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Gas Condensate PVT –
What's Really Important and Why?

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Goals

Give a review of the key PVT data dictating *recovery* and *well performance* of gas condensate resevoirs.

Understanding the importance of specific PVT data in the context of their importance to specific *mechanisms of recovery and flow behavior*.

Introduction

- **Gas condensate engineering =**
  Gas engineering + extra "magic"

- **Which PVT properties are important …**
  and why?

- **Engineering tasks**

Topics of Discussion

- PVT Experiments
- Initial Fluids in Place and Depletion Recoveries
- Condensate Blockage
- Gas Cycling Condensate Recoveries
- EOS Modeling

- Concluding Remarks

Three Examples

- **Example 1**. A small offshore "satellite" reservoir with high permeability (kh=4,000 md-m), initially undersaturated by 400 bar, and with a test yield of 300 STB/MMscf.

- **Example** 2. A large offshore deep-water reservoir with moderate permeability (kh=1000 md-m), initially saturated or near-saturated (?), large structural relief, and a test yield of 80 STB/MMscf. A single (and very expensive) discovery well has been drilled.

- **Example 3**. An onshore "old" undeveloped gas cap with well-defined initial volume (by production oil wells and pressure history), uncertain initial composition (estimated initial yield of 120 STB/MMscf), partially depleted due to long-term production of underlying oil, and low permeability (kh=300 md-m).

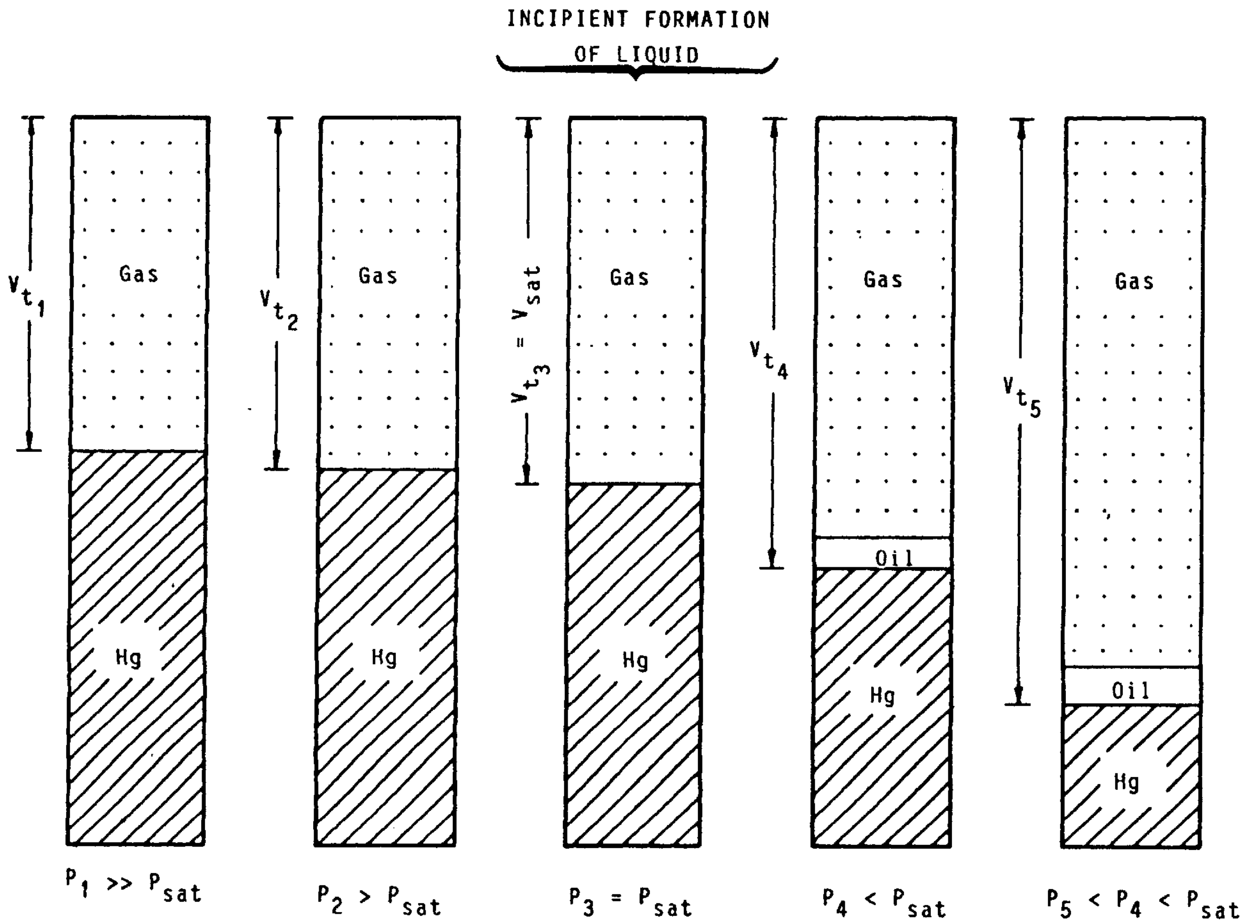
PVT Priority Lists
Vary for Each Reservoir

Different fields require different degrees of accuracy for different PVT properties -- depending on:

- **field development strategy**
  (depletion vs. gas cycling)
- **low or high permeability**
- **saturated or highly undersaturated**
- **geography *(offshore vs. onshore)***
- **number of wells available for delineation and development**

PVT Experiments

Constant Composition (Mass) Expansion Test



Data

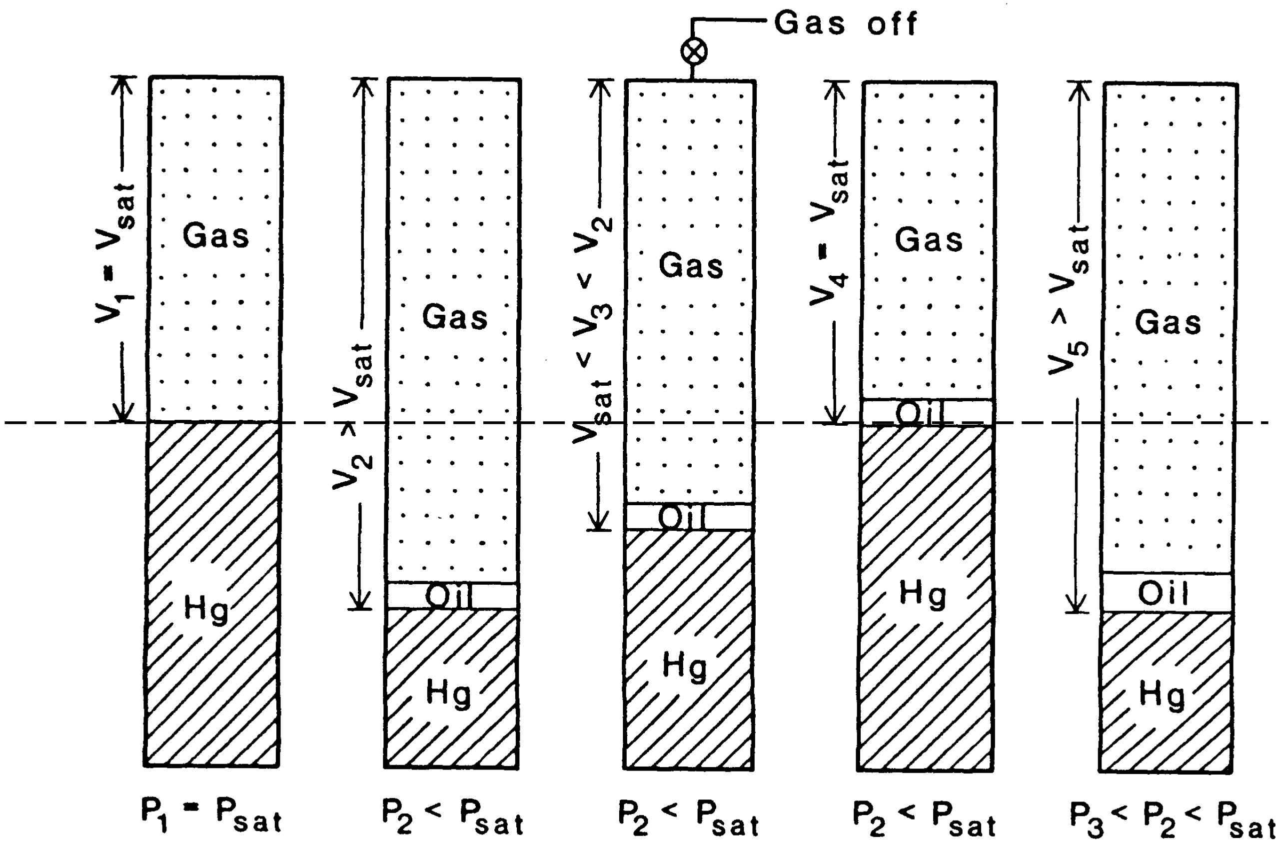
P_s

Z

V_{ro}-V_o/V_t

PVT Experiments

Constant Volume Depletion Test



Data

P_s

y_i

G_p/G

Z

V_{ro}

Initial Fluids in Place (IFIP) and Depletion Recoveries

- Gas Z-factor
- Compositional (C_{6+}) Variation During Depletion
- Compositional Variation with Depth
- Dewpoint Pressure
- Gas-Oil Contacts

Gas Z-Factor

Z-factor is the only PVT property which always needs accurate determination in a gas condensate reservoir.

- Initial gas and condensate in place
- Gas and condensate recovery as a function of pressure during depletion drive

Compositional (C7+) Variation During (CVD) Depletion

- Forecast the condensate rate profile
- Calculate gas and condensate recovery profiles (neglecting water influx/expansion)
- Defining Gas Cycling Potential

Condensate Recoveries from CVD & CCE Data

$$RF_{oD} = \left(1 - \frac{(p/Z)_d}{(p/Z)_i}\right) + \frac{(p/Z)_d}{(p/Z)_i} \cdot \sum_{k=1}^{N} \left(\frac{\Delta n_p}{n_d}\right)_k \cdot \frac{(1/r_{si} + C_{og})}{(1/r_{sk} + C_{og})}$$

$$r_s \cong \frac{z_{6+}}{1 - z_{6+}} \cdot \frac{1}{C_{og}}$$

$$C_{og} = \frac{R\,T_{sc}}{P_{sc}} \cdot \frac{\rho_{6+}}{M_{6+}}$$

CVD Data Conversion to Surface Oil and Gas Recoveries

Based on Simplified Surface Flash (Surface Gas = C6- and Surface Oil = C7+)

C7+ Mole Weight	161	kg/kmol
C7+ Density	830	kg/m3
Cog	122	Sm3/Sm3 (assumed constant)
(p/z)i/(p/z)d	0.9120	

Input (red)

	P	Z	n_p/n	dnp/nd	y_{7+}	Approx. Solution OGR r_s	RFg	RFo
	bara		%	%	mol-%	Sm3/Sm3	%	%
Pi	532	1.2172	0.000		3.996	3.407E-04	0.00	0.00
Pd	430	1.0788	0.000	0.000	3.996	3.407E-04	8.80	8.80
	408		2.710	2.710	3.339	2.827E-04	11.29	10.87
	372		7.070	4.360	3.366	2.851E-04	15.29	14.22
	320		14.720	7.650	2.875	2.423E-04	22.35	19.24
	272		24.420	9.700	2.245	1.880E-04	31.36	24.21
	221		36.060	11.640	1.742	1.451E-04	42.22	28.83
	170		49.130	13.070	1.302	1.080E-04	54.48	32.72
	121		62.630	13.500	1.055	8.727E-05	67.17	35.97
	62		79.160	16.530	0.675	5.562E-05	82.76	38.52

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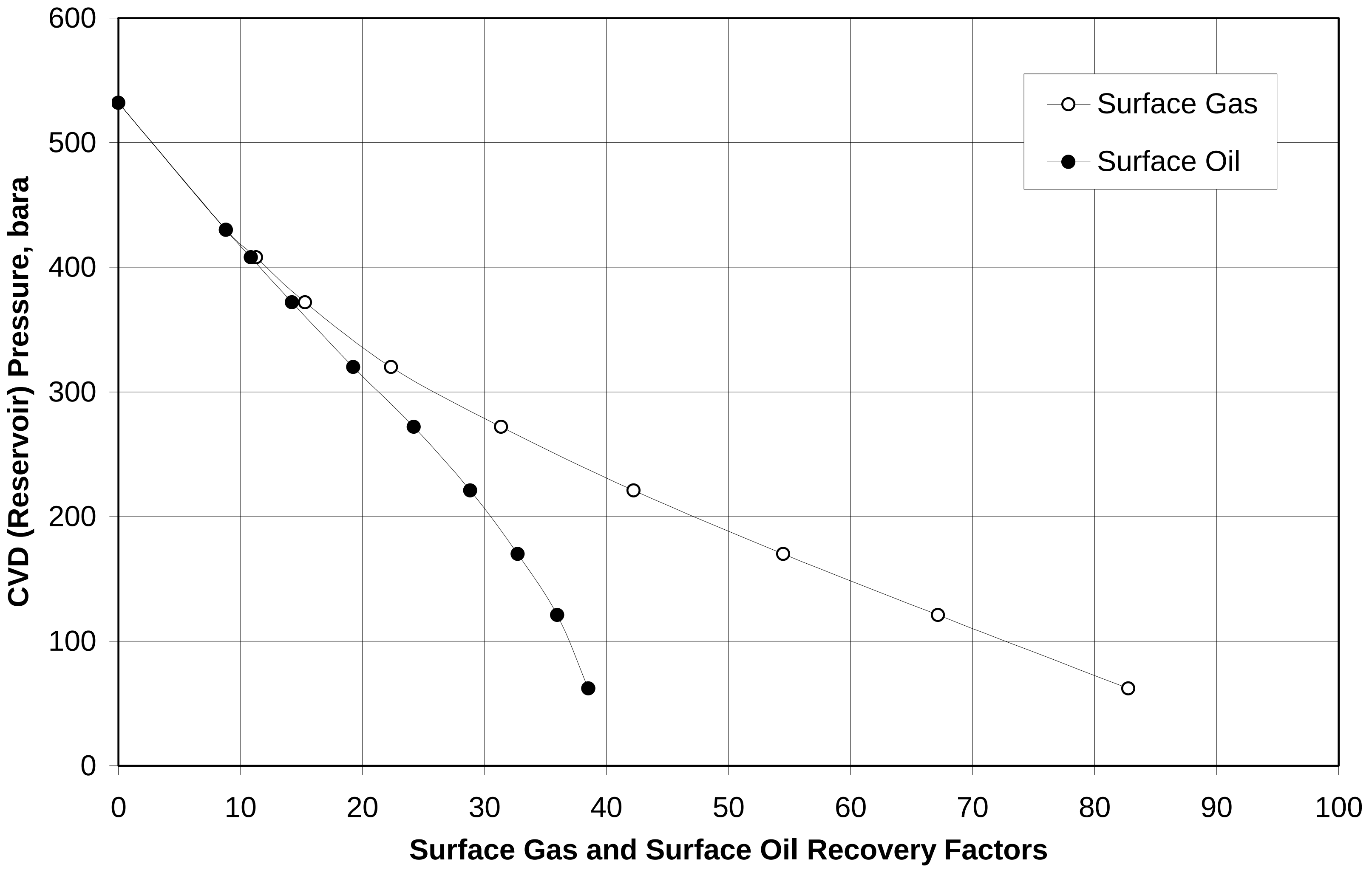

Surface Gas
Surface Oil
CVD (Reservoir) Pressure, bara
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
Surface Gas and Surface Oil Recovery Factors

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Dewpoint Pressure

- **Dewpoint marks the pressure where:**
  - **Reservoir gas phase**
    (= producing wellstream)
    starts becoming leaner
  - Incipient condensate phase appears

Compositional Variation with Depth

- Effect of a gradient on IFIPs
- Prediction of gas-oil contact using a theoretical gradient model
- Effect of compositional gradients on depletion (and cycling) recoveries

Condensate Blockage

Near-Wellbore Steady State Region

Relative Permeability

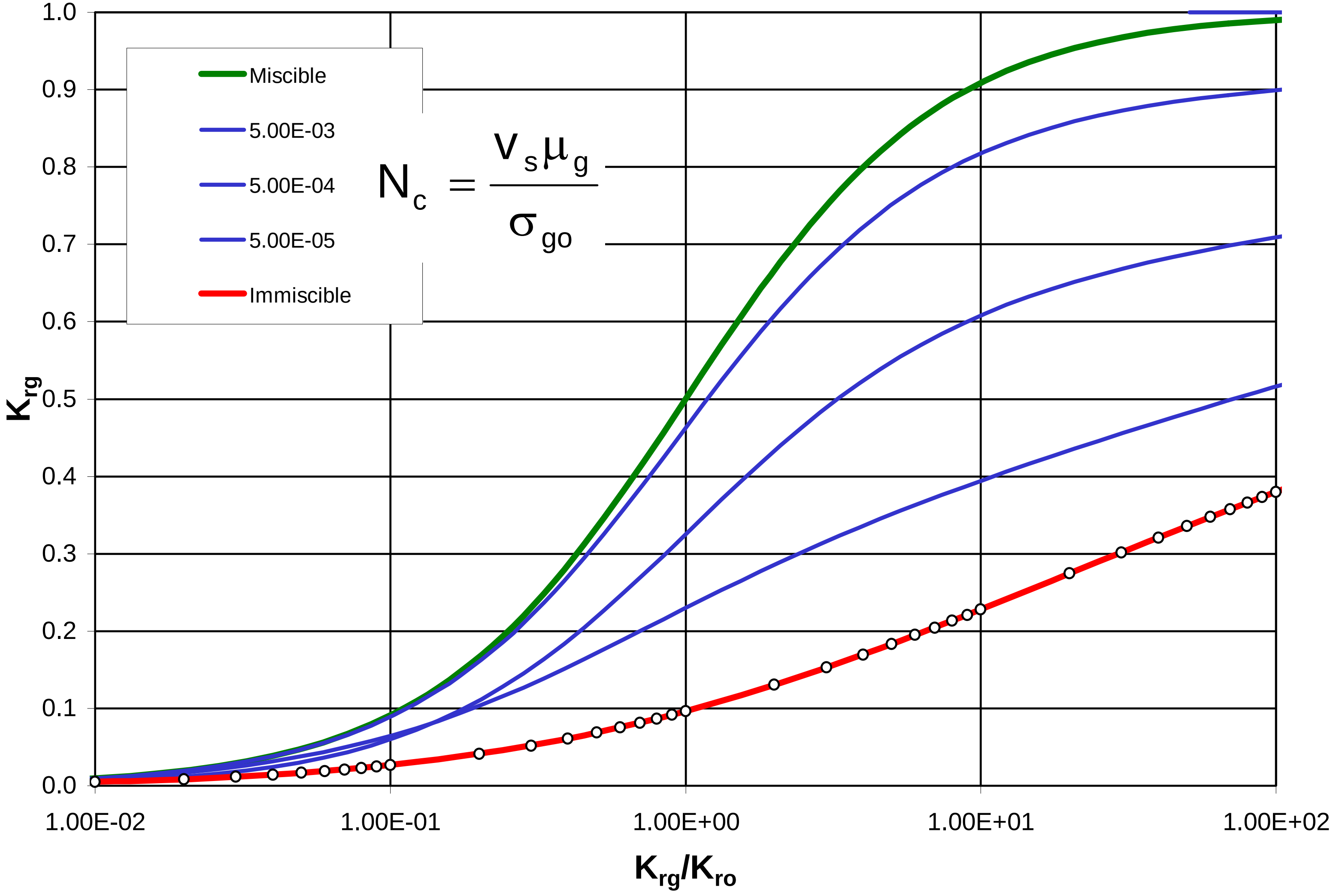
$$k_{rg} = f(k_{rg}/k_{ro})$$

"Pure" PVT

$$k_{rg}/k_{ro} = (1/V_{ro} - 1)(\mu_g/\mu_o)$$

Condensate Blockage

Near-Wellbore Steady State Region



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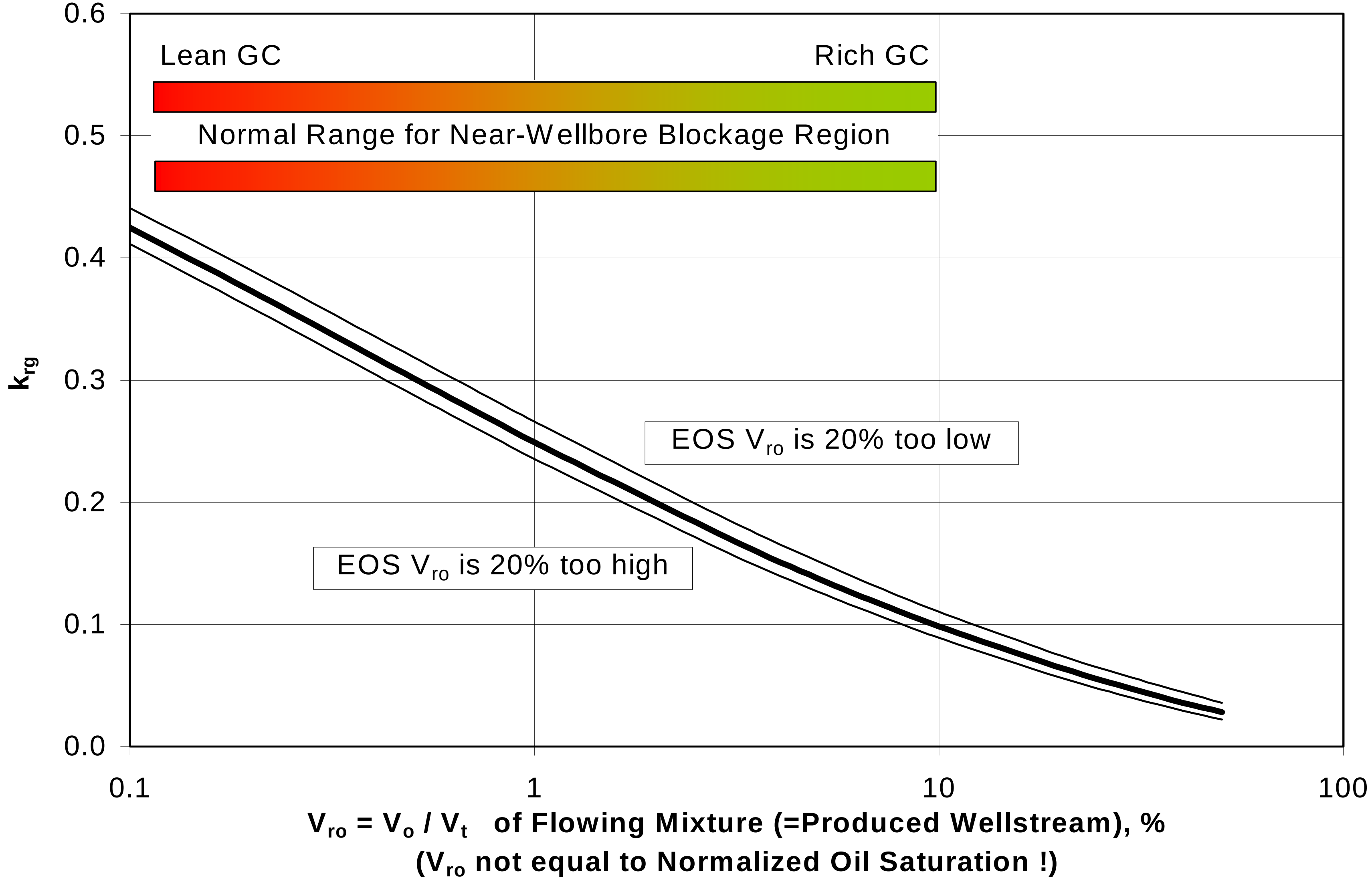
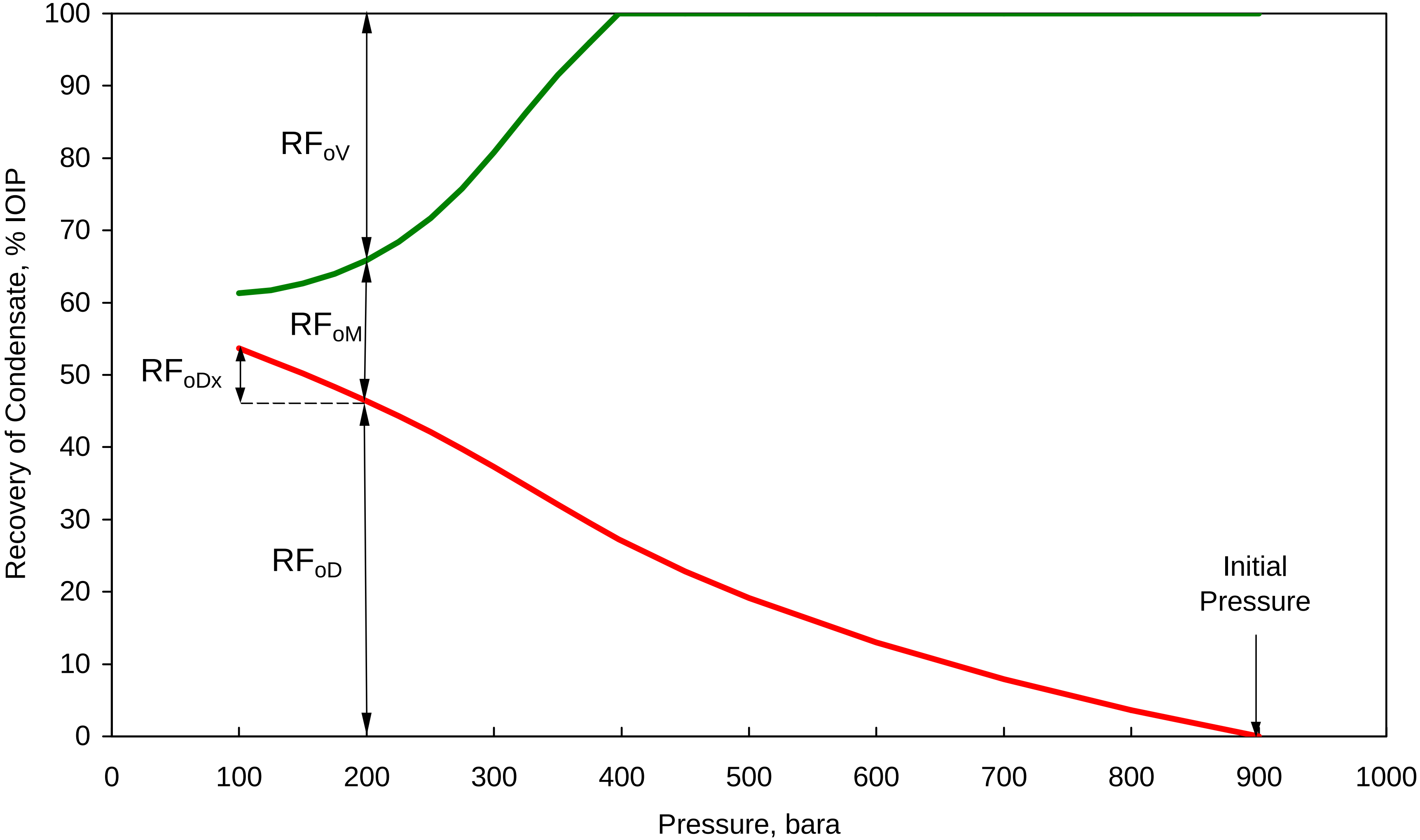


Lean GC
Rich GC
Normal Range for Near-Wellbore Blockage Region
EOS V_{ro} is 20% too low
EOS V_{ro} is 20% too high
k_{rg}
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.1
1
10
100
V_{ro} = V_o / V_t of Flowing Mixture (=Produced Wellstream), %
(V_{ro} not equal to Normalized Oil Saturation !)

Gas Cycling

- Evaluating Gas Cycling Potential using Depletion (CVD & CCE) Data

- Evaluating Different Components of Condensate Recovery
  - Initial Depletion
  - Gas-Gas Miscible
  - Vaporization
  - Post-Cycling Depletion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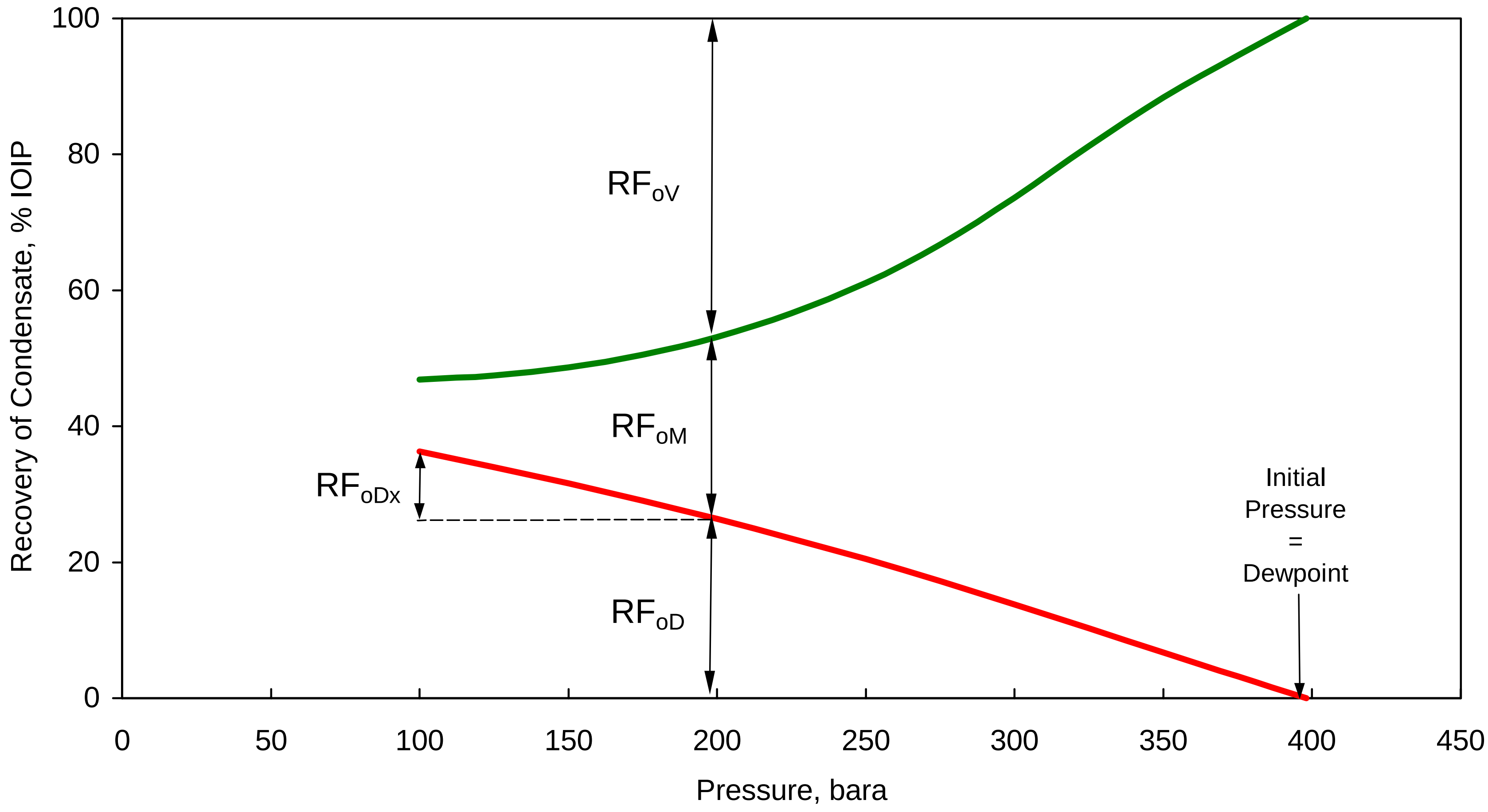
100
90
80
70
60
50
40
30
20
10
0
Recovery of Condensate, % IOIP
RF_{oV}
RF_{oM}
RF_{oDx}
RF_{oD}
Initial
Pressure
0
100
200
300
400
500
600
700
800
900
1000
Pressure, bara



Recovery of Condensate, % IOIP
Pressure, bara
0
20
40
60
80
100
0
50
100
150
200
250
300
350
400
450
RFoV
RFoM
RFoDx
RFoD
Initial
Pressure
=
Dewpoint

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Gas Cycling Ultimate Condensate Recovery

Cycling Above Dewpoint

$$RF_{oult} = RF_{oD} + E_S \cdot RF_{oM} + (1 - E_S) \cdot RF_{oDx}$$

Cycling Below Dewpoint

$$RF_{oult} = RF_{oD} + E_S \cdot \left(RF_{oM} + E_V \cdot RF_{oV} \right) + (1 - E_S) \cdot RF_{oDx}$$

E_S = final sweep efficiency at the end of cycling

E_V = final efficiency of vaporized retrograde condensate

Gas Cycling Ultimate Condensate Recovery

Data from CVD and CCE							Calculated			
Pressure bara	r_s Sm3/Sm3	B_{gd} m3/Sm3	Visg cp	npw/nd %	Z-factor	Vro %	RF_{oD} %	RF_{gD} %	RF_{oM} %	RF_{oV} %
900	8.07E-04	3.69E-03	0.062265	0.0	1.928	0.000	0.0	0.00	100.0	0.0
800	8.07E-04	3.83E-03	0.057694	0.0	1.778	0.000	3.6	3.64	100.0	0.0
700	8.07E-04	4.01E-03	0.053105	0.0	1.628	0.000	7.9	7.89	100.0	0.0
600	8.07E-04	4.24E-03	0.04843	0.0	1.477	0.000	13.0	12.97	100.0	0.0
500	8.07E-04	4.56E-03	0.043548	0.0	1.325	0.000	19.2	19.17	100.0	0.0
450	8.07E-04	4.78E-03	0.040966	0.0	1.249	0.000	22.8	22.84	100.0	0.0
398	8.07E-04	5.07E-03	0.038125	0.0	1.171	0.000	27.2	27.21	100.0	0.0
375	7.62E-04	5.21E-03	0.035959	3.3	1.138	2.581	29.5	29.43	96.0	4.0
350	7.09E-04	5.39E-03	0.033592	7.1	1.105	5.222	32.1	32.14	91.5	8.5
325	6.45E-04	5.61E-03	0.031119	11.4	1.075	7.973	34.7	35.22	86.3	13.7
300	5.75E-04	5.89E-03	0.028633	16.1	1.049	10.401	37.3	38.73	80.8	19.2
275	5.06E-04	6.24E-03	0.026314	21.2	1.027	12.042	39.8	42.64	75.8	24.2
250	4.46E-04	6.70E-03	0.024242	26.6	1.008	12.933	42.1	46.89	71.7	28.3
225	3.95E-04	7.28E-03	0.022415	32.5	0.993	13.297	44.3	51.45	68.4	31.6
200	3.52E-04	8.04E-03	0.020816	38.6	0.980	13.317	46.4	56.27	65.9	34.1
175	3.16E-04	9.06E-03	0.019427	45.1	0.970	13.108	48.4	61.35	64.0	36.0
150	2.86E-04	1.04E-02	0.018235	51.9	0.963	12.738	50.2	66.62	62.6	37.4
125	2.64E-04	1.24E-02	0.017226	59.0	0.958	12.246	52.0	72.06	61.7	38.3
100	2.52E-04	1.55E-02	0.016382	66.2	0.957	11.674	53.6	77.62	61.3	38.7

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"Representative" Samples

- "Reservoir Representative"
  - *Any uncontaminated fluid sample that produces from a reservoir is automatically representative of that reservoir.* ***After all, the sample is produced from the reservoir!***
- "Insitu Representative"
  - *A sample representative of the original fluid in place (usually of a limited volume within the reservoir)*
  - *Accuracy of PVT Data ≠ Insitu Representivity of Sample*

EOS Modeling

- Molar composition and C_{7+} Properties
- Splitting the plus fraction (3-5 C_{7+})
- Tuning EOS parameters
- "Common" EOS model for multiple reservoir fluids
- Reducing number of components ("pseudoizing")

Pseudoization Example

Component	EOS22	EOS19	EOS12	EOS10	EOS9	EOS6	EOS4	EOS3
N2	N2	C1N2	C1N2	C1N2	C1N2	C1N2		
CO2	CO2	CO2	CO2	CO2				
C1	C1				CO2C2	C02C2		
C2	C2	C2	C2	C2			C1N2CO2C2-C6	C1N2CO2C2-C6
C3	C3	C3	C3	C3	C3			
IC4	IC4							
		IC4NC4	IC4NC4	IC4NC4	IC4NC4			
NC4	NC4							
						C3-C6		
IC5	IC5							
		IC5NC5	IC5NC5	IC5NC5	IC5NC5			
NC5	NC5							
C6	C6	C6	C6	C6	C6			
C7	C7	C7						
			C7C8					
C8	C8	C8						
C9	C9	C9		C7C8C9F1F2	C7C8C9F1F2	C7C8C9F1F2	C7C8C9F1F2	
C10+	F1	F1	C9F1F2					
	F2	F2						
								C7C8C9F1-F8
	F3	F3						
	F4	F4	F3-F5					
	F5	F5						
				F3-F8	F3-F8	F3-F8	F3-F8	
	F6	F6						
	F7	F7	F6-F8					
	F8	F8						
	F9	F9	F9	F9	F9	F9	F9	F9

EOS Modeling

Generating Black-Oil PVT Tables

- **Extrapolating saturated tables**
- **Non-monotonic saturated oil properties**
- **Consistency between black-oil and EOS models**
- **Handling saturated gas/oil systems**
- **Initializing reservoirs with compositional gradients**

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Definition of Black-Oil PVT Properties

$$B_o = \frac{V_o}{V_{oo}} = \text{oil formation volume factor}$$

$$R_s = \frac{V_{go}}{V_{oo}} = \text{solution gas-oil ratio}$$

$$B_{gd} = \frac{V_g}{V_{gg}} = \text{dry gas formation volume factor}$$

$$r_s = \frac{V_{og}}{V_{gg}} = \text{solution oil-gas ratio}$$

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r_s/B_{gd}

"surface oil in place per reservoir gas volume"

(equivalent to CVD y_{6+})

The term r_s/B_{gd} is the quantity needed by "geologists" to convert reservoir gas pore volumes to surface oil – a kind of "oil FVF (B_o)" for the reservoir gas phase.

For compositionally-grading reservoirs with a transition from gas to oil through an undersaturated (critical) state, the term r_s/B_{gd} = $1/B_o$ *exactly* at the gas-oil contact.

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Conclusions

For calculation of initial gas and condensate in place the key PVT data are:

- Initial Z-factor
- Initial C_{6+} molar content

In terms of black-oil PVT properties, the two "equivalent" PVT quantities are:

- B_{gd}
- r_s/B_{gd}

Conclusions

The constant-composition and constant-volume-depletion tests provide the key data for quantifying recovery of produced gas and condensate during depletion.

Above the dewpoint depletion recoveries of gas and condensate are equal and are given by the variation of Z-factor with pressure.

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Conclusions

For calculation of condensate recovery and varying yield (producing oil-gas ratio) during depletion it is critical to obtain

Accurate measurement of C_{6+} (r_s) variation in the produced gas from a constant volume depletion test.

Conclusions

For near-saturated gas condensate reservoirs producing by pressure depletion:

cumulative condensate produced is insensitive to whether the reservoir is initialized with or without a compositional gradient

even though initial condensate in place can be significantly different for the two initializations

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Conclusions

Oil viscosity should be measured and modeled accurately to properly model condensate blockage and the resulting reduction in gas deliverability.

The (CCE) oil relative volume V_{ro} has only a "secondary" effect on the modeling of condensate blockage.

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Conclusions

For gas cycling projects above the dewpoint, PVT properties have essentially no effect on condensate recovery because the displacement will always be miscible.

Only the definition of initial condensate in place is important. Gas viscosity has only a minor effect on gas cycling.

Conclusions

For gas cycling below the dewpoint, the key PVT properties are:

- Z-factor variation during depletion
- C_{6+} content in the reservoir gas during depletion
- C_{6+} vaporized from the reservoir condensate into the injection (displacement) gas.