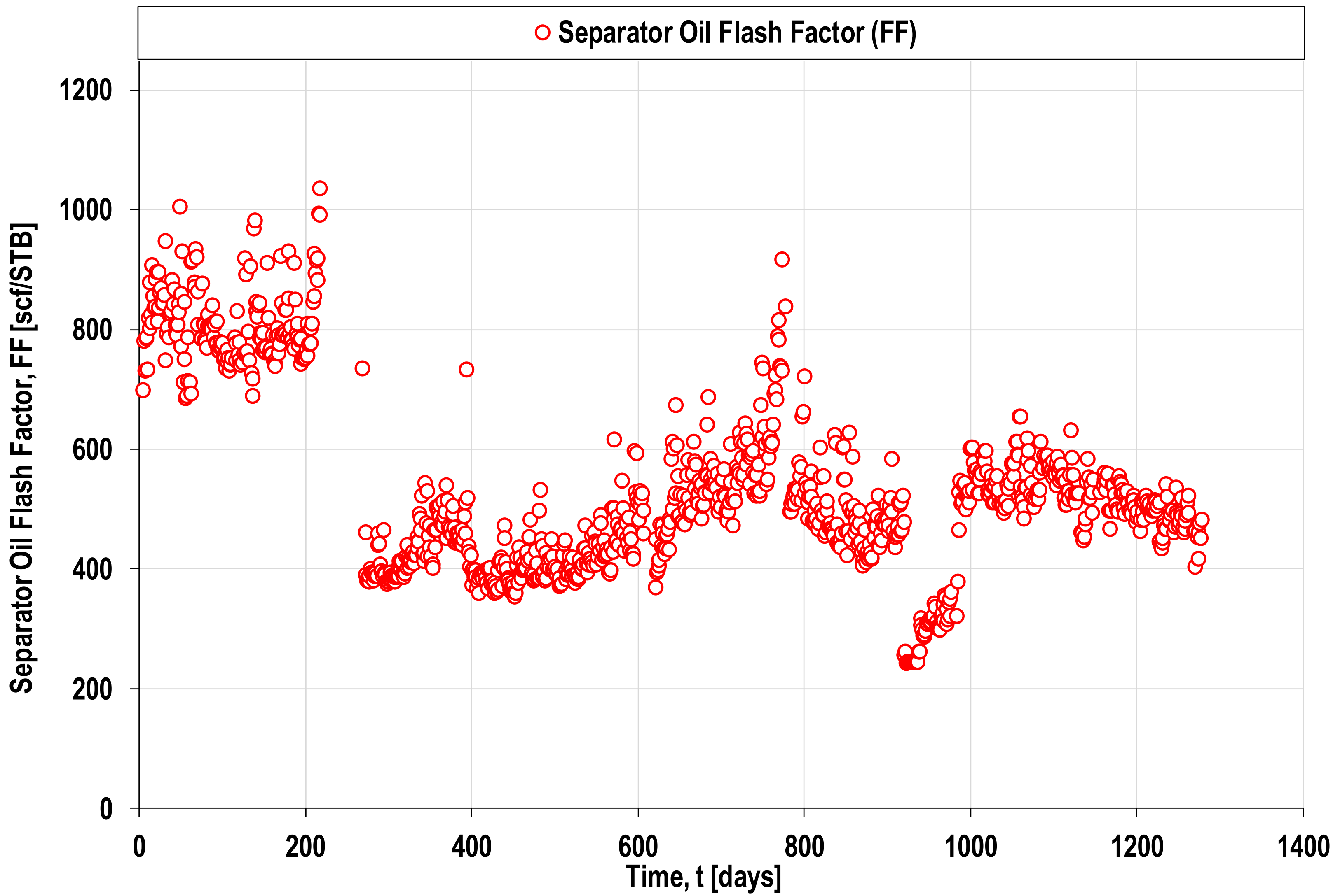
… and the Associated Daily Flash Factor



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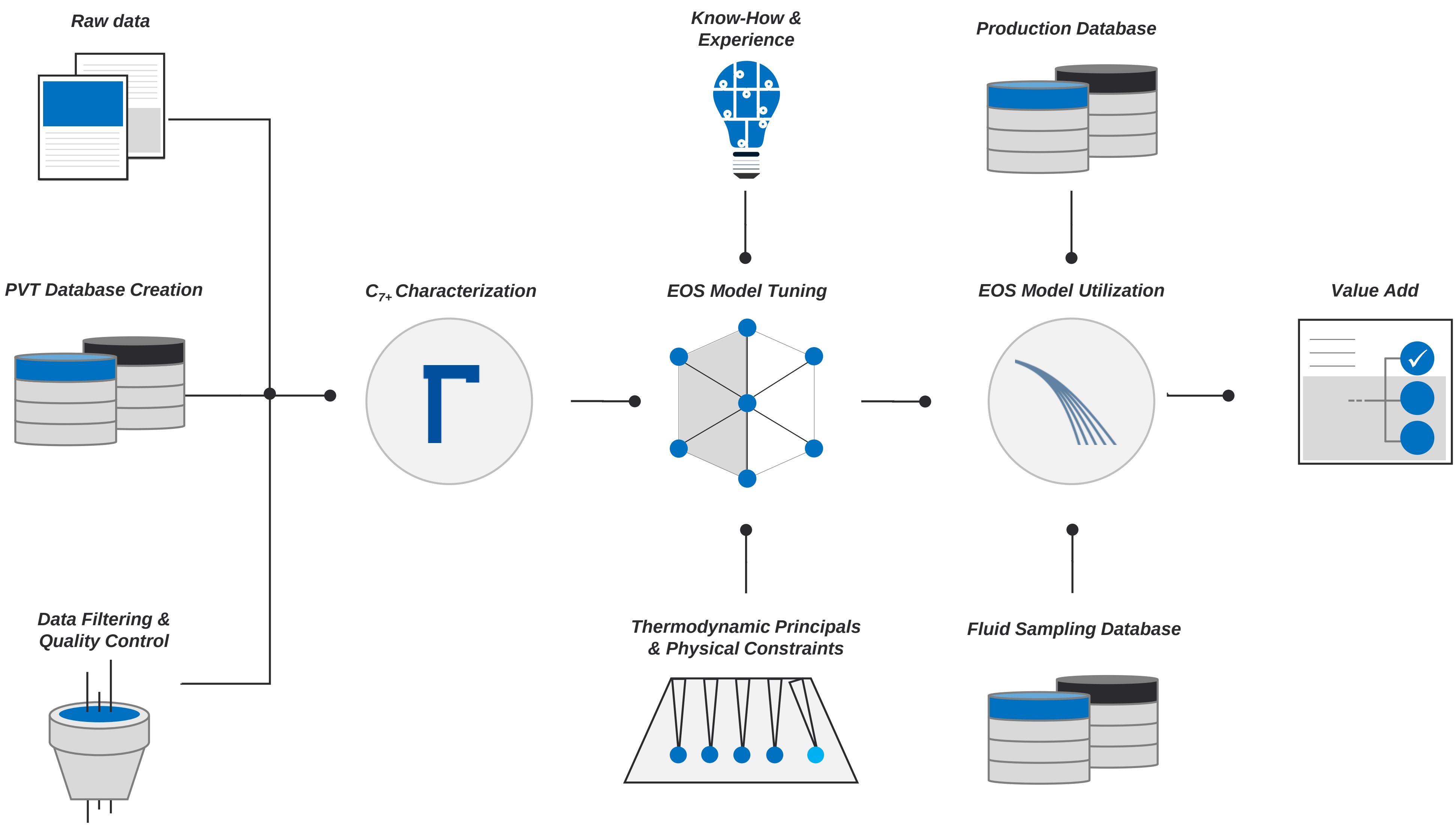
⚠ Advanced Topic

EOS Workflow

EOS Workflow



Heptanes Plus (C_{7+}) Characterization

Carbon Number	Formula	Number of Isomers
C_1	CH_4	1
C_2	C_2H_6	1
C_3	C_3H_8	1
C_4	C_4H_{10}	2
C_5	C_5H_{12}	3
C_6	C_6H_{14}	5
C_7	C_7H_{16}	9
C_8	C_8H_{18}	18
C_9	C_9H_{20}	35
C_{10}	$C_{10}H_{22}$	75
C_{11}	$C_{11}H_{24}$	159
C_{12}	$C_{12}H_{26}$	355
C_{13}	$C_{13}H_{28}$	802
C_{14}	$C_{14}H_{30}$	1858

More Complex & Unknown

It is impossible with chemical separation techniques to identify the C_{7+} components individually

Even if they were identified, it would not be possible to measure the critical properties and other EOS parameters for fluids heavier than C_{20}

This problem is solved practically by making approximate characterization of the heavier compounds with experimental and mathematical methods

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Heptanes Plus (C_{7+}) Characterization

Carbon Number	Formula	Number of Isomers
C_1	CH_4	1
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C_3	C_3H_8	1
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C_5	C_5H_{12}	3
C_6	C_6H_{14}	5
C_7	C_7H_{16}	9
C_8	C_8H_{18}	18
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C_{13}	$C_{13}H_{28}$	802
C_{14}	$C_{14}H_{30}$	1858

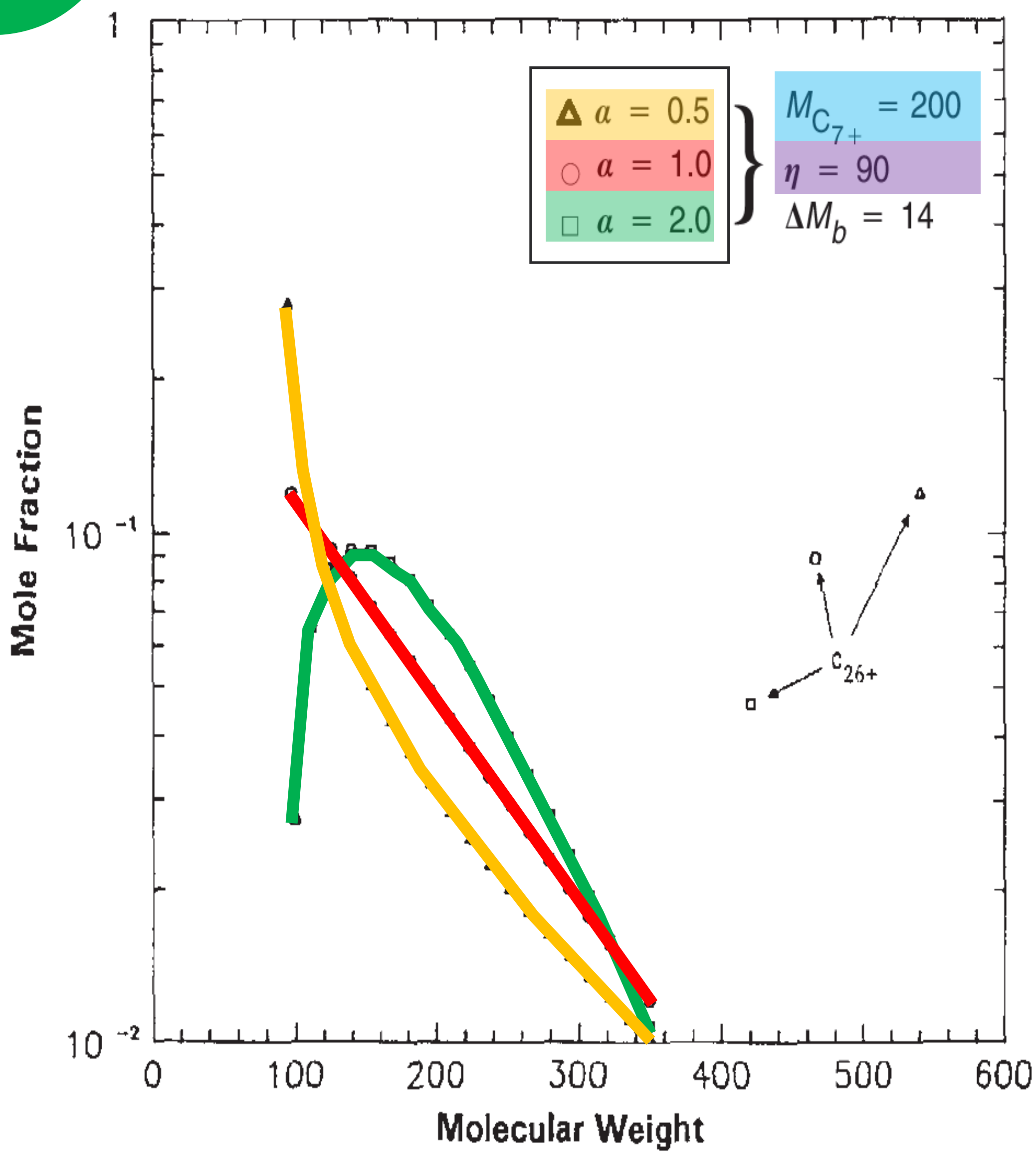
More Complex & Unknown

The approximate procedure can be split into three main tasks:

1. Dividing the C_{7+} into a number of fractions with known molar compositions
2. Defining the molecular weight, specific gravity, and boiling point of each fraction
3. Estimating the critical properties (Tc, Pc), acentric factor, volume shift, and the BIP's for each of the fractions

1

Modeling of C_{7+} - Gamma Model



Need 3 parameters for gamma model:

Average Molecular Weight – MW-C7+

Bound – η

Shape – α

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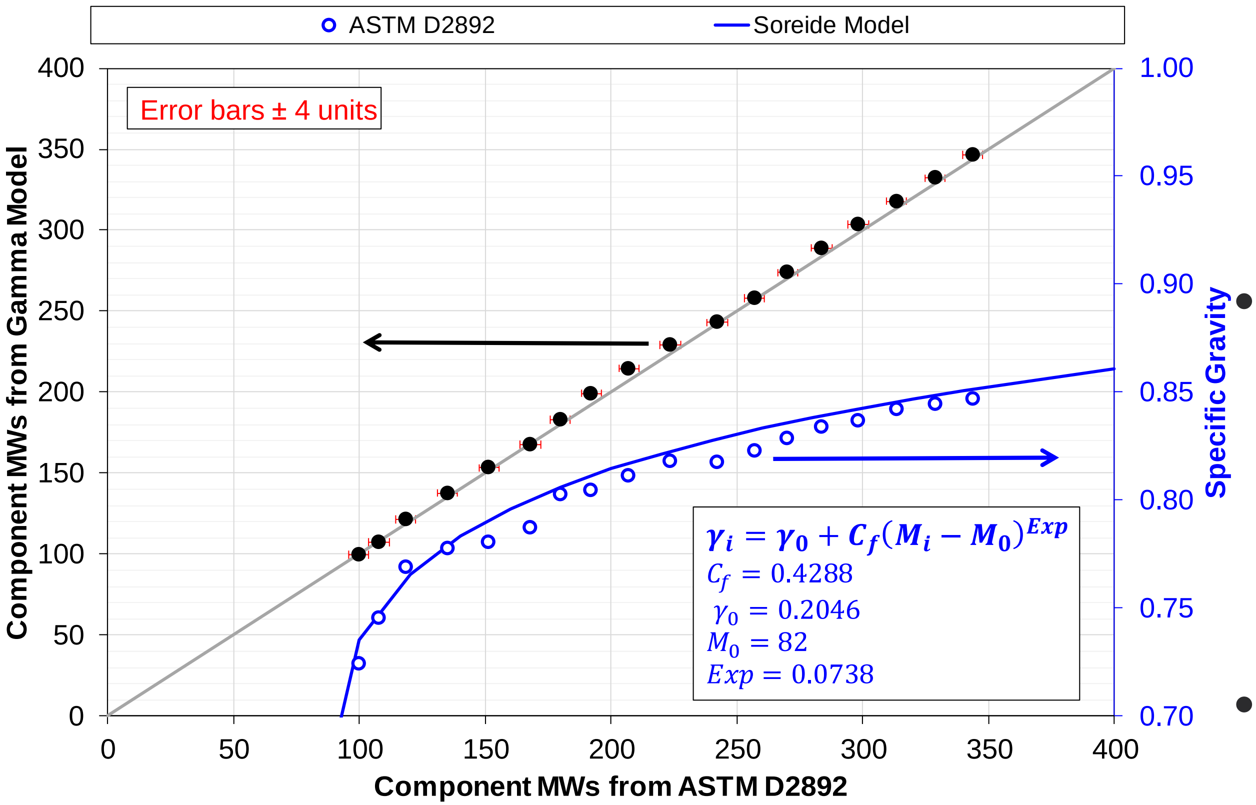
M-γ Relationship



- Tuned gamma model should give M_i close to measured (ASTM) data
- Tuned M-γ relationship will then give γ_i close to measured (ASTM) data
- $s_i = f(\gamma_i)$ should give all surface oil densities within 1-2%

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3 Tc, pc, ω_i and BIPS

Average C_{n+} fractions properties can be estimated as follows:

- T_{ci}, p_{ci} are function of T_{bi} and γ_i – Twu correlation
- Volume shifts, $s_i = f(\gamma_i)$ – Calc. from EOS to match given SG
- $\omega_i = f(T_{ci}, p_{ci}, T_{bi})$ – Edmister correlation
- BIPS - k_{ij} estimated from Chueh correlation using v_{ci} and v_{cj}
    - $v_{ci} = f(T_{bi}$ and $\gamma_i)$ – Twu correlation

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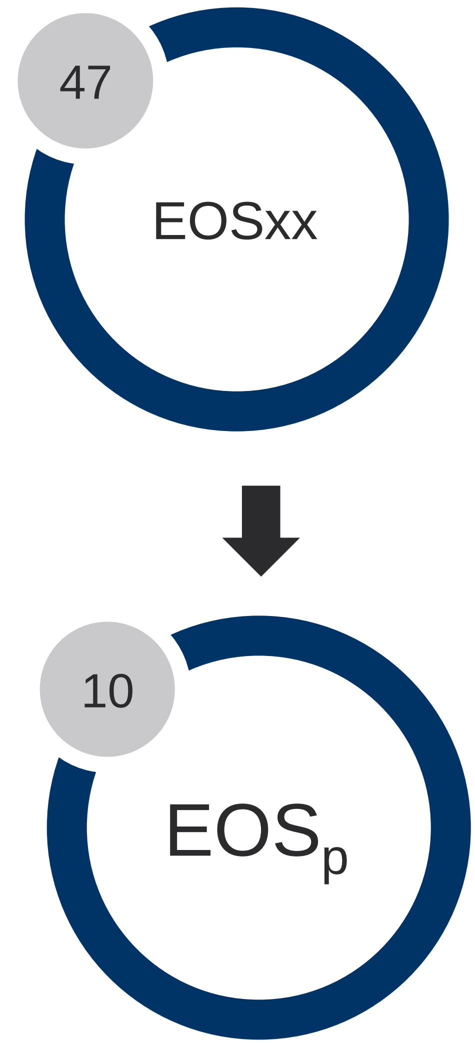
Pseudoization / Lumping

Lumping/pseudoization is the process of going from a detailed EOS to an EOS with less resolution that still accurately predict the PVT properties of ***relevant*** fluids



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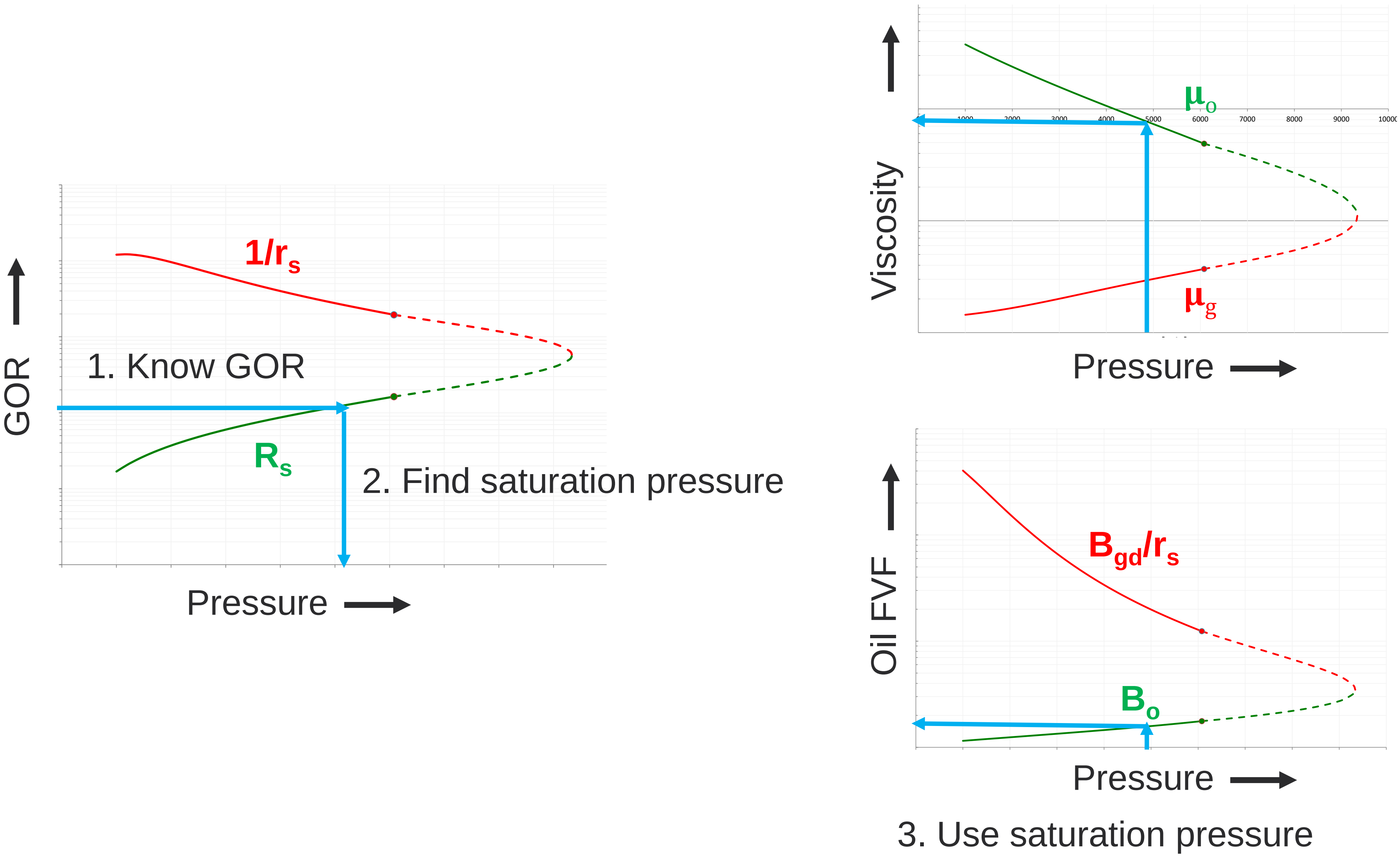
⚠ Advanced Topic

Extrapolated BOTs

Why p-x | p-GOR(R_s|$1/r_s$)?



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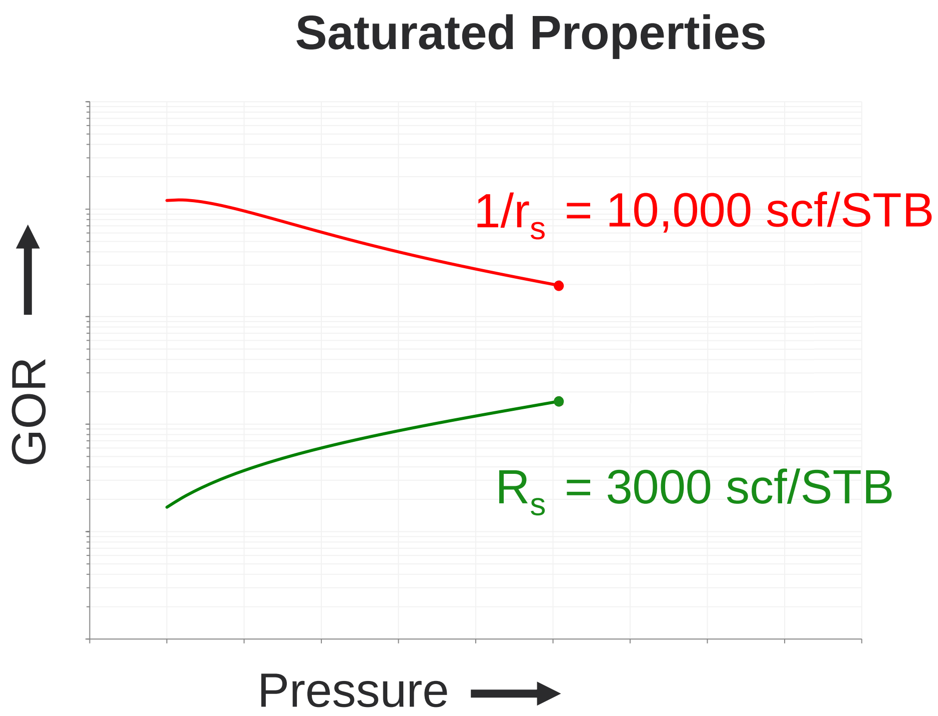
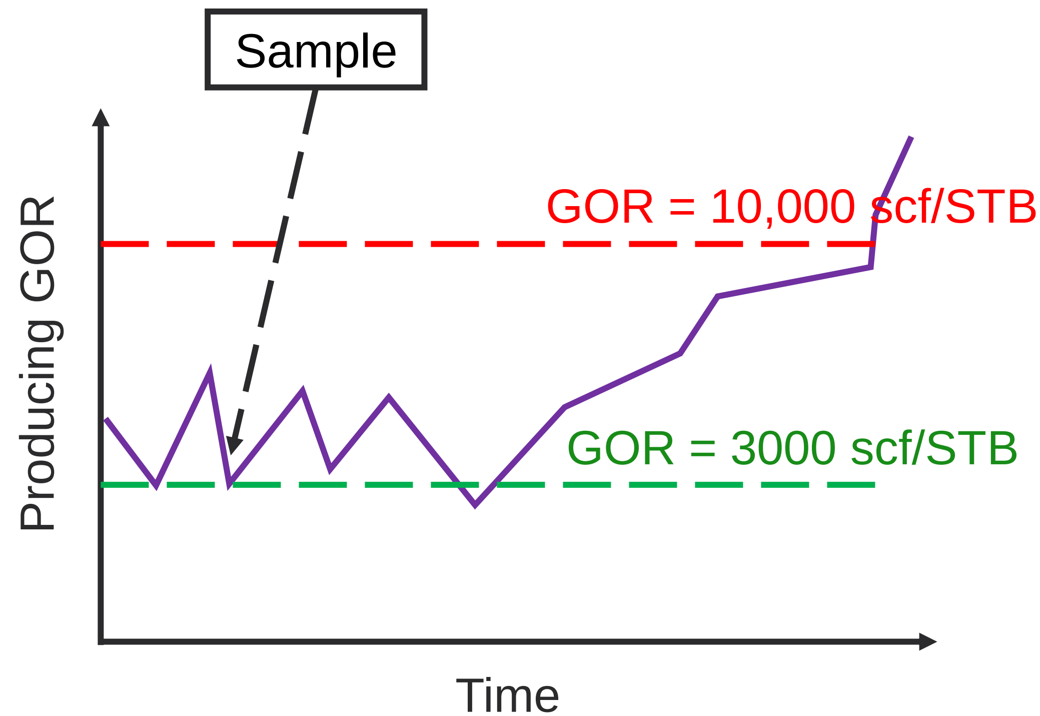
Why Extrapolate the Black Oil Table?

Example 1: GOR as history matching parameter





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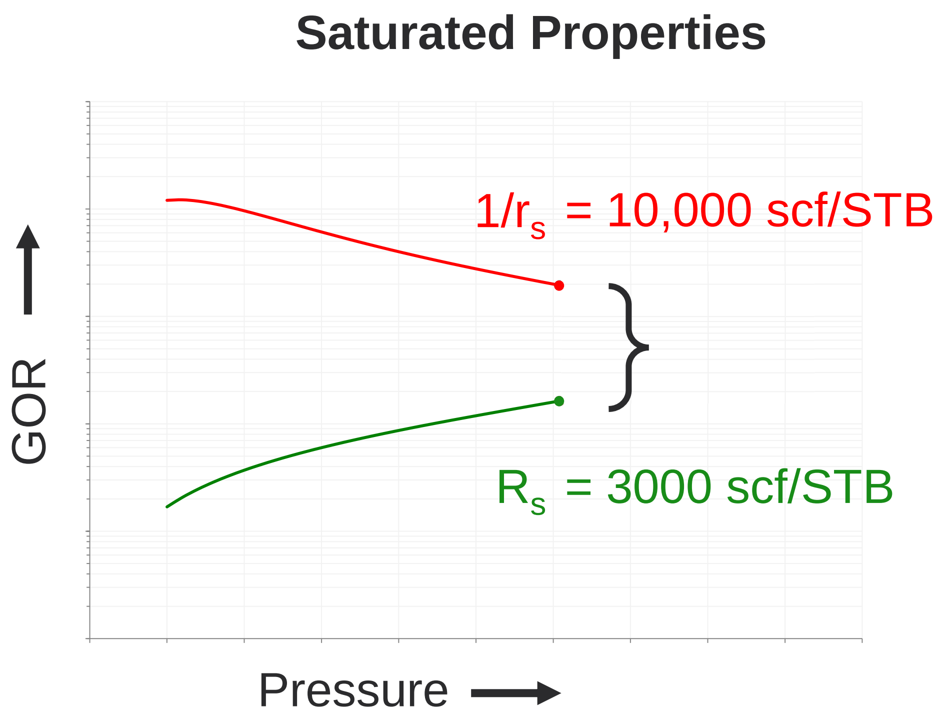
Why Extrapolate the Black Oil Table?

Example 1: GOR as history matching parameter

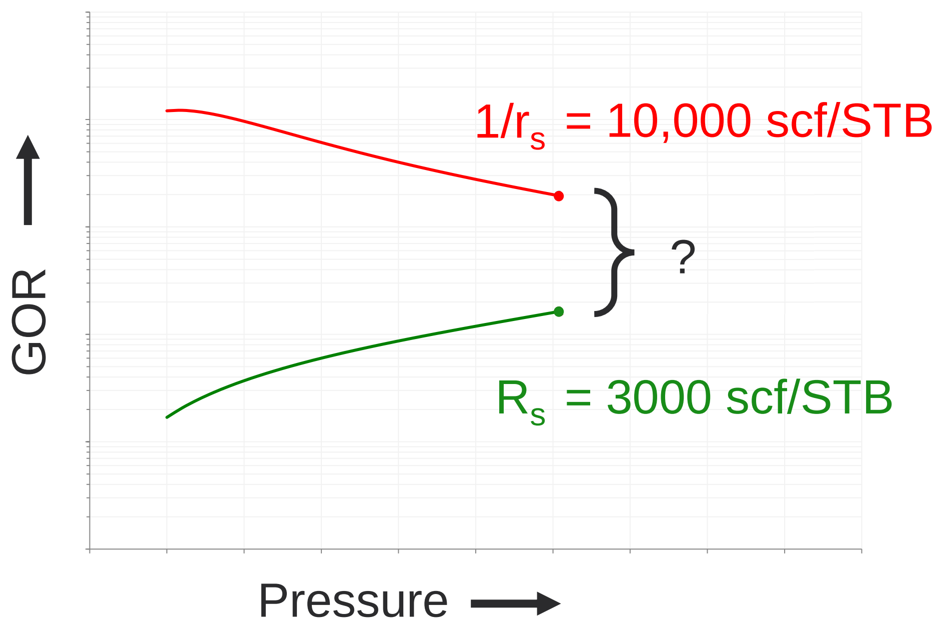


What if we want to initialize with a R_s of 4000 scf/STB? No data in this case …

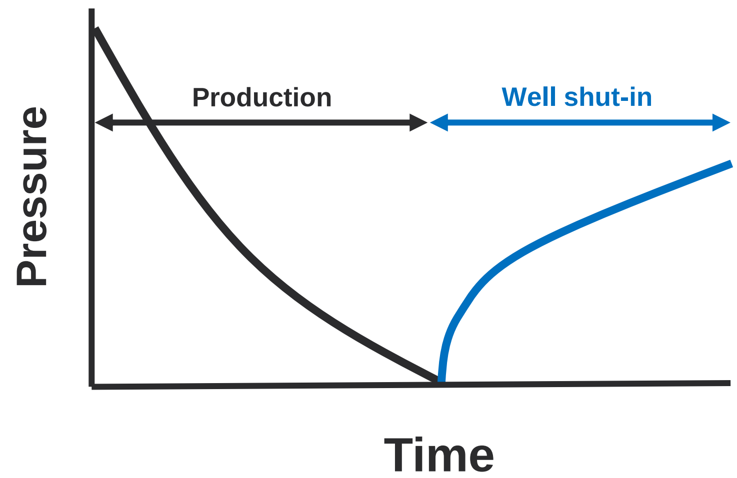
Why Extrapolate the Black Oil Table?

Example 2: Multi-phase RTA & Simulation will almost always require saturated properties for all GORs

Saturated Properties



Example



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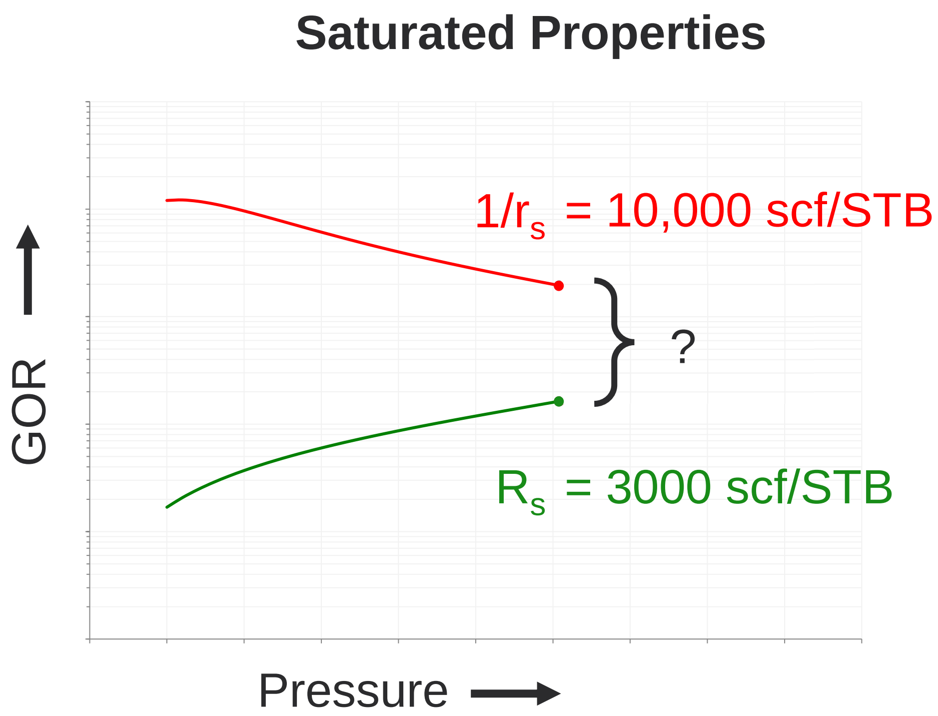
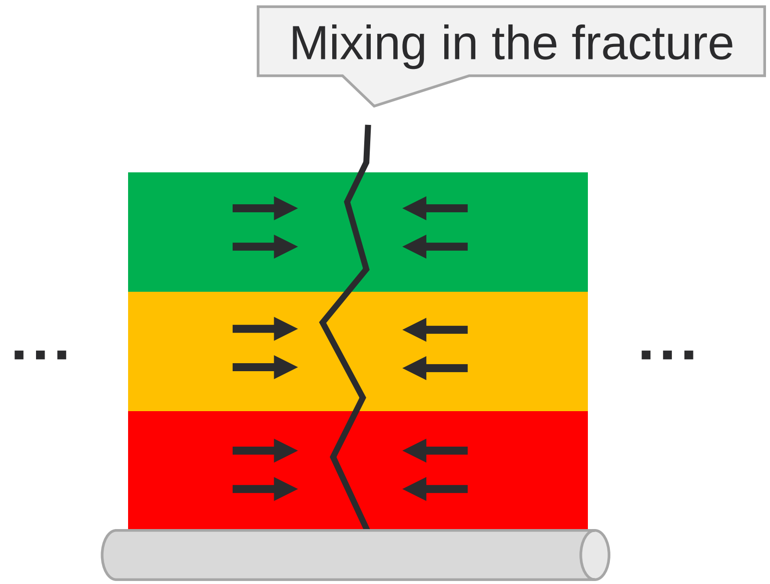
Why Extrapolate the Black Oil Table?

Example 3: Different Layers w/ Different Fluids





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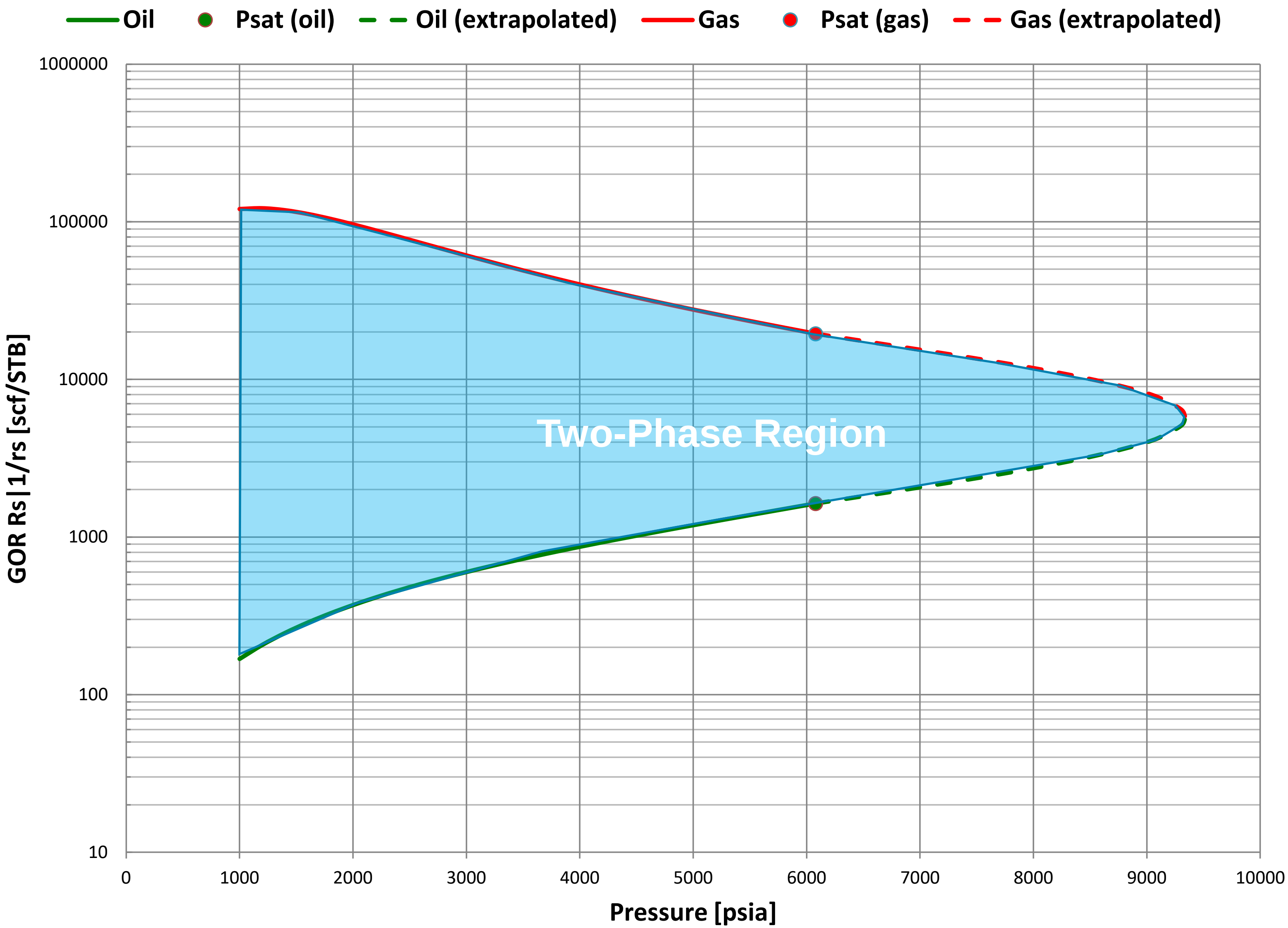
Example: Black Oil Table



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Example: Black Oil Table

For the following cases

i. GOR = 1,504 scf/STB and grid cell pressure = 8500 psia

ii. GOR = 15,024 scf/STB and grid cell pressure = 8500 psia

iii. GOR = 10,000 scf/STB and grid cell pressure = 5000 psia

Use the plot *“GOR vs. pres”* and determine what type of fluid associated with each of the cases above.

- Two-Phase Saturated | Single-Phase Oil | Single-Phase Gas

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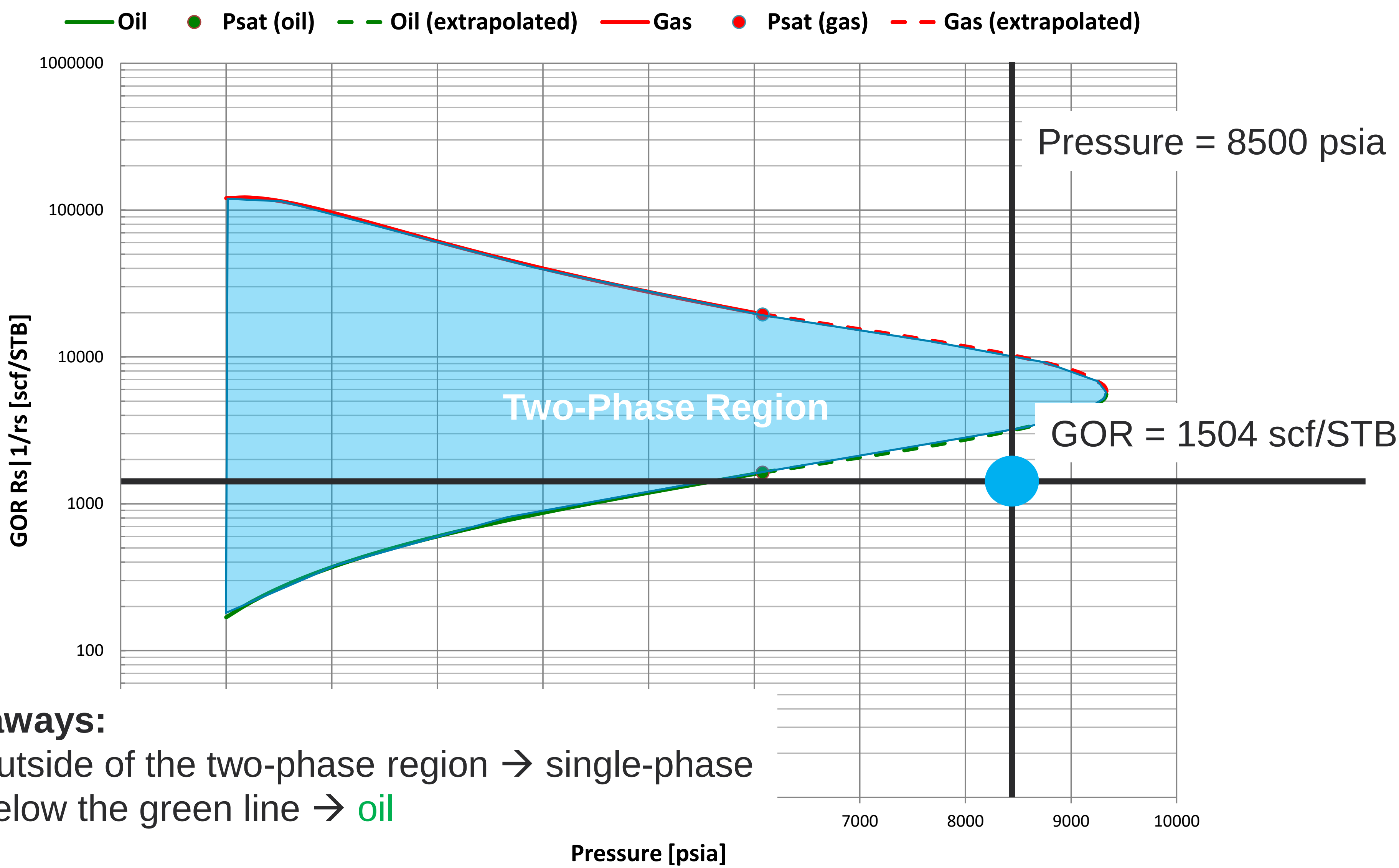
Fluid Type Case i

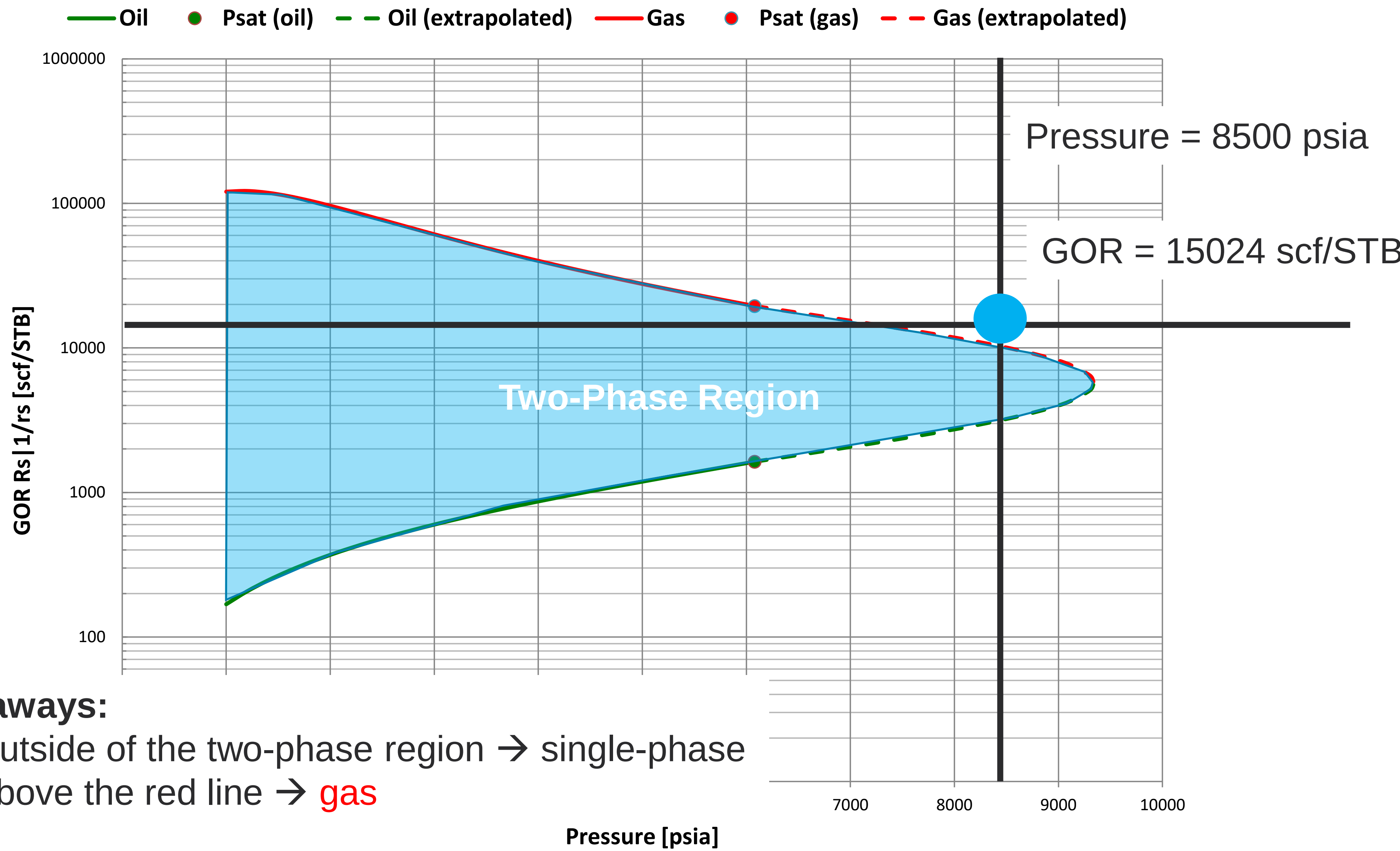


Takeaways:

i) Outside of the two-phase region → single-phase

ii) Below the green line → oil

Fluid Type Case ii



Takeaways:

i) Outside of the two-phase region → single-phase

ii) Above the red line → gas

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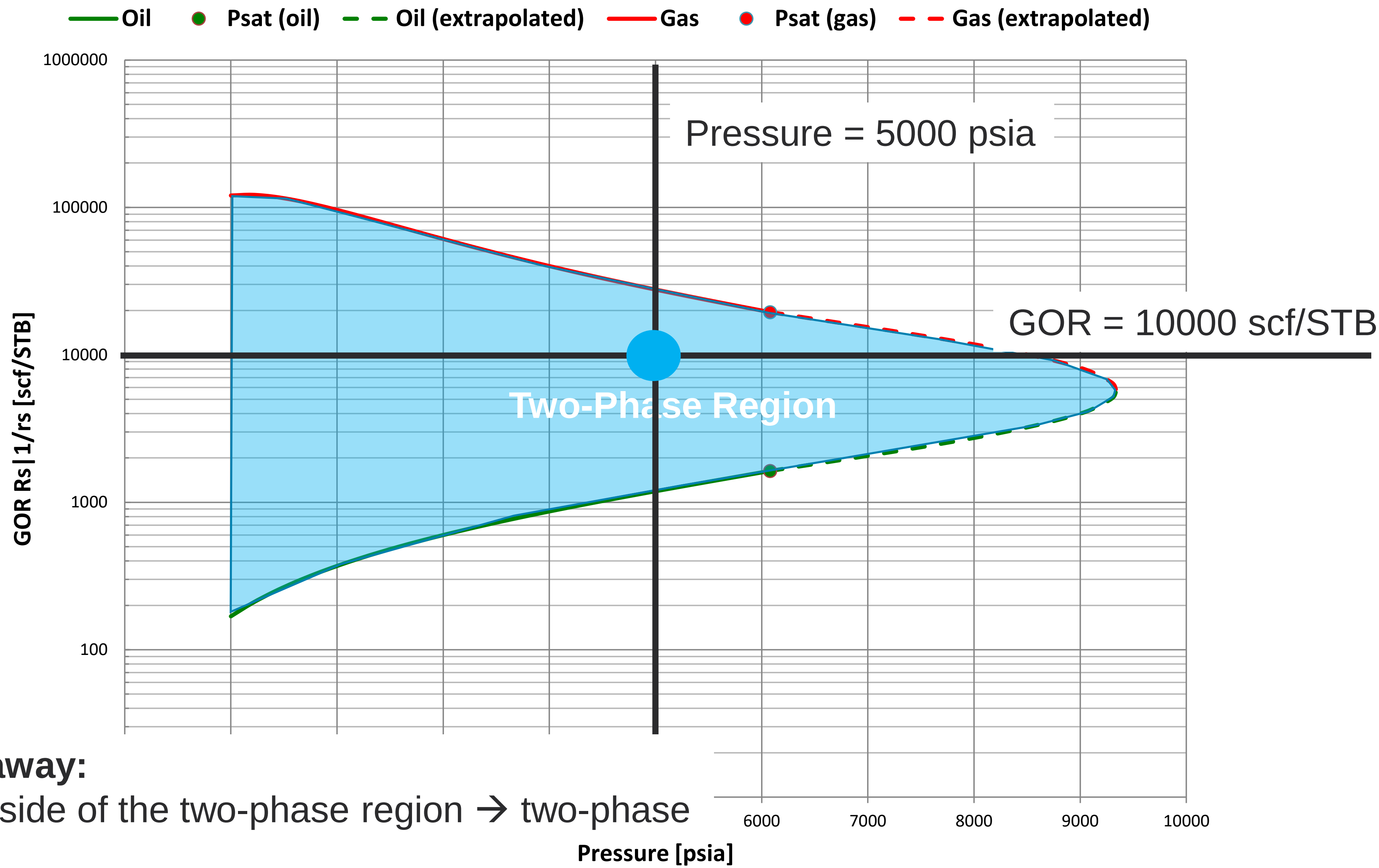
Fluid Type Case iii



Takeaway:

i) Inside of the two-phase region → two-phase

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Advanced Topic

Compositional Tracking

Use Readily Available Data + EOS!

Seed Compositions

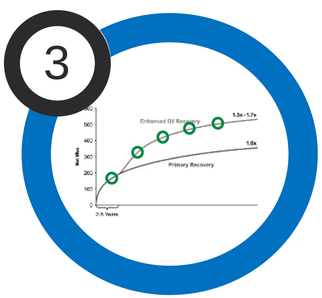
1

Welltest Database

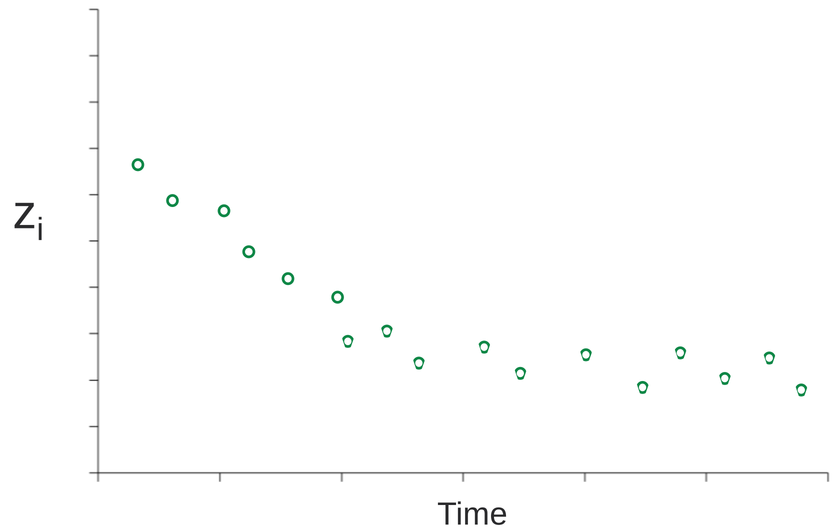
2

Production Database

3



Daily Wellstream (z_i) Compositions



*IPTC-19596 summarize methodologies

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Estimate Wellstream Composition

Requirements:

- A properly tuned EOS Model
- Separator rates (GOR_{sep})
- Separator conditions (p_{sep},T_{sep})
- "Seed feed" – estimate of z_i

Estimate Wellstream Composition

Method:

- Flash "seed feed" to p_{sep} | T_{sep} → y_i, x_i
- Recombine y_i | x_i at GOR_{sep} → z_i

$$n_i = x_i\left(\frac{q_{om}}{v_o}\right) + y_i\left(\frac{q_{gm}}{v_g}\right)$$

v: molar volume – M/ρ (calculated from EOS model)

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Estimate Wellstream Composition

Method:

Regress until z_i + EOS matches

- Sep. gas. (yi) ≈ N_2, CO_2, C_1, …,C_6
- Sep. GOR ≈ C_{7+} amounts
- Liquid API ≈ C_{7+} component distribution

“Shale” PVT

“Shale” Characteristics … a PVT Perspective

1. Span a wide range of fluids (low to high GOR)
2. Initially slightly undersaturated / saturated*
3. Rapid decline in bottomhole pressure (p_{wf})
4. Producing GOR – $f(p_{wf})$

*with some exceptions (e.g. Bakken, Eagle Ford, Duvernay)

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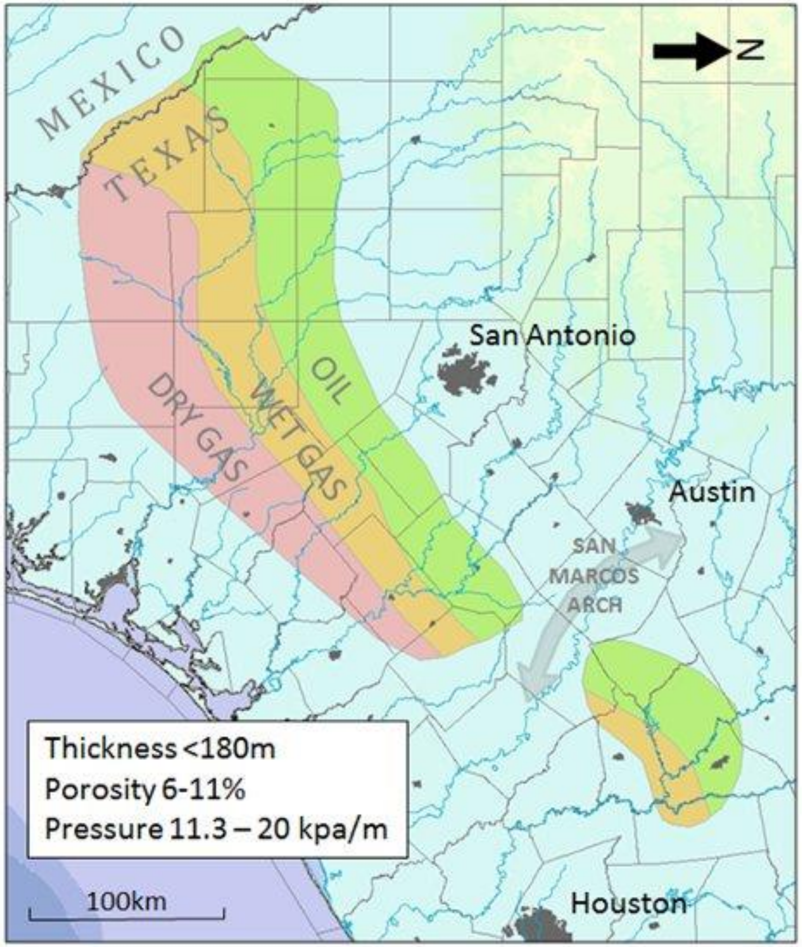
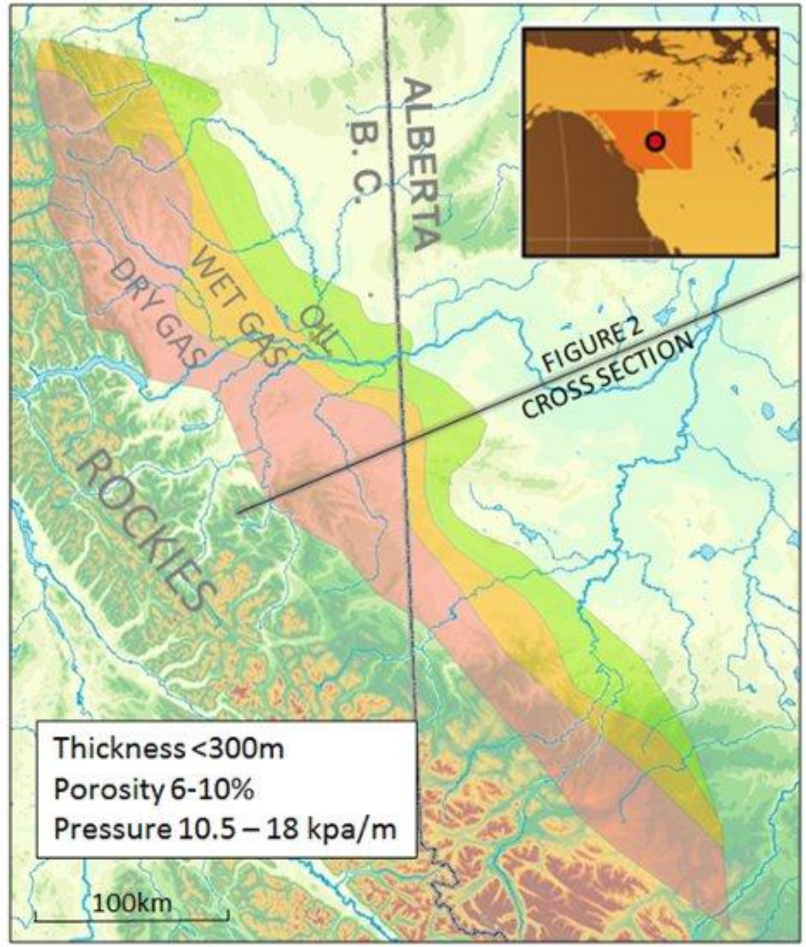
1 "Shale" Basins Span a Wide Range of Fluids

EAGLE FORD SHALE (rotated 90°)



MONTNEY SILTSTONE



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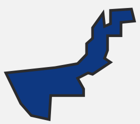
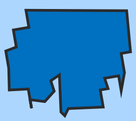
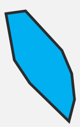
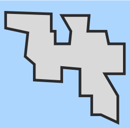
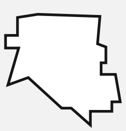
2

Slightly Undersaturated/Saturated

Basin		Initial Reservoir Pressure, p_{Ri} (psia)	Saturation Pressure Range, p_{sat} (psia)	
	**Eagle Ford**	4000 – 10000	2000 - 7000	✓
	**Bakken**	5000 – 9500	1500 – 3500	–
	**Montney**	3000 – 7000	2000 - 7000	✓
	**SCOOP/STACK**	3500 - 9500	2000 - 7000	✓
	**Permian**	3000-10000	1000 – 7000	✓

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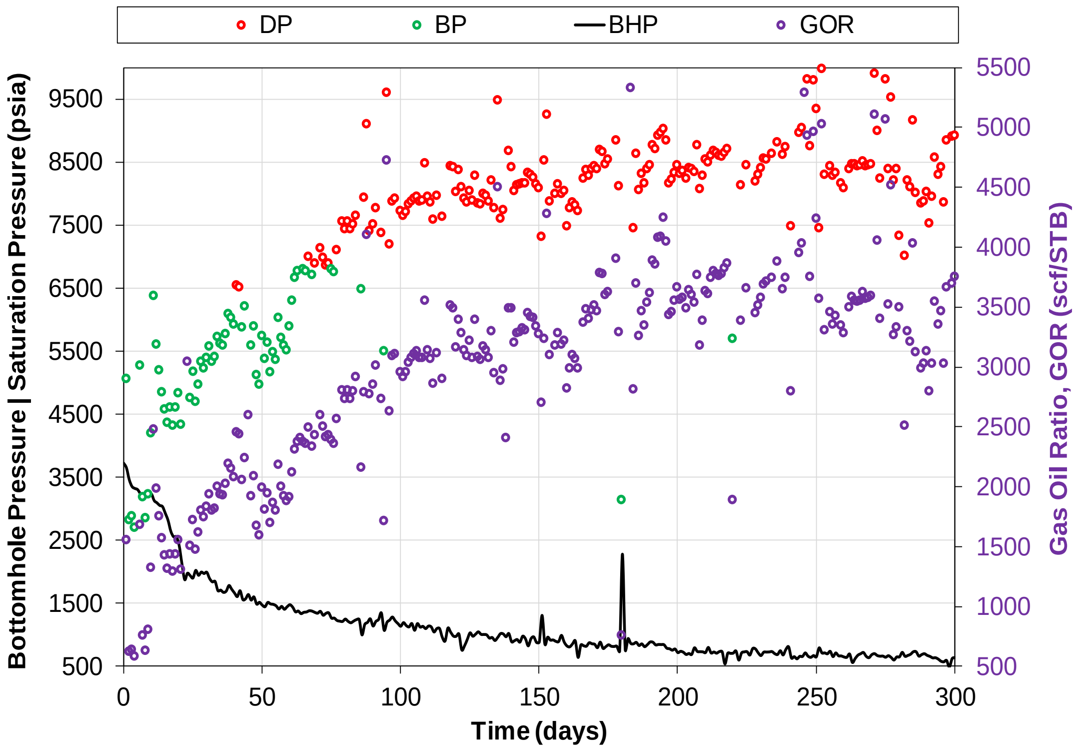
3 Rapid decline in bottomhole pressure (p_{wf})



Source: Fluid Sampling in Tight Unconventionals (Carlsen et al. 2019)

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"Unconventional" Well Performance

- Producing GOR strong function of
  - Initial GOR (composition)
  - Flowing bottomhole pressure – p_{wf}
  - Degree of undersaturation (p_{Ri}-p_{sat})
  - PVT model
  - Rel. perm
  - Infinite acting | boundary dominated periods

  → most unknown: GORi, rel. perm, IA/BD
- *"Conventional" reservoirs – GOR(p_{avg})*

Sources: Whitson and Sunjerga 2012; Jones 2017

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What does this Imply?

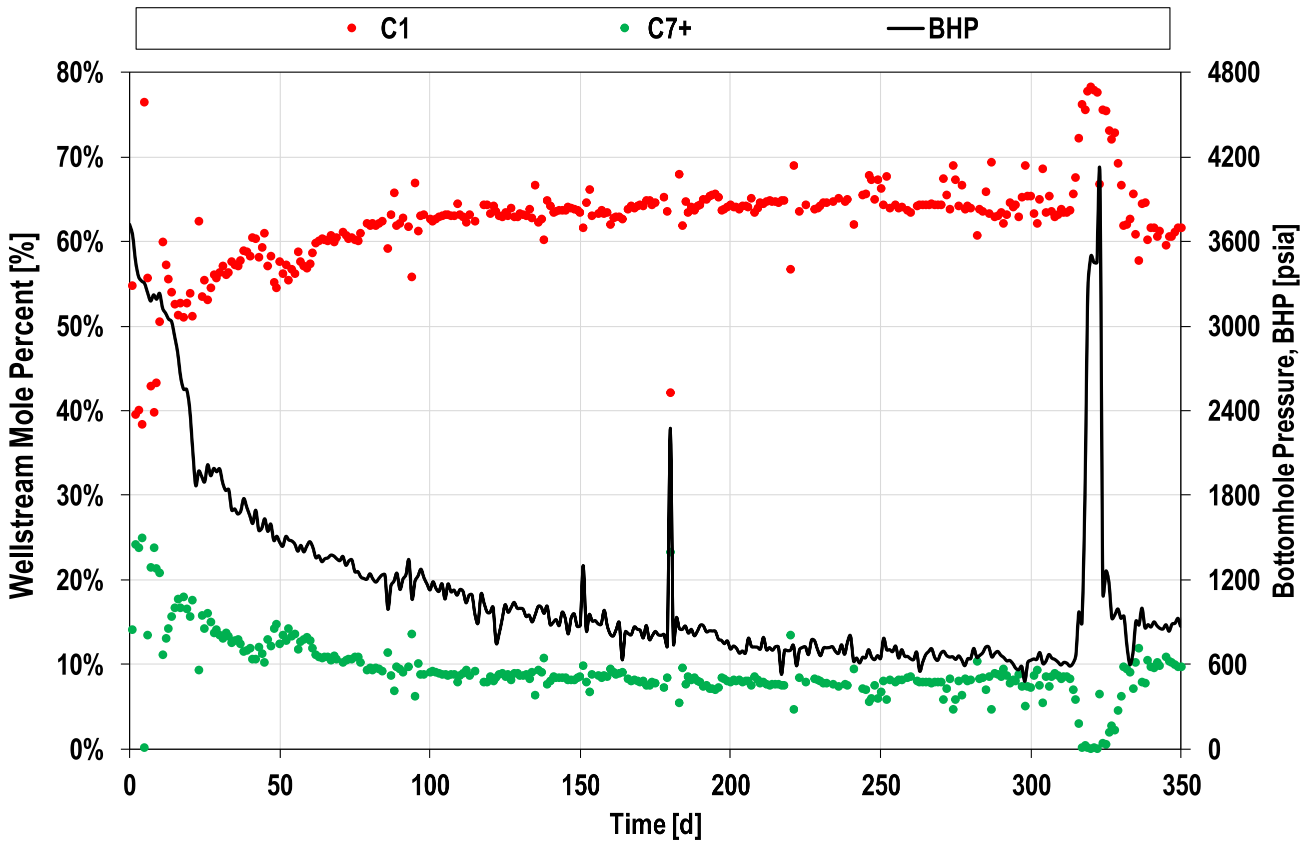
- Change in “produced fluid properties”

i.e. GOR | STO API

⬇

- Produced compositions are changing!

Produced Compositions are Changing Fast!



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Unconventional Fluids Systems

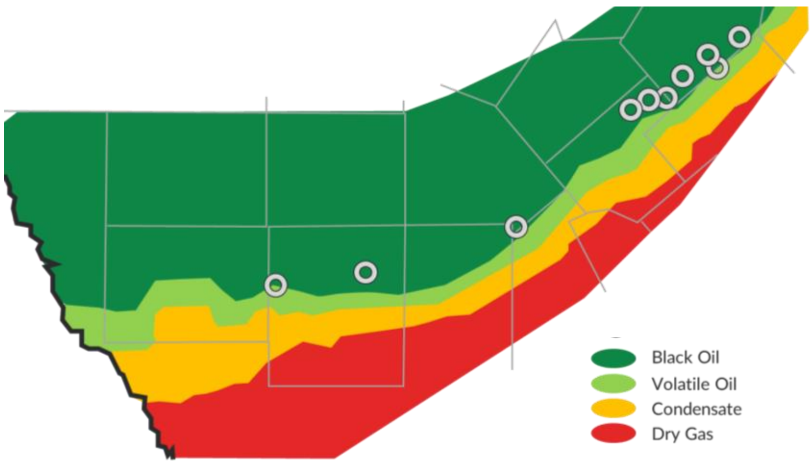

Exhibit strong field-wide fluid consistency

i.e. molecular weight – specific gravity relationship

PVT properties are highly “correlatable” across one field/basin

→ allows for the use of one unified fluid model (field-wide EOS)

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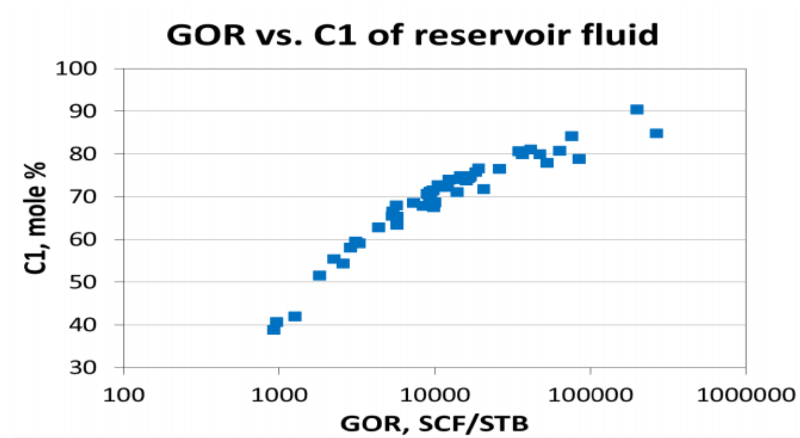
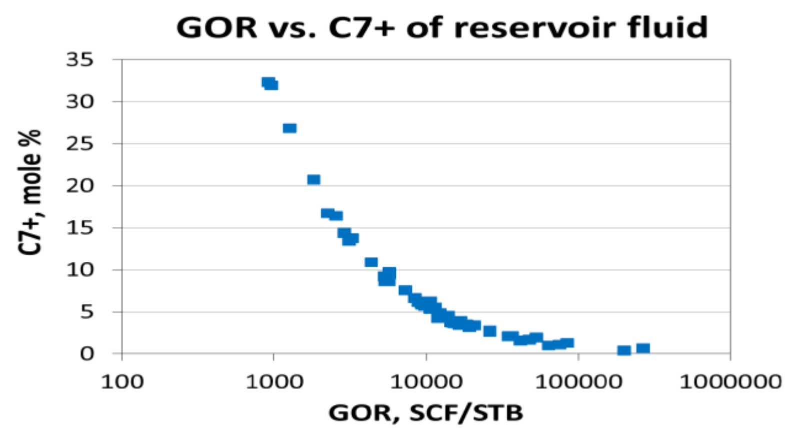
Unconventional Fluids Systems

"PVT correlations demonstrate strong field-wide consistency although the reservoir fluid (i.e. composition) varies significantly.

PVT properties can be estimated from one key parameter: GOR. This contrasts from reservoir fluid complexity in conventional reservoirs."



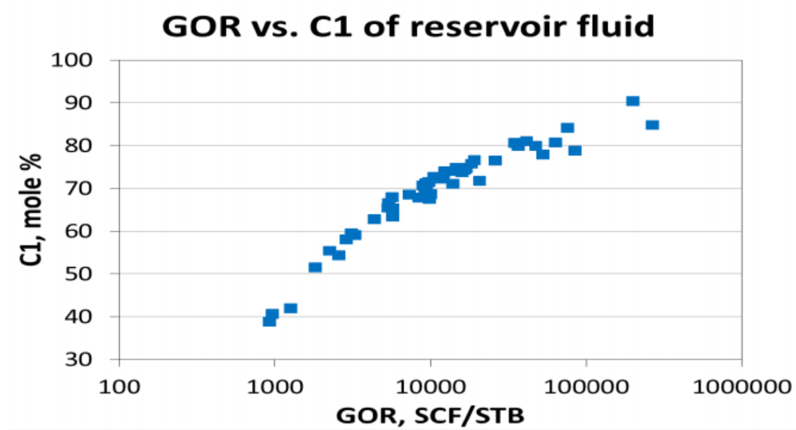


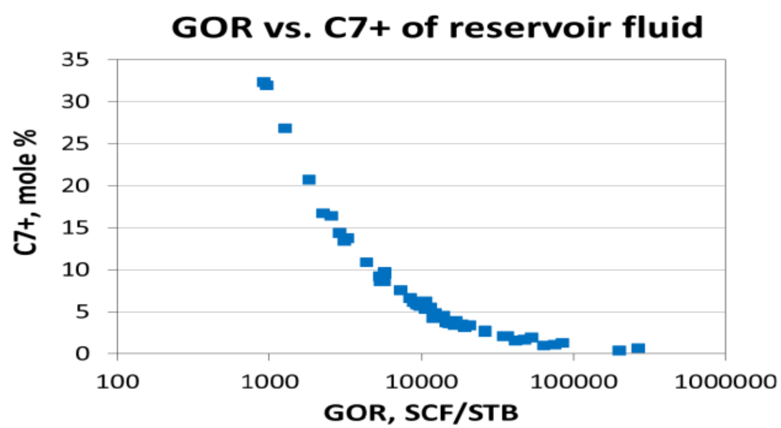
Tao Yang (Statoil | Equinor) PVT Specialist Lead
Whitson employee (1999-2005)

Unconventional Fluids Systems

"In conventional rocks, due to relatively high permeability, fluids migrate within the reservoir with a complex charging and mixing history…

The fluid mobility in shale reservoirs is much lower, reflecting the dramatically lower permeability."





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Whitson employee (1999-2005)

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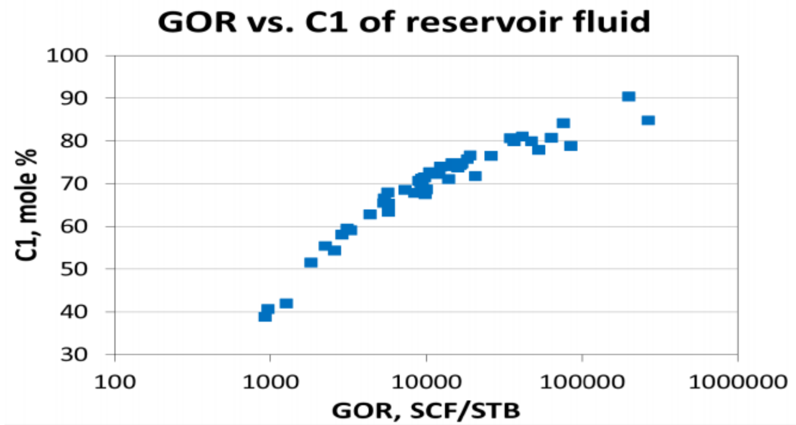
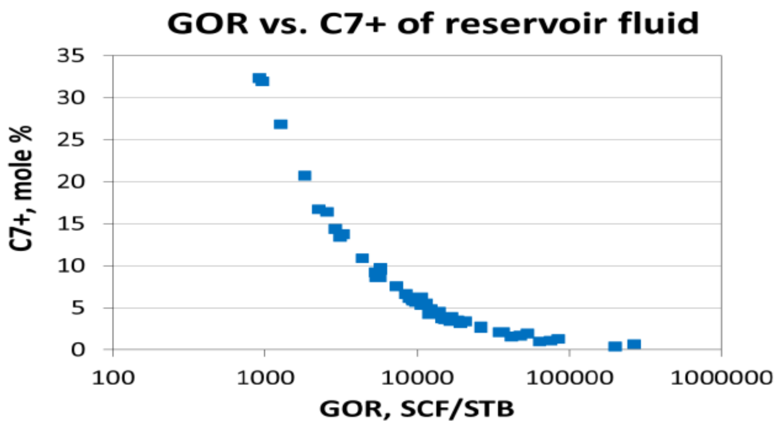
Unconventional Fluids Systems

“Fluid communication and migration is limited. Reservoir fluid differences are dominantly determined by thermal maturity, which is the main reason behind the consistent PVT correlations over large areas.”





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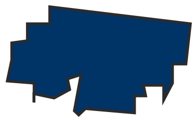
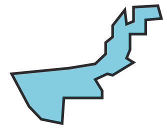
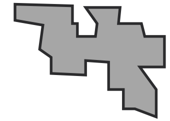
So … what's different between the basins?

"C_{7+} Characterization"

Basin A	Basin B	Basin C
		

$$(\bar{C}_{11})_A \neq (\bar{C}_{11})_B \neq (\bar{C}_{11})_C$$

$$(\bar{C}_{12})_A \neq (\bar{C}_{12})_B \neq (\bar{C}_{12})_C$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$(\bar{C}_{30p})_A \neq (\bar{C}_{30p})_B \neq (\bar{C}_{30p})_C$$

Can be radically different