Saudi Aramco – Course in Advanced Fluid PVT Behavior

SPE 63087

Guidelines for Choosing Compositional and Black-Oil Models for Volatile Oil and Gas-Condensate Reservoirs

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PERA

Purpose

When Use a Black-Oil Model ?

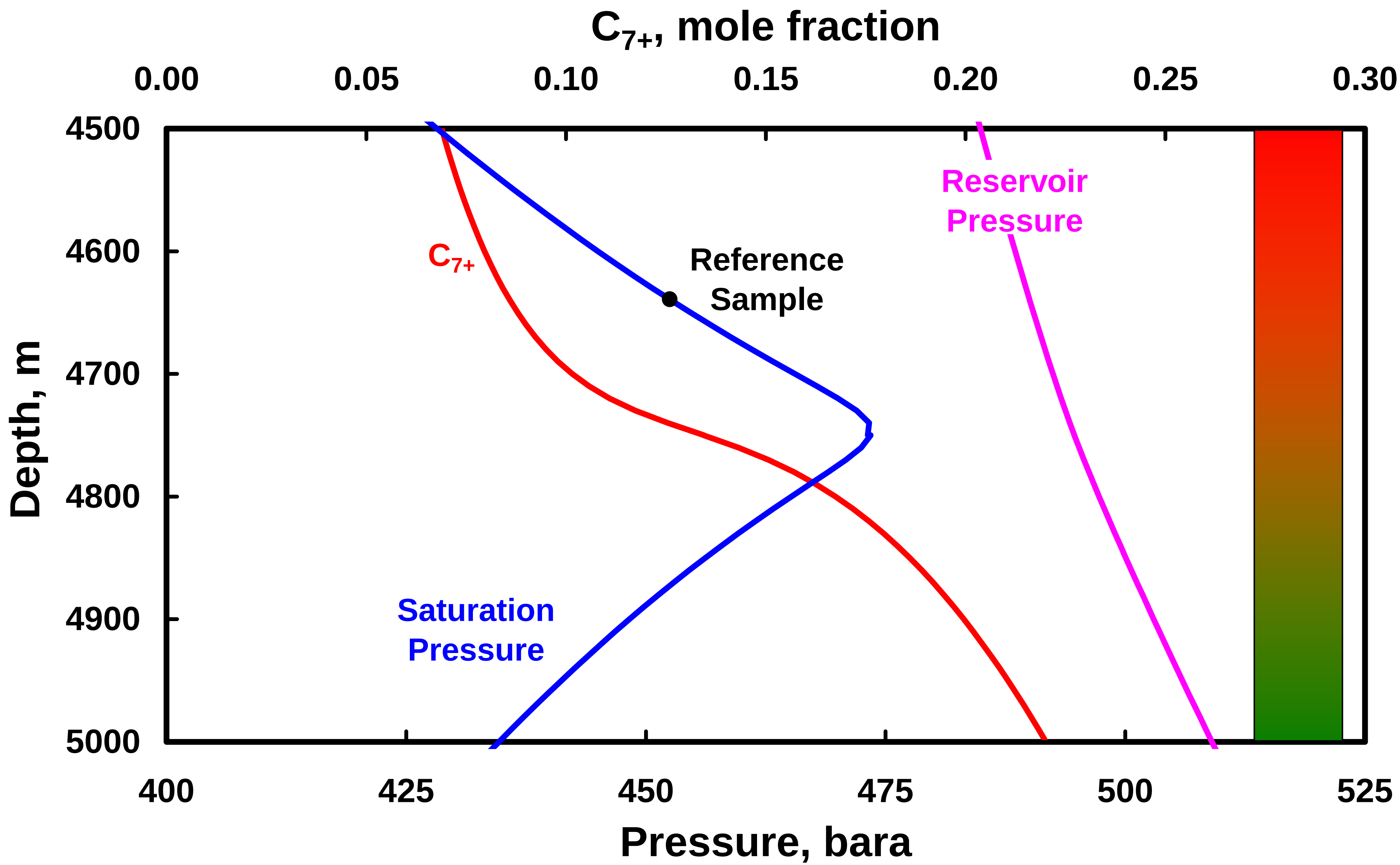
When is an EOS Model Required?

Method of Study

- **PVT**
  - Fluids selection
  - EOS and viscosity models
  - Component grouping (“pseudoization”)
  - Generating black-oil PVT tables
- **Reservoir fluid initialization**
  - EOS vs Black-Oil IFIP
- **Reservoir recovery mechanism**
  - Depletion
  - Gas injection

Reservoir Fluid System

- Fluid system selected from a North Sea field
- Reference depth — 4640 m (15220 ft)
  - C_{7+} — 8.58 mole %
  - Dewpoint pressure — 452 bara (6550 psia)
  - Initial reservoir pressure — 490 bara (7100 psia)
  - Solution gas-oil ratio — 1100 Sm^3/Sm^3 (6200 scf/STB)
- Undersaturated by 21 bar at GOC



C7+, mole fraction
0.00
0.05
0.10
0.15
0.20
0.25
0.30
4500
4600
4700
4800
4900
5000
Depth, m
Reservoir
Pressure
C7+
Reference
Sample
Saturation
Pressure
400
425
450
475
500
525
Pressure, bara

EOS and Viscosity Models

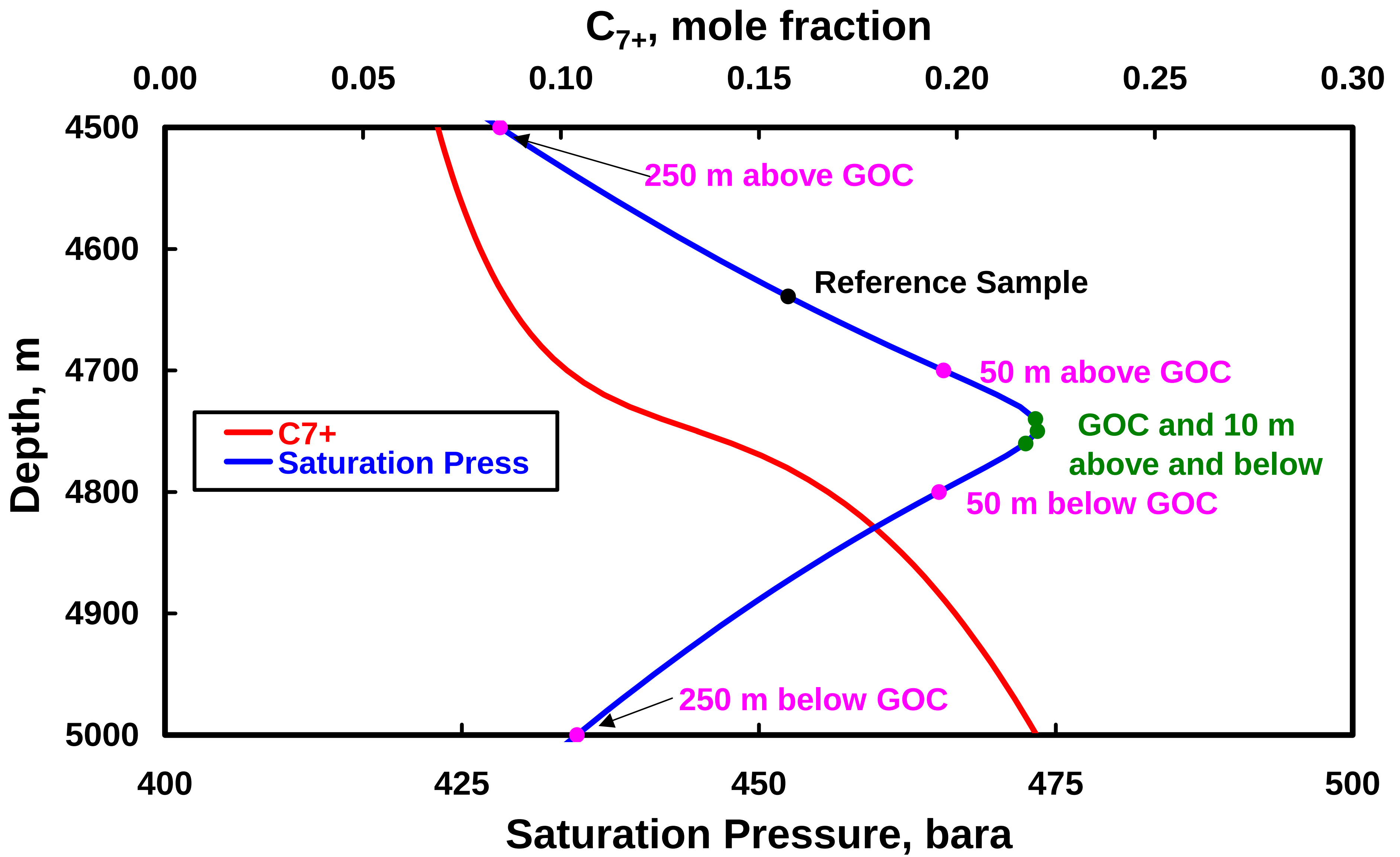
- **SRK equation of state**
- **22-components – 12 C_{7+}**
- **LBC viscosity correlation**

Pseudoization

Reducing Number of Components

EOS22
EOS19 EOS12 EOS10 EOS9
EOS6
EOS4 EOS3

- Stepwise grouping of components
- Regress to maintain best-fit of EOS22
  - wide range of P-T-composition space
- Final check with reservoir simulation



C7+, mole fraction
0.00
0.05
0.10
0.15
0.20
0.25
0.30
4500
4600
4700
4800
4900
5000
Depth, m
250 m above GOC
Reference Sample
50 m above GOC
GOC and 10 m
above and below
50 m below GOC
250 m below GOC
C7+
Saturation Press
400
425
450
475
500
Saturation Pressure, bara

Black-Oil PVT Properties

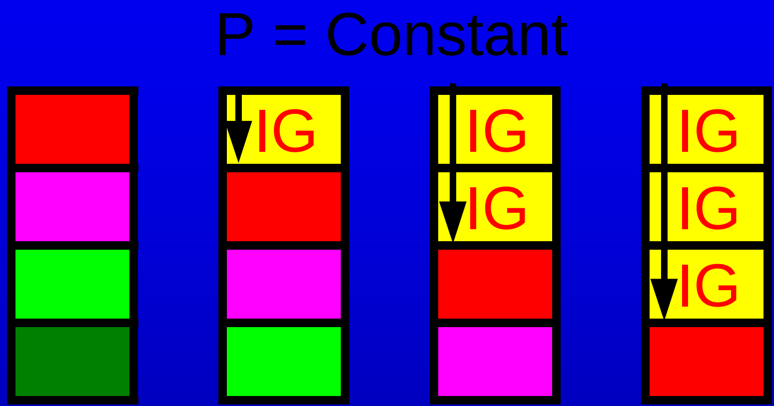
- EOS to Black-Oil properties generated using Whitson-Torp procedure
  - Combine depletion test with surface process
- Undersaturated GOC
  - Use critical fluid (CCE)
- Saturated GOC
  - GOC gas (CVD) : gas properties
  - GOC oil (DLE) : oil properties
- Surface densities
  - Best-fit reservoir oil and gas densities

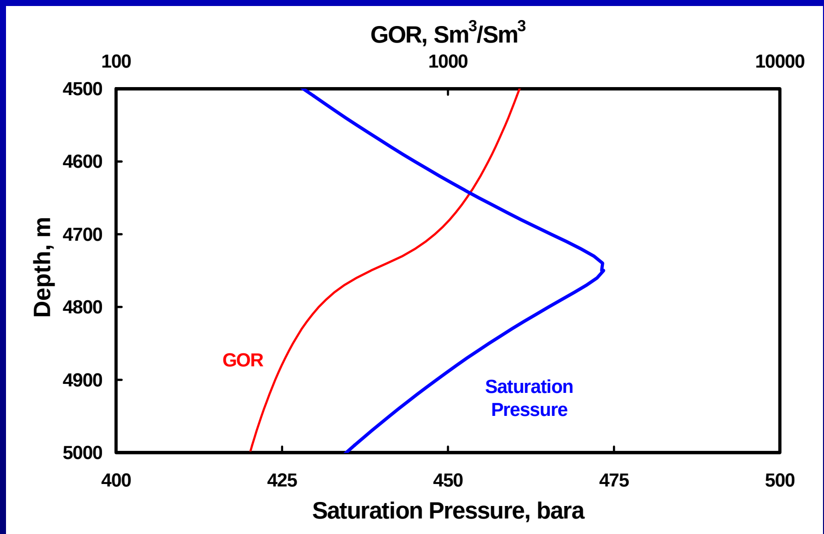
Reservoir Fluid Initialization

Obtain Accurate & Consistent Fluids In-Place

- **EOS Models**
  - **Use original EOS to generate compositional gradient**
  - **Manually pseudoize compositions**

Initializing Black-Oil Models



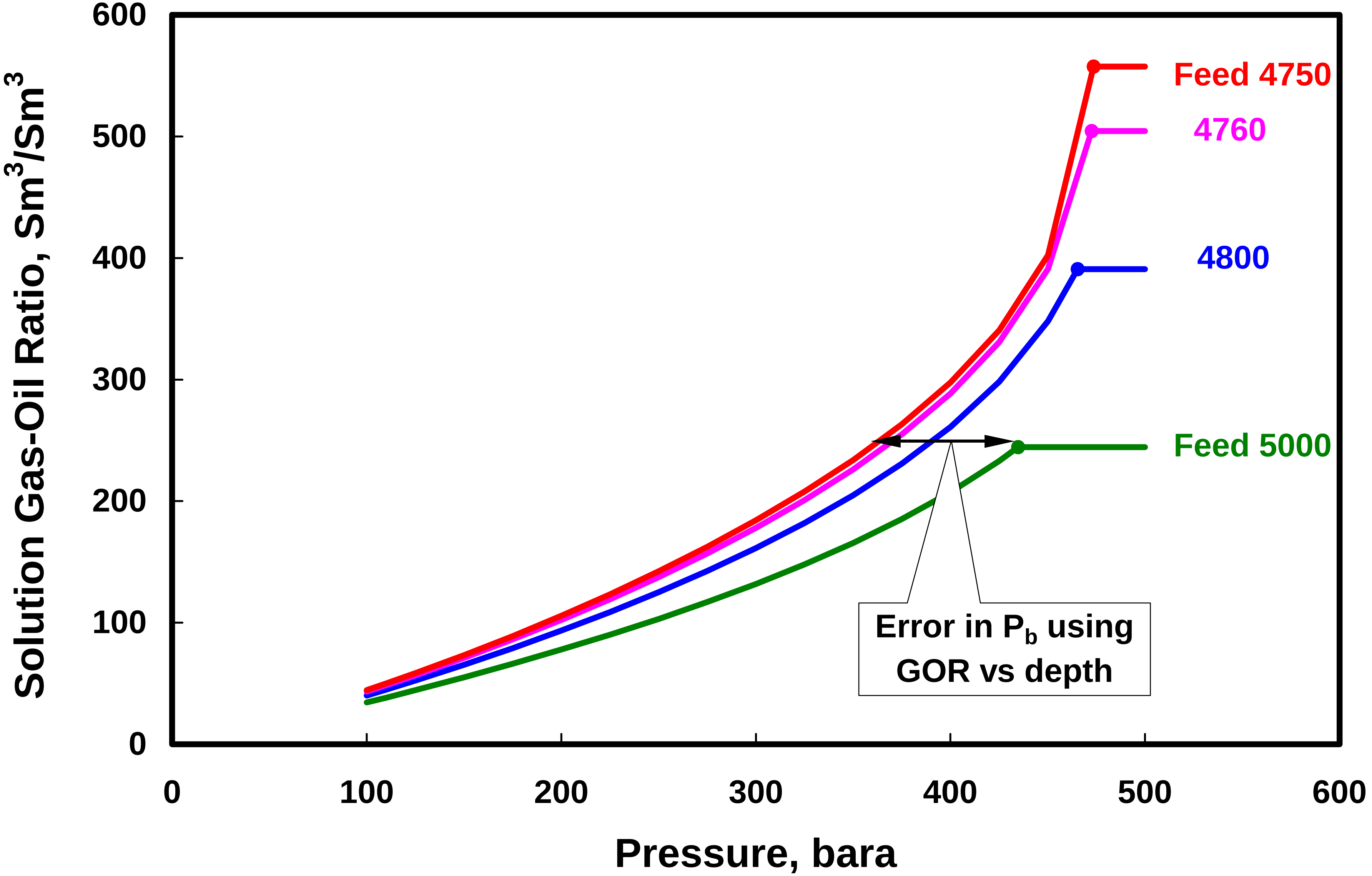


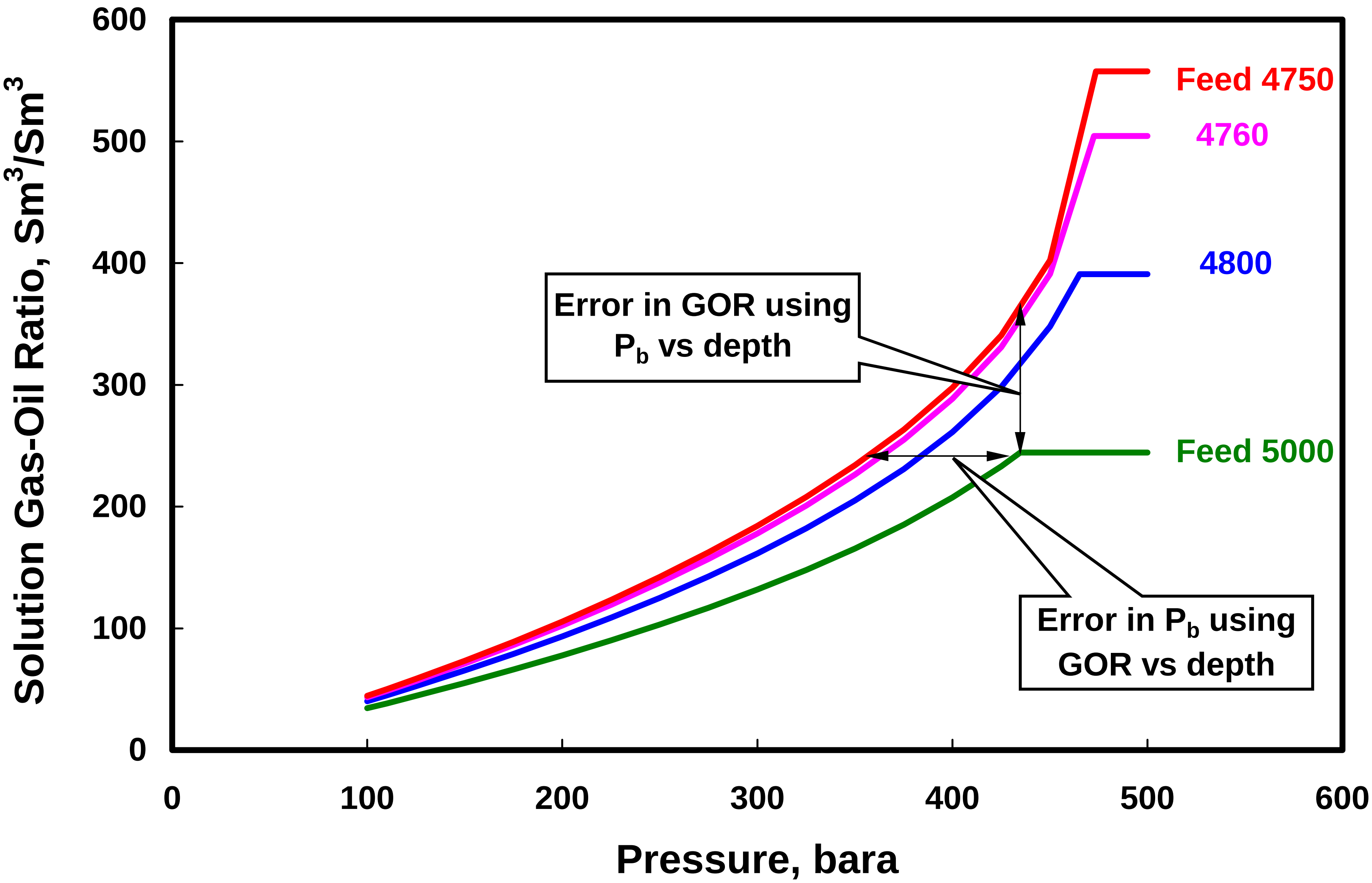
- **Only a single black-oil PVT table should be used** *(E100 API Tracking option,Only Oil)*

- **Two options to initialize a black-oil model**
  - **Solution GOR vs depth**
  - **Saturation pressure vs depth**

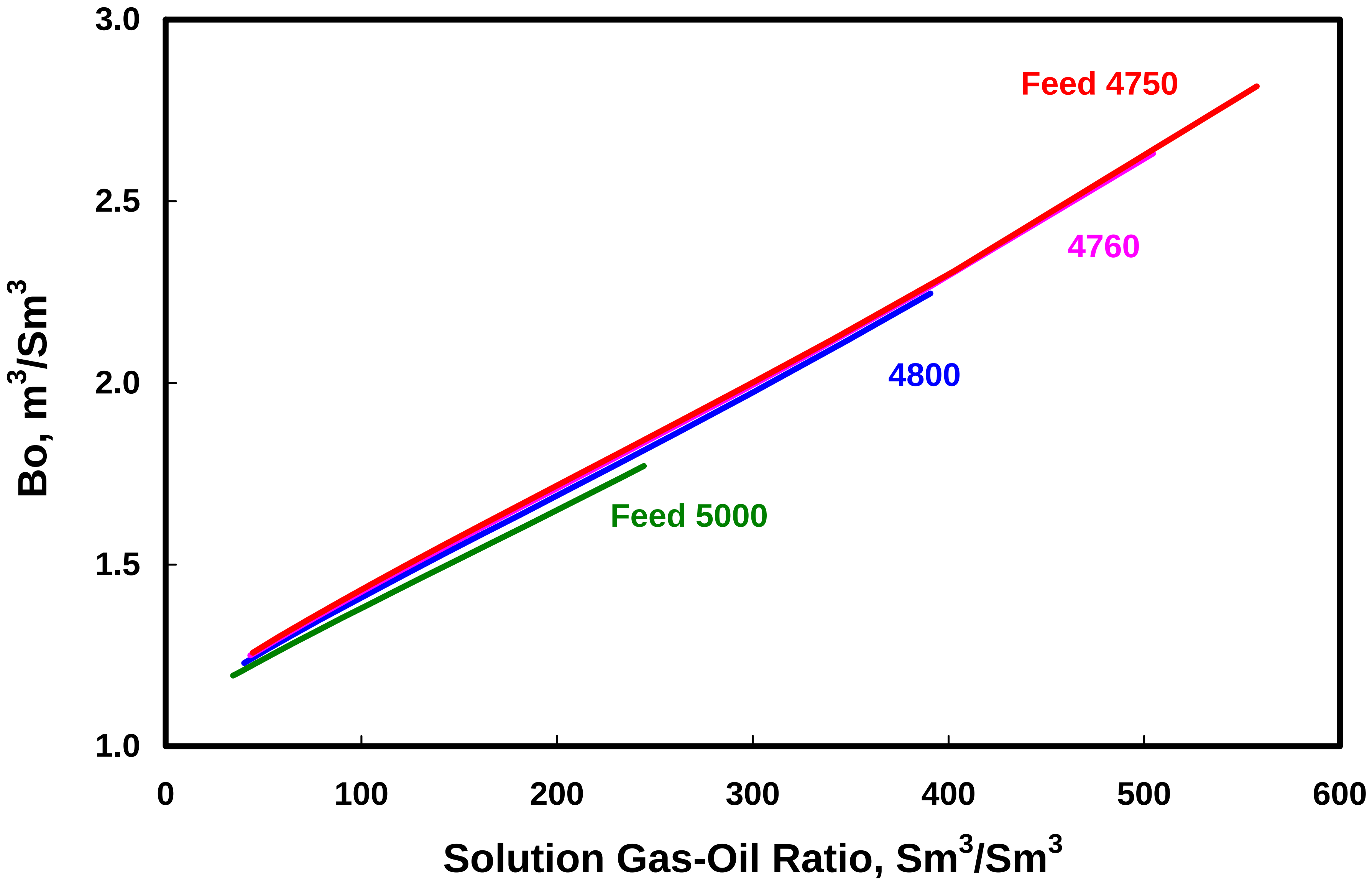
Initializing Black-Oil Models

- Only a single black-oil PVT table can be used in a compositional varying reservoir with vertical communication. Because the black oil PVT table is connected to the grid block not to the fluid.
- Two options are available to initialize a black-oil model
  - Solution GOR or OGR versus depth
  - Saturation pressure versus depth

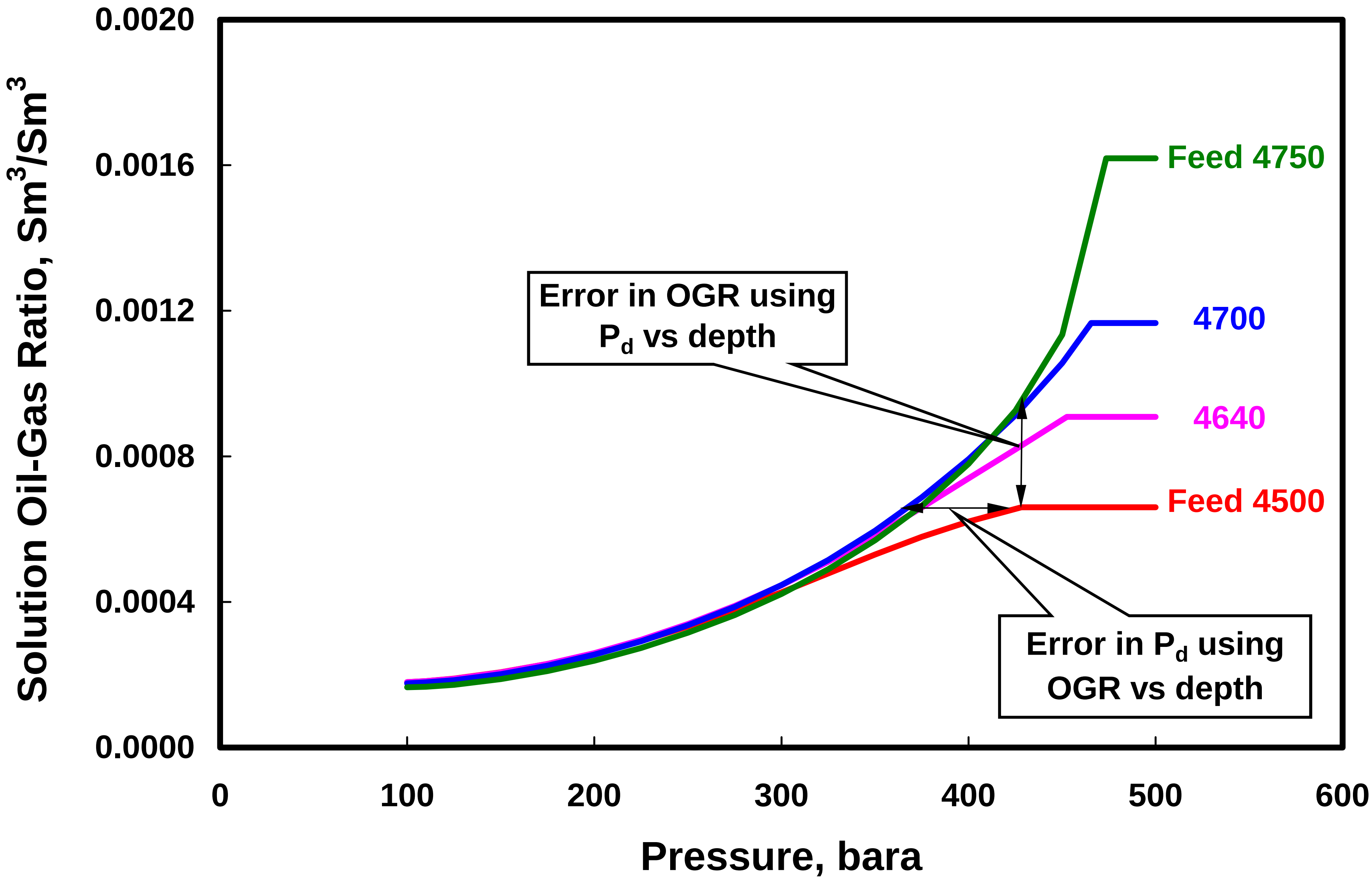

Solution Gas-Oil Ratio, Sm3/Sm3
Pressure, bara
0
100
200
300
400
500
600
Feed 4750
4760
4800
Feed 5000
Error in Pb using
GOR vs depth



Solution Gas-Oil Ratio, Sm3/Sm3
Pressure, bara
0
100
200
300
400
500
600
Feed 4750
4760
4800
Feed 5000
Error in GOR using Pb vs depth
Error in Pb using GOR vs depth



Bo, m3/Sm3
3.0
2.5
2.0
1.5
1.0
0
100
200
300
400
500
600
Solution Gas-Oil Ratio, Sm3/Sm3
Feed 4750
4760
4800
Feed 5000


Solution Oil-Gas Ratio, Sm3/Sm3
0.0020
0.0016
0.0012
0.0008
0.0004
0.0000
0
100
200
300
400
500
600
Pressure, bara
Feed 4750
4700
4640
Feed 4500
Error in OGR using Pd vs depth
Error in Pd using OGR vs depth

Initializing Black-Oil Models

- Only a single black-oil PVT table should be used
- Two options are available to initialize a black-oil model
  - Solution GOR or OGR versus depth
  - Saturation pressure versus depth

Simulation Model Initialization

CASE	IOIP (10^6 Sm^3)	IGIP (10^9 Sm^3)	ΔIOIP (%)	ΔIGIP (%)
EOS22	13.22	11.02	-	-
BO 22 (GOR vs D)	13.15	11.08	-0.55	0.51
BO 22 (Psat vs D)	14.78	10.74	11.82	-2.53

Simulation Model Initialization				
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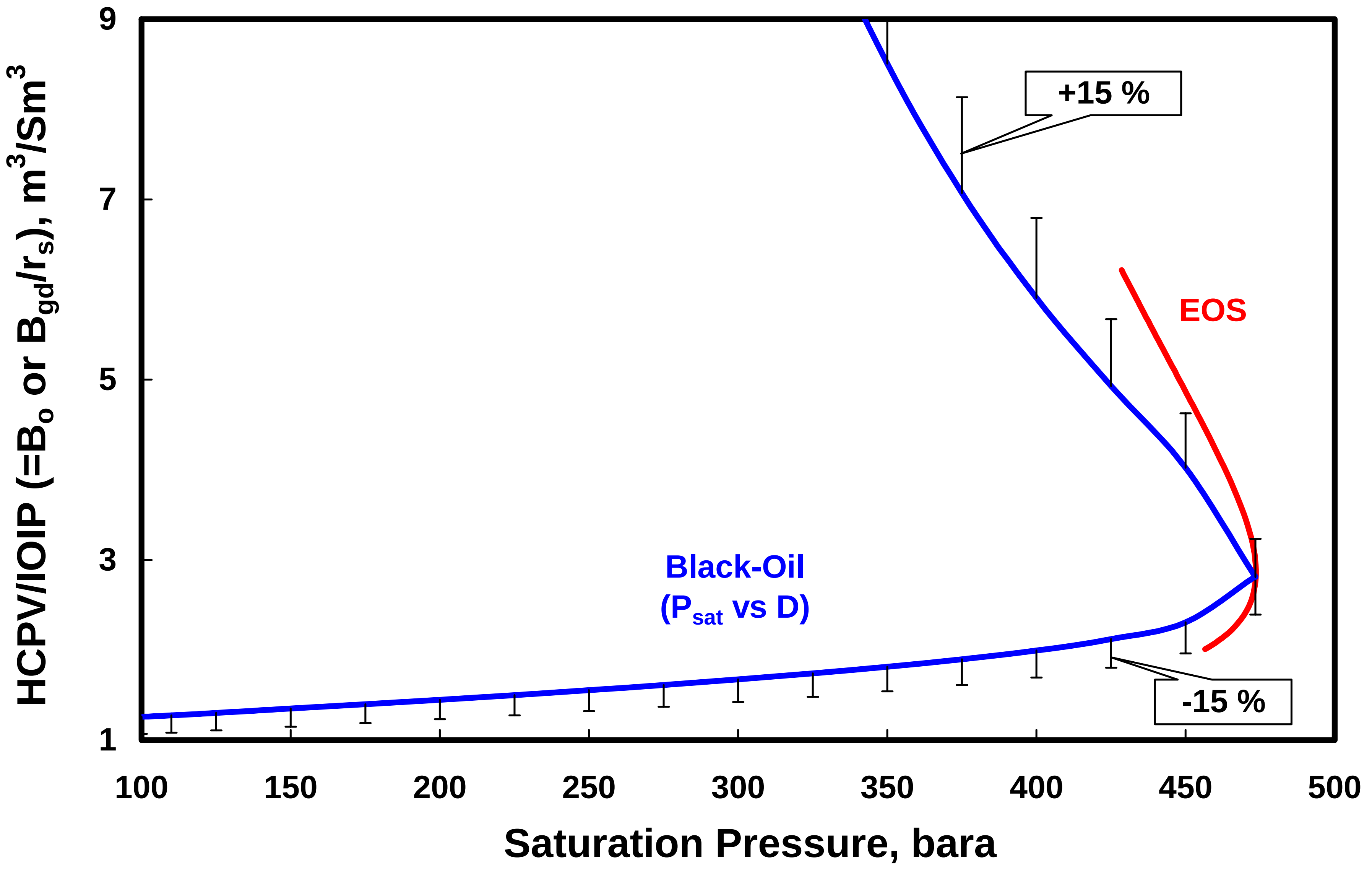


HCPV/IOIP (=B$_o$ or B$_{gd}$/r$_s$), m^3/Sm^3
9
7
5
3
1
100
150
200
250
300
350
400
450
500
Saturation Pressure, bara
+15 %
-15 %
EOS
Black-Oil
(P$_{sat}$ vs D)

Initializing Black-Oil Models

Conclusions

- **Generate black-oil PVT data using GOC feed or (GOR or OGR)$_{max}$ feed**
- **Use solution GOR/OGR versus depth**
- **Errors in saturation pressure gradient**
  - **Due to using a single BO PVT table**
  - **Causes small error in recoveries that are maximum just when the reservoir pressure drops below initial saturation pressure**

<u>Don’t use saturation pressure versus depth !!!</u>

Black-Oil PVT Properties Injection Cases

- Different methods for extrapolation of BO PVT tables for gas injection have been tested.

- The recommended
  - Fully swell “original” reservoir oil.
  - Deplete stepwise to original bubblepoint (+)
  - Splice resulting “extrapolated” BO table with original oil BO table

Can only be applied in special situations

Reservoir Simulation Model

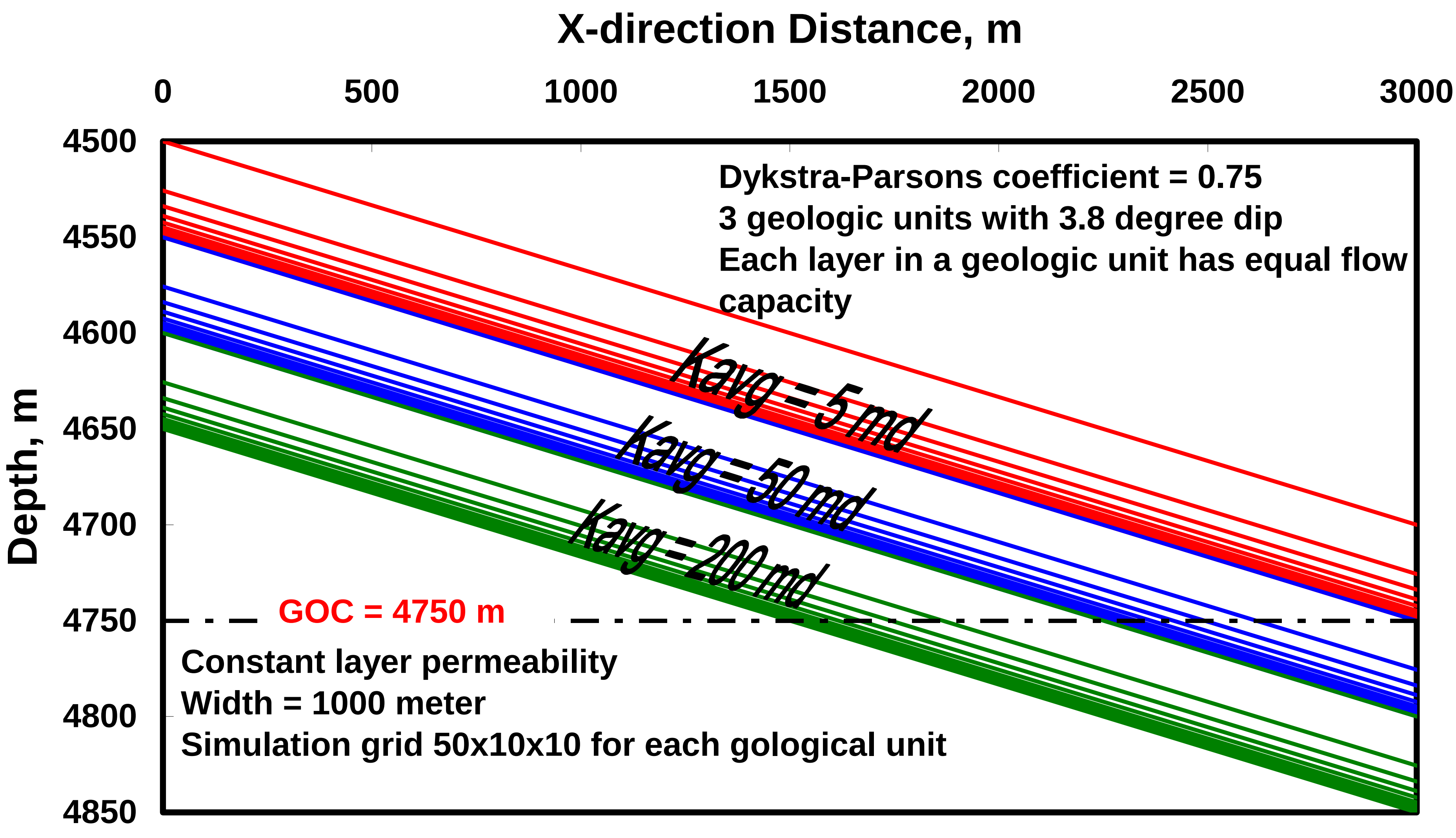
- General model characteristics
- Different fluid systems
- Varying geological units
  - Heterogeneity

Simulation Model Information

- Eclipse 100 98a for black-oil and eclipse 300 98a for compositional simulation
- Implicit method in black-oil simulation
- Adaptive implicit method (AIM) in compositional simulation

Reservoir and Rock Properties	
Absolute Horizontal permeability, md	5 - 200
Top geologic unit, md	5
Middle geologic unit, md	50
Bottom geologic unit, md	200
Vertical/Horizontal permeability ratio	0.1
Dykstra-Parsons coefficient	0.75
Porosity, %	15
Reservoir Height, m (3 units, 50 m each)	150
Rock Compressibility, bar^{-1}	4.00E-5
Irreducible Water Saturation, %	26
Initial Reservoir Pressure, bara at 4750 m	494.68
Initial Reservoir Temperature, ^oC	163
Initial Gas-Oil Contact, m	4750
Critical Gas Saturation, %	2.0
Critical Oil Saturation, %	22.7

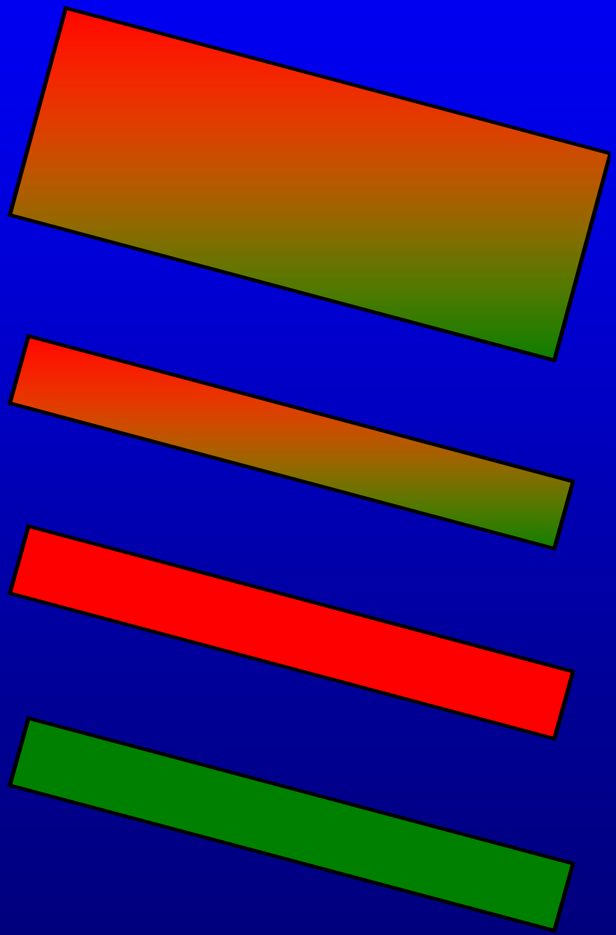
Simulation Model



Simulation
Production Constraints

- **Maximum withdrawal rate about 10 % hydrocarbon pore volume per year**
- **Minimum well bottom hole pressure - 100 bara in depletion cases and 300 bara in injection cases**
- **Simulated 10 years for *depletion cases* and 15 years for *injection* cases**

Different Fluid Systems



Initial fluid in place comparison

Compositional gradient

Gas constant composition

Oil constant composition

Reservoir Simulation Examples

- Depletion (16 cases in the paper; >50 cases total)
- Gas injection (23 cases reported in the paper)

Eclipse data files are available upon request

Simulation Cases and Performance - Depletion

Case Name	File Name	Case Description	Model	Reservoir Performance: AFTER 3 YEARS FOPR Sm3/d	FGOR m3/Sm	RFo %	AFTER 5 YEARS FOPR Sm3/d	FGOR m3/Sm	RFo %	AFTER 10 YEARS FOPR Sm3/d	FGOR m3/Sm	RFo %
EOS Models												
D1	A1C1X	Near Critical Fluid (Vro max =55%), EOS 6	EOS6	495	1674	17.9	264	2448	22.5	14	4134	26.9
	A1C3X	Near Critical Fluid (Vro max =55%), EOS 22	EOS22	505	1626	17.8	284	2243	22.5	8	5514	26.9
D2	A1C4X	Near Critical Fluid (Vro max =55%), EOS 3	EOS3	343	2646	16.3	161	4362	19.3	43	7450	22.1
onstant												
	1X	Near Critical Fluid (Vro max =55%)	EOS6									
	1		BO6									
		Rich Gas Condensate (Vro max = 28% and rs = 0.00115 Sm3/Sm3)	EOS6									
			BO6									
		Volatile Oil (Bob = 2.3 and RS = 407 Sm3/Sm3)	EOS6									
			BO6									
		Medium Rich Gas Condensate (Vro Max = 12% and rs = 0.00066 Sm3/Sm3)	EOS6									
			BO6									
D7	D5X	Slightly Volatile Oil (Bob = 1.8 and RS = 256 Sm3/Sm3)	EOS6									
	D5		BO6	810	812	19.9	472	1043	24.7	16	973	28.6
Initial Fluid, Variable												
D8		and some GC with fluid gradient as in bottom layer	EOS6	432	1982	24	216	3123	28.2	66	4882	32.6
					1965	24.8	219	3097	29.1	73	4753	33.4
D9		ensate and Oil with fluid gradient as in middle layer			2558	20.3	190	3709	24.7	45	5266	29.5
					2550	20.6	191	3687	25	44	5101	29.8
D10		Condensate fluid gradient as in top layer.			1900	9.3	165	2390	13.2	86	3405	19.4
					1835	8.9	158	2270	12.6	87	3203	18.6
D11		Condensate fluid gradient as in top layer (k=50 md)			2766	20.4	186	3870	25.5	61	5310	31.4
					2765	20.8	187	3862	25.9	57	5271	31.8
Perm												
D12	D3F2X	Volatile Oil, Permeability High-Top			3187	10.7	134	4470	12.5	0	5397	14.2
	D3F2				3324	10.5	128	4631	12.3	0	5243	13.8
D13	D3F3X	Volatile Oil, Permeability High-Middle			3205	12.4	133	4514	14.2	0	5452	15.9
	D3F3		BO6	247	3302	12.4	130	4617	14.1	0	5807	15.7
Saturated GOC												
D14	D3M2X		EOS6	340	2526	19.8	185	3646	24	72	5031	28.7
	D3M2_CCE		BO6	316	2756	19.2	170	4003	23.1	65	5572	27.5
	D3M2_DLE		BO6	301	2899	18.9	158	4324	22.6	57	6051	26.6
	D3M2_MIX		BO6	344	2527	19.8	190	3586	24.1	74	4888	29
D15	D3M2E2X		EOS6	352	2482	25.5	196	3545	30.7	74	5180	36.7
	D3M2E2_CCE		BO6	332	2651	24.8	182	3844	29.7	69	5518	35.3
	D3M2E2_DLE		BO6	317	2783	24.4	169	4142	29.1	63	6016	34.2
	D3M2E2_MIX		BO6	360	2436	25.6	202	3451	31.1	79	4845	37.4
D16	D3M2E2X_3W_	Oil and Gas gradient (3 wells- top, middle & bottom)	EOS6	362	2392	22.7	203	3404	28.2	80	4809	34.5
			BO6	370	2347	23.2	208	3323	28.9	82	4660	35.4
		Structurally bottom well (P5010)	EOS6	162	1726	-	84	2672	-	30	4136	-
			BO6	155	1823	-	83	2739	-	31	4015	-
		Structurally middle well (P2505)	EOS6	102	2871	-	60	3875	-	25	5215	-
			BO6	108	2706	-	63	3687	-	25	5052	-
		Structurally top well (P0101)	EOS6	98	2993	-	59	3970	-	25	5235	-
			BO6	107	2743	-	63	3722	-	25	5061	-

Case

D1

File Name

A1C1X

Case Description

Near Critical Fluid

PVT Model

EOS6

GOR(3) **GOR(10)** **RFo(10)**

495 **1674** **17.9%**

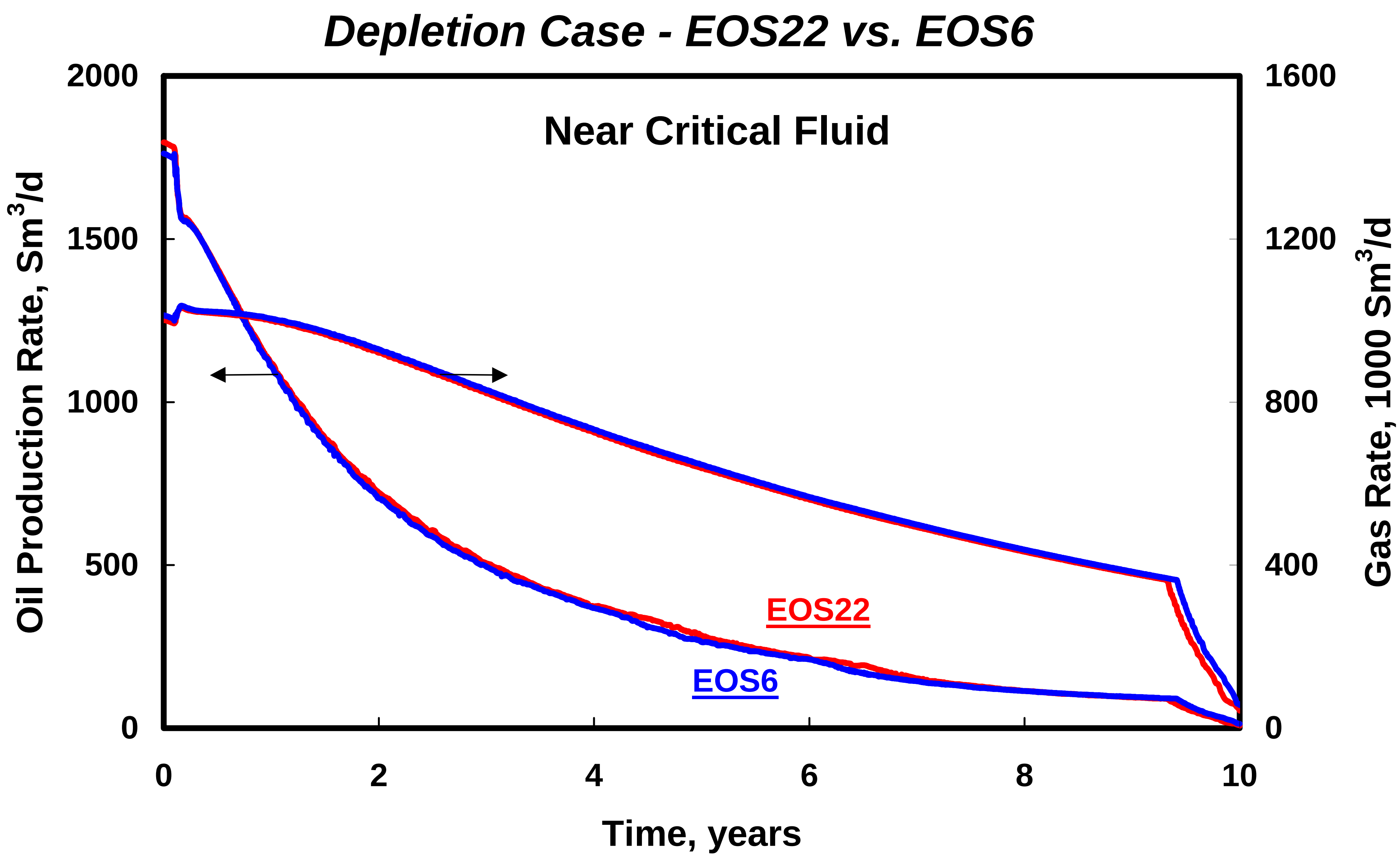
EOS22 versus EOS6

- Near-critical fluid system with constant composition
  - Depletion example
  - Gas injection example

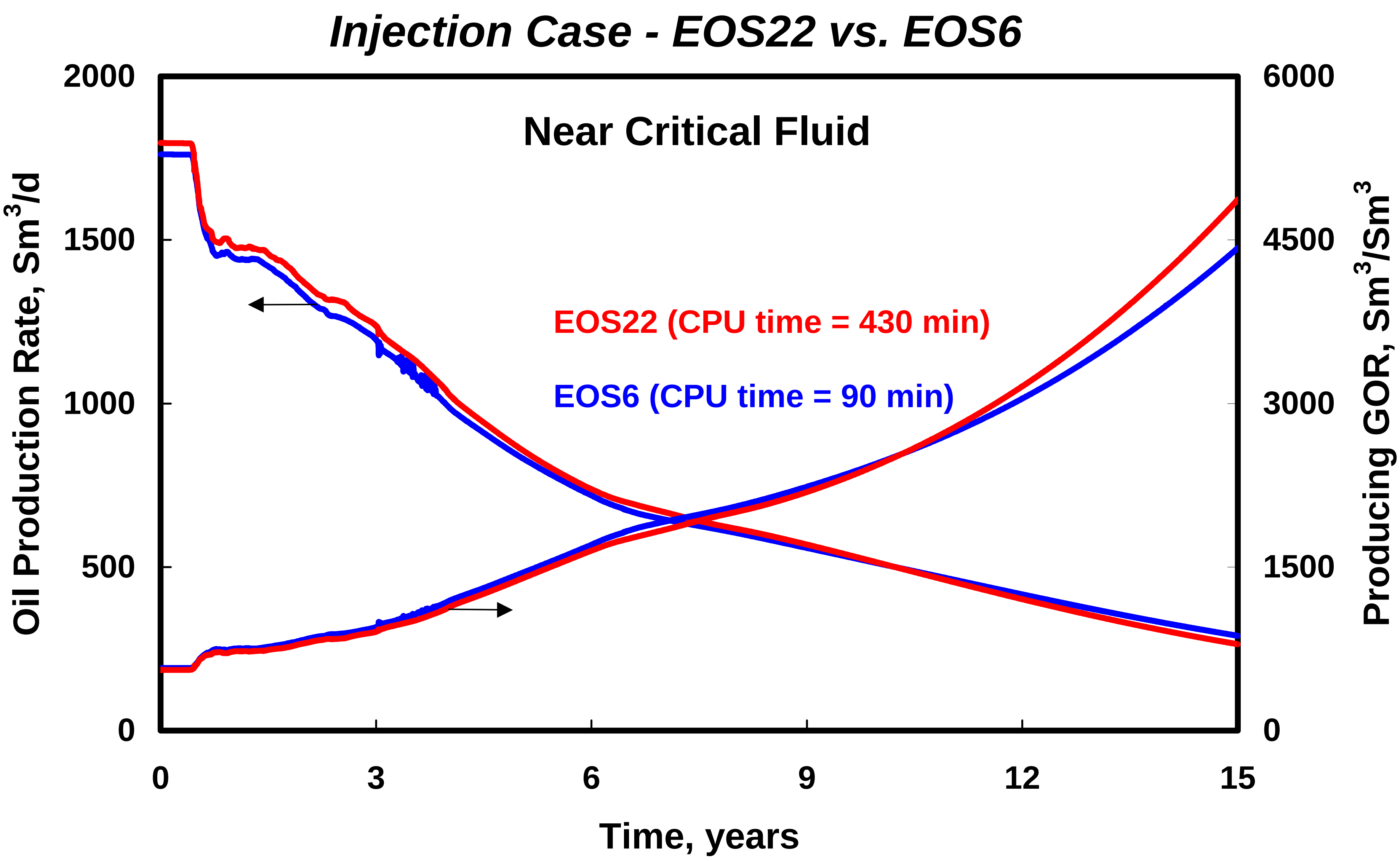
EOS Model Initialization

CASE	IOIP (10^6 Sm^3)	IGIP (10^9 Sm^3)	ΔIOIP[a] (%)	ΔIGIP[a] (%)
EOS22	13.22	11.02	-	-
EOS6, Method A	13.34	11.03	0.94	0.07
EOS6, Method B	12.96	11.13	-1.98	1.00
EOS6, Method C	13.10	11.08	-0.88	0.56

(a) Deviations relation to EOS22 values



Depletion Case - EOS22 vs. EOS6
Near Critical Fluid
Oil Production Rate, Sm3/d
Gas Rate, 1000 Sm3/d
Time, years
EOS22
EOS6
2000
1500
1000
500
0
1600
1200
800
400
0
0
2
4
6
8
10

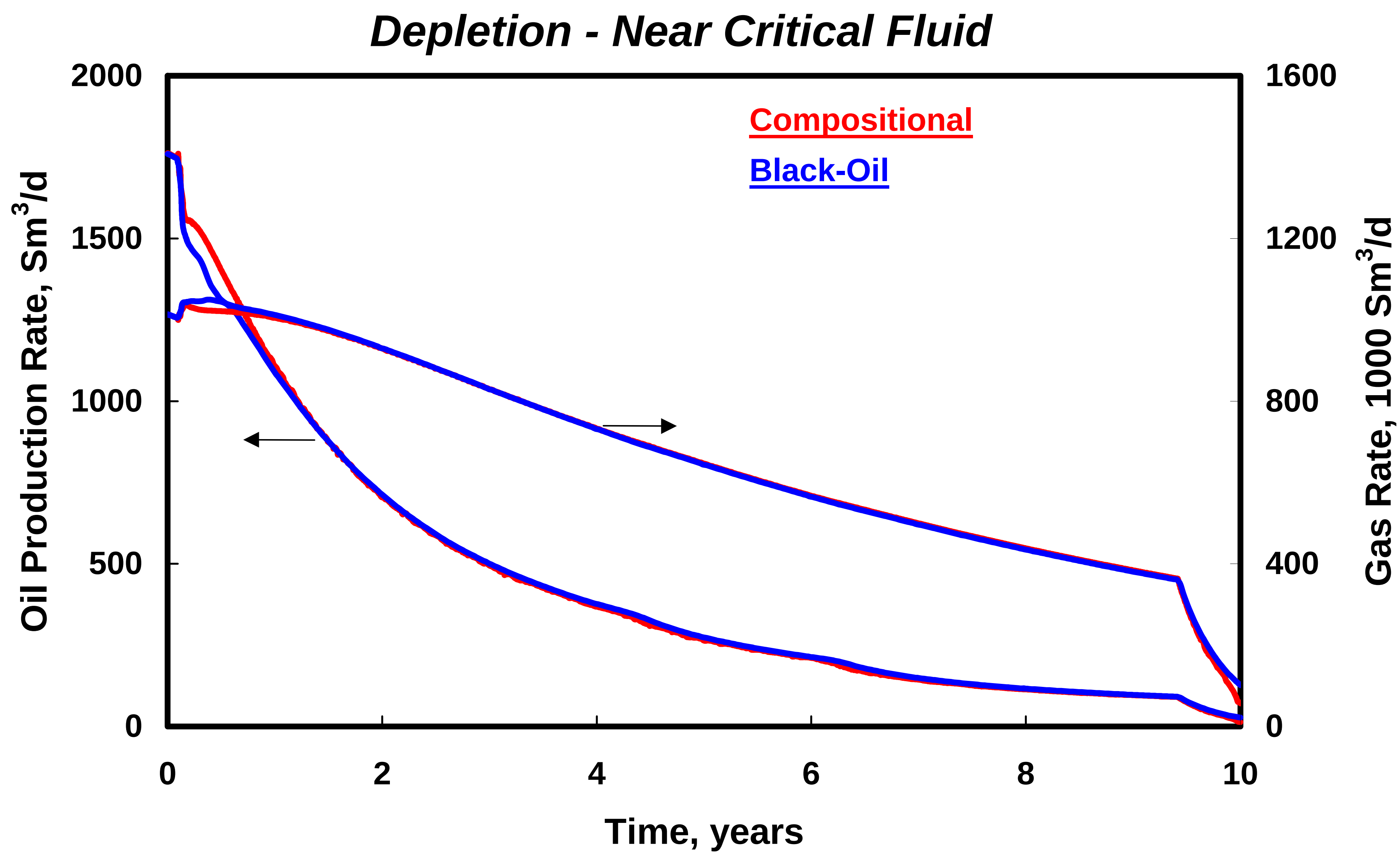


Injection Case - EOS22 vs. EOS6
Near Critical Fluid
EOS22 (CPU time = 430 min)
EOS6 (CPU time = 90 min)
Oil Production Rate, Sm3/d
Producing GOR, Sm3/Sm3
Time, years
2000
1500
1000
500
0
6000
4500
3000
1500
0
0
3
6
9
12
15

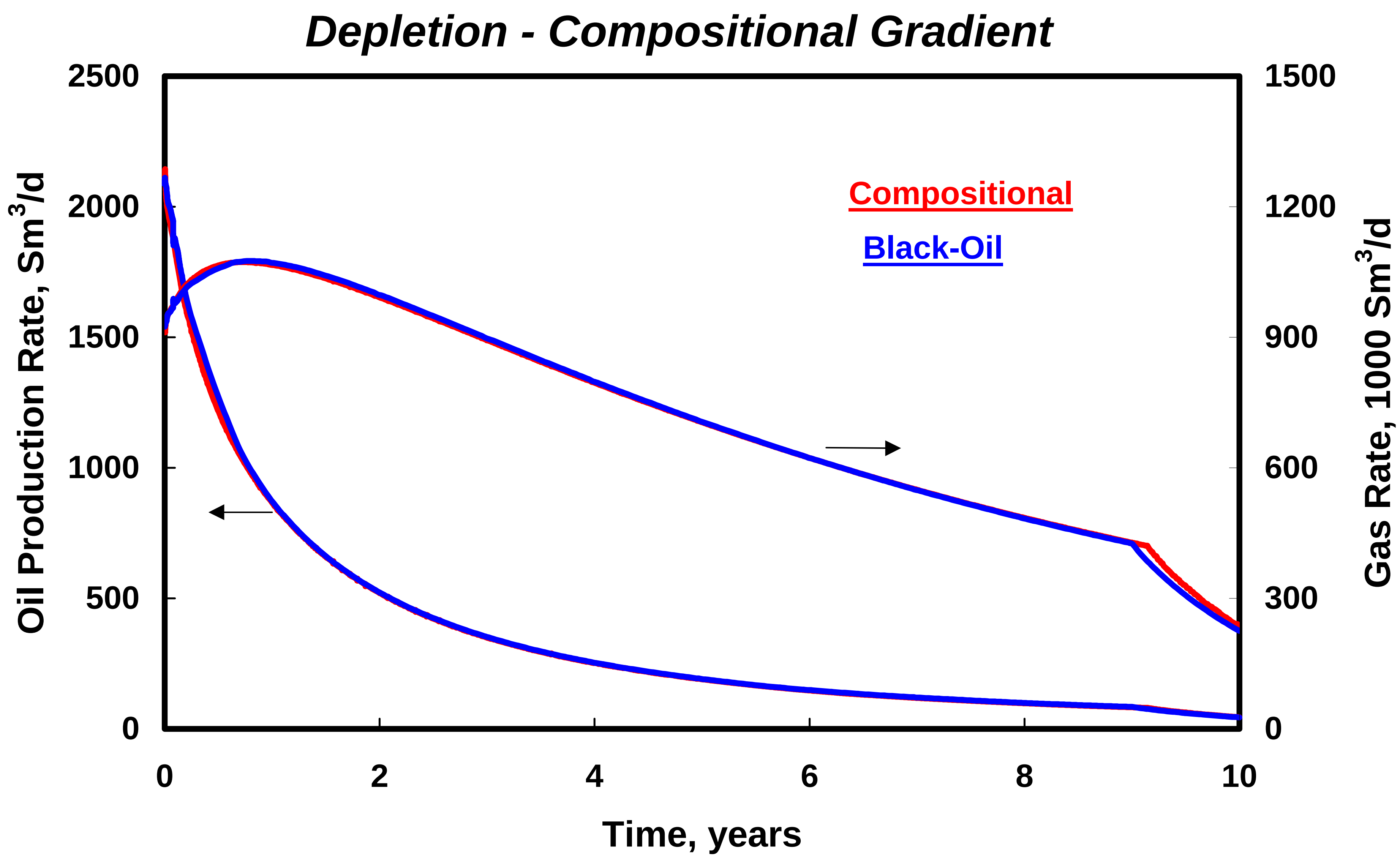
BOvsEOS Reservoir Simulations
Depletion Cases Examples

6-component EOS model and corresponding black-oil model used in all subsequent simulation

- **Undersaturated GOC**
  - **Near-critical fluid with constant composition**
  - **Near-critical to volatile oil with compositional gradient**



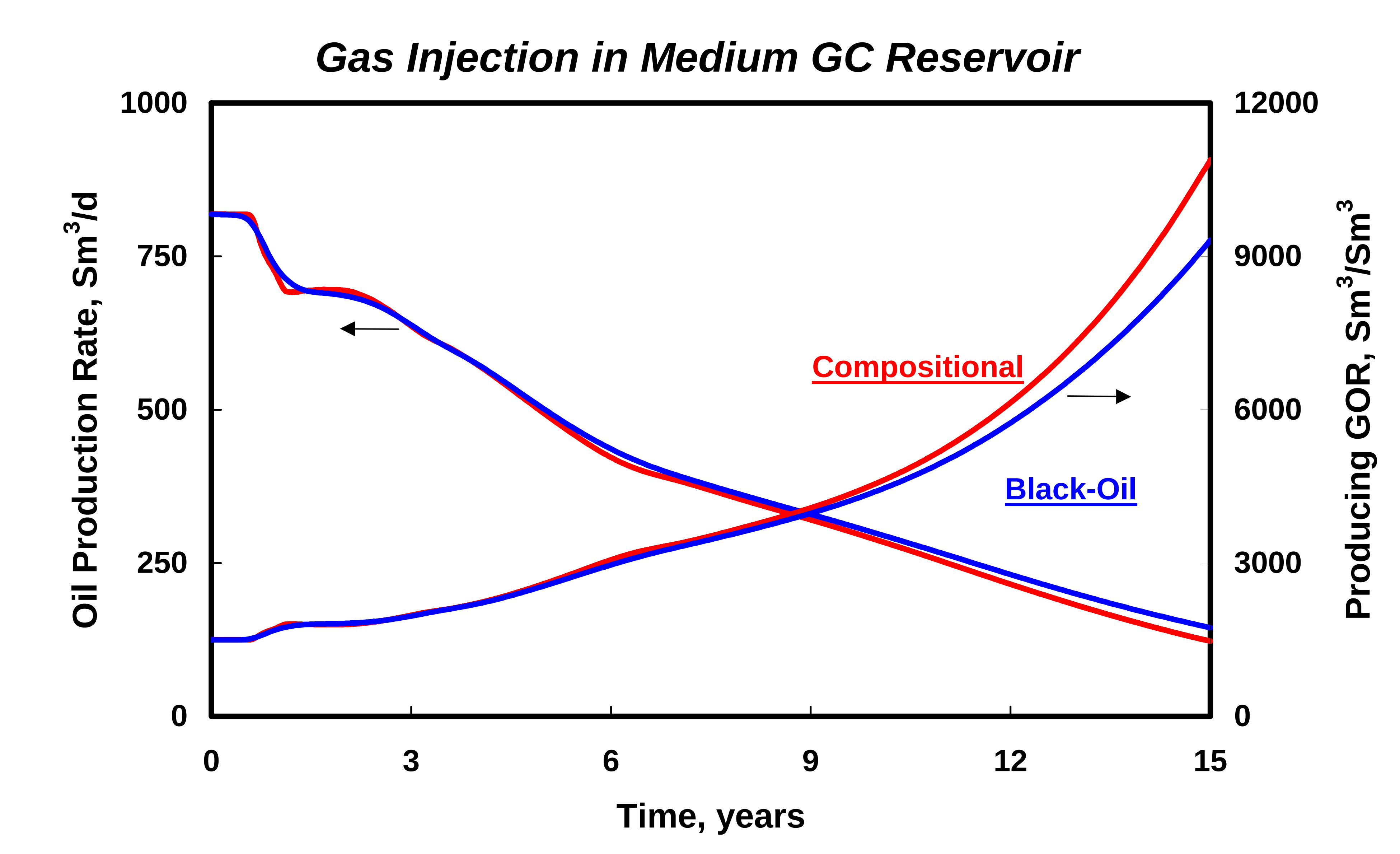
Depletion - Near Critical Fluid
Compositional
Black-Oil
Oil Production Rate, Sm3/d
Gas Rate, 1000 Sm3/d
Time, years
2000
1500
1000
500
0
1600
1200
800
400
0
0
2
4
6
8
10


Depletion - Compositional Gradient
Compositional
Black-Oil
Oil Production Rate, Sm³/d
Gas Rate, 1000 Sm³/d
Time, years
2500
2000
1500
1000
500
0
1500
1200
900
600
300
0
0
2
4
6
8
10

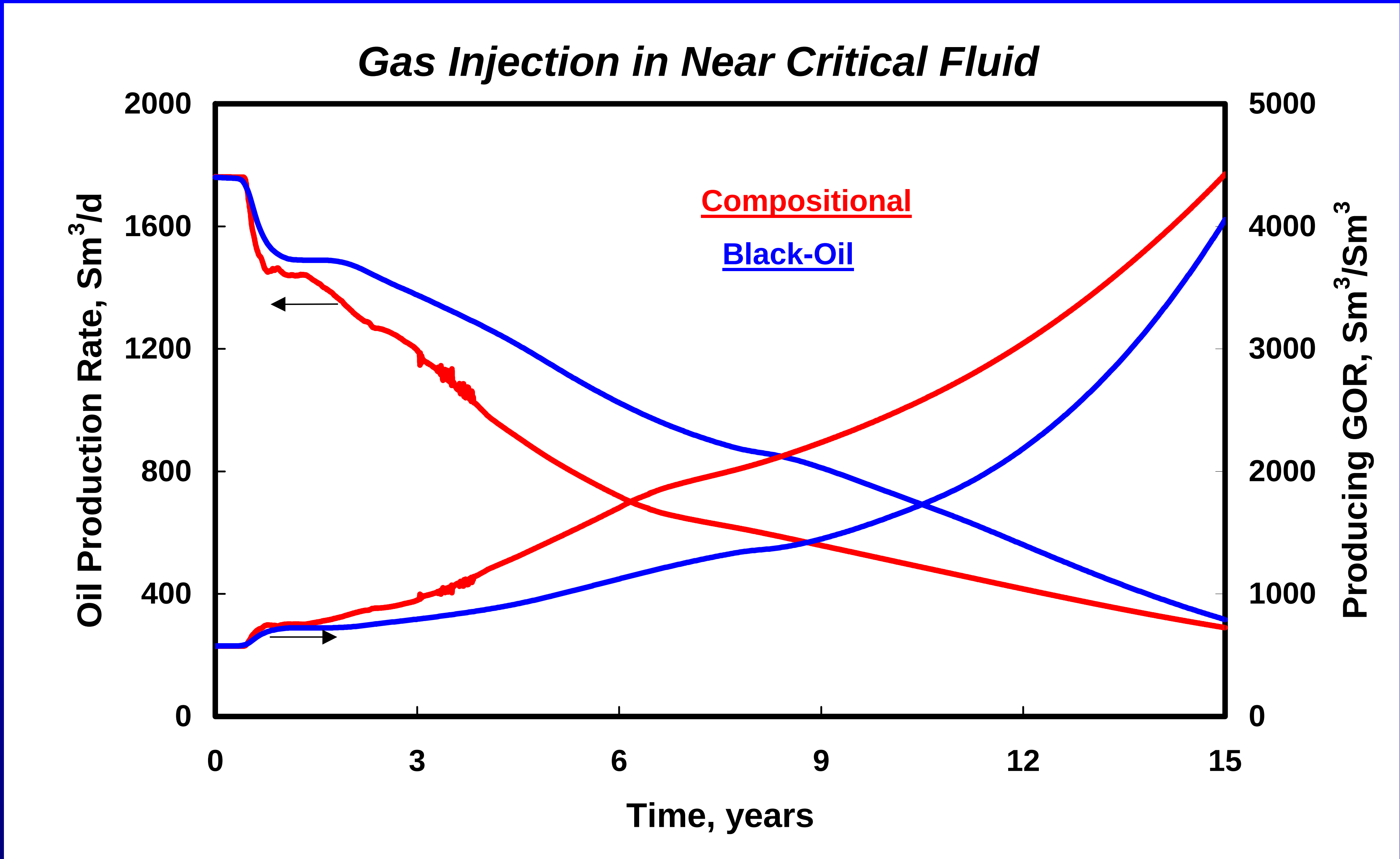
BOvsEOS Reservoir Simulations Gas Injection Cases Examples

Full Pressure Maintenance

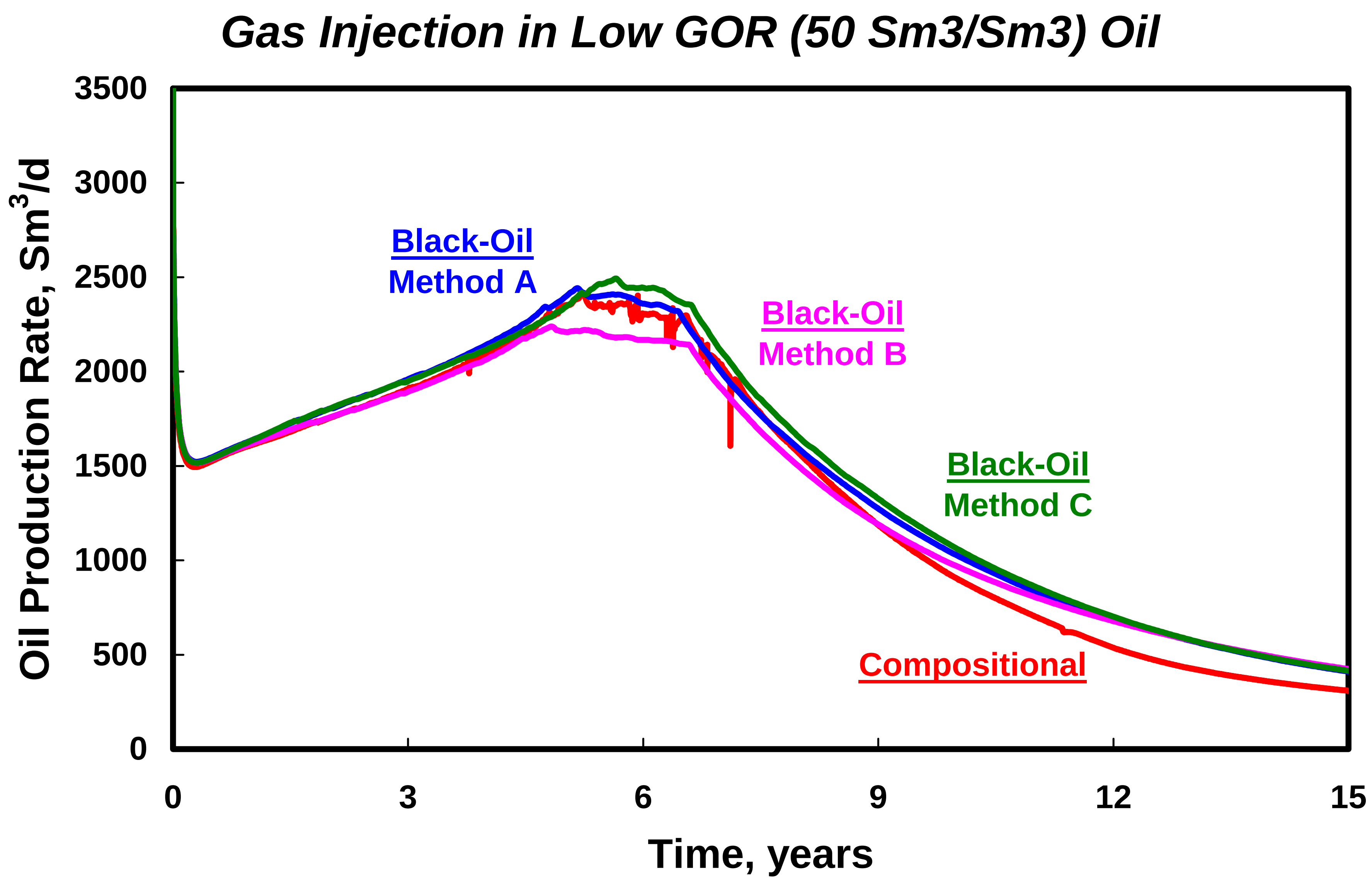
- Gas condensate reservoirs with constant composition
  - Medium rich gas condensate reservoir
  - Near critical fluid reservoir
- Oil reservoir with constant composition
  - Low GOR slightly undersaturated oil reservoir
  - Slightly volatile oil reservoir
- Reservoir with compositional gradient



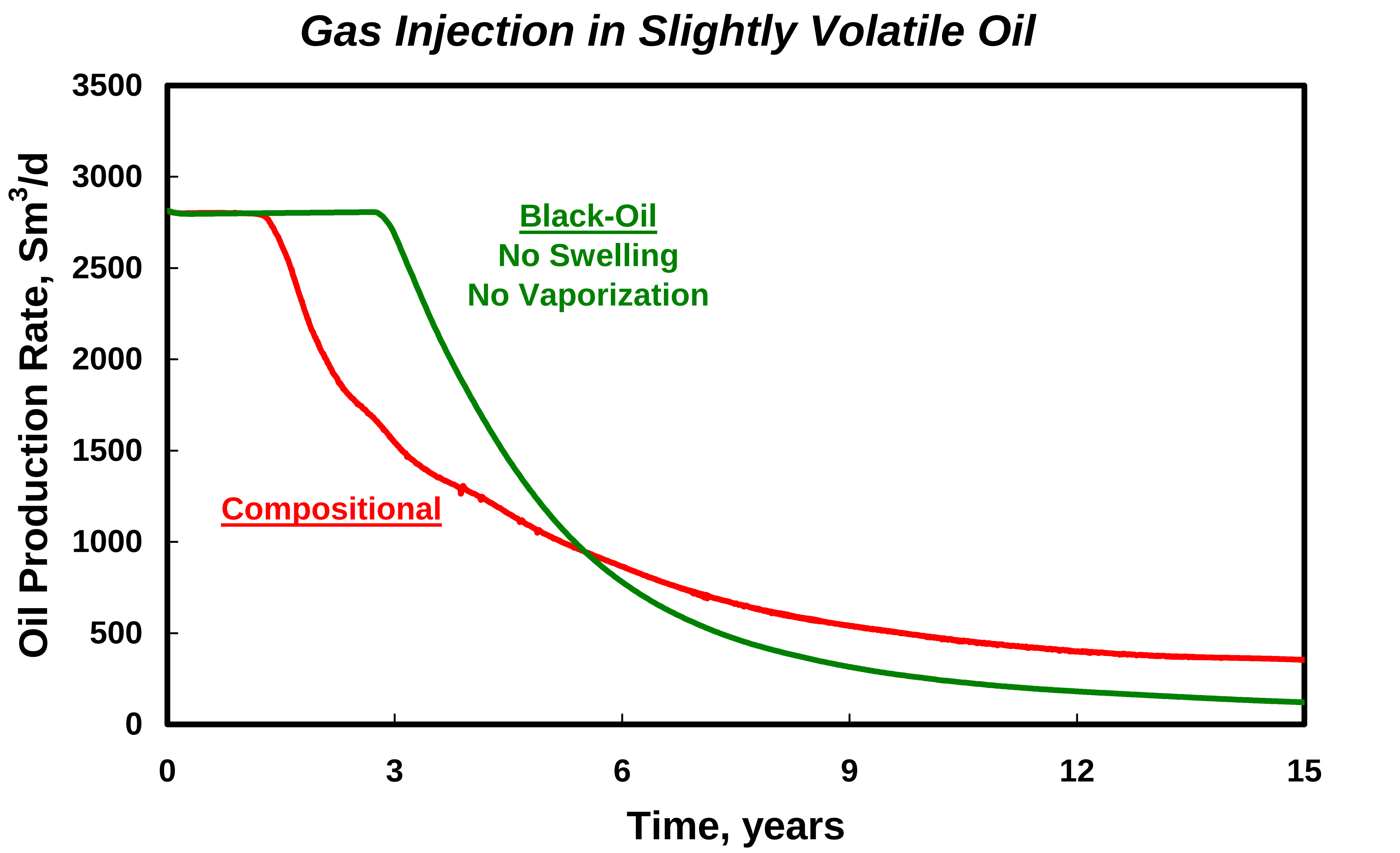
Gas Injection in Medium GC Reservoir
1000
750
500
250
0
Oil Production Rate, Sm³/d
12000
9000
6000
3000
0
Producing GOR, Sm³/Sm³
0
3
6
9
12
15
Time, years
Compositional
Black-Oil



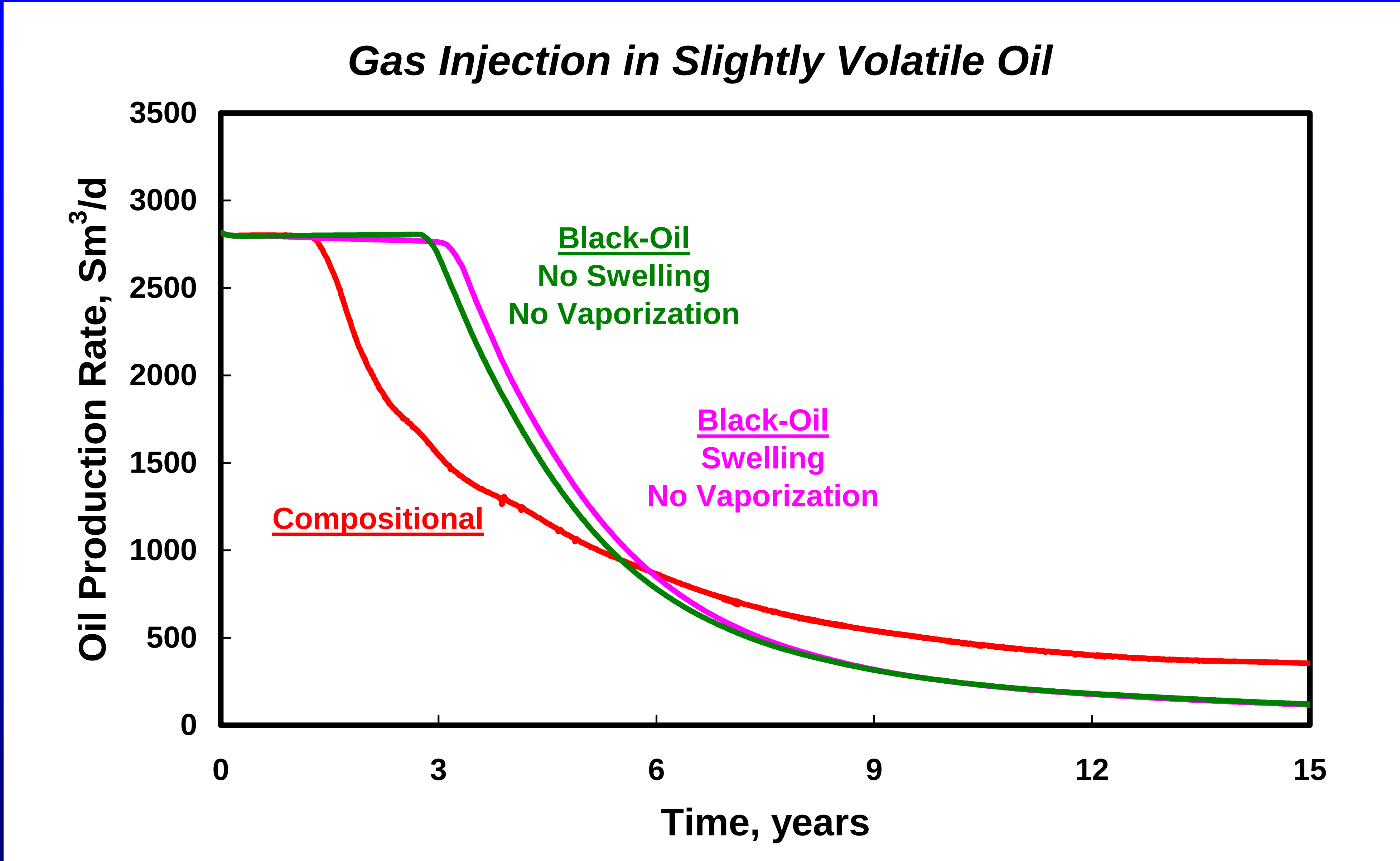
Gas Injection in Near Critical Fluid
Compositional
Black-Oil
Oil Production Rate, Sm3/d
Producing GOR, Sm3/Sm3
Time, years
2000
1600
1200
800
400
0
5000
4000
3000
2000
1000
0
0
3
6
9
12
15



Gas Injection in Low GOR (50 Sm3/Sm3) Oil
Oil Production Rate, Sm3/d
Time, years
3500
3000
2500
2000
1500
1000
500
0
0
3
6
9
12
15
Black-Oil
Method A
Black-Oil
Method B
Black-Oil
Method C
Compositional

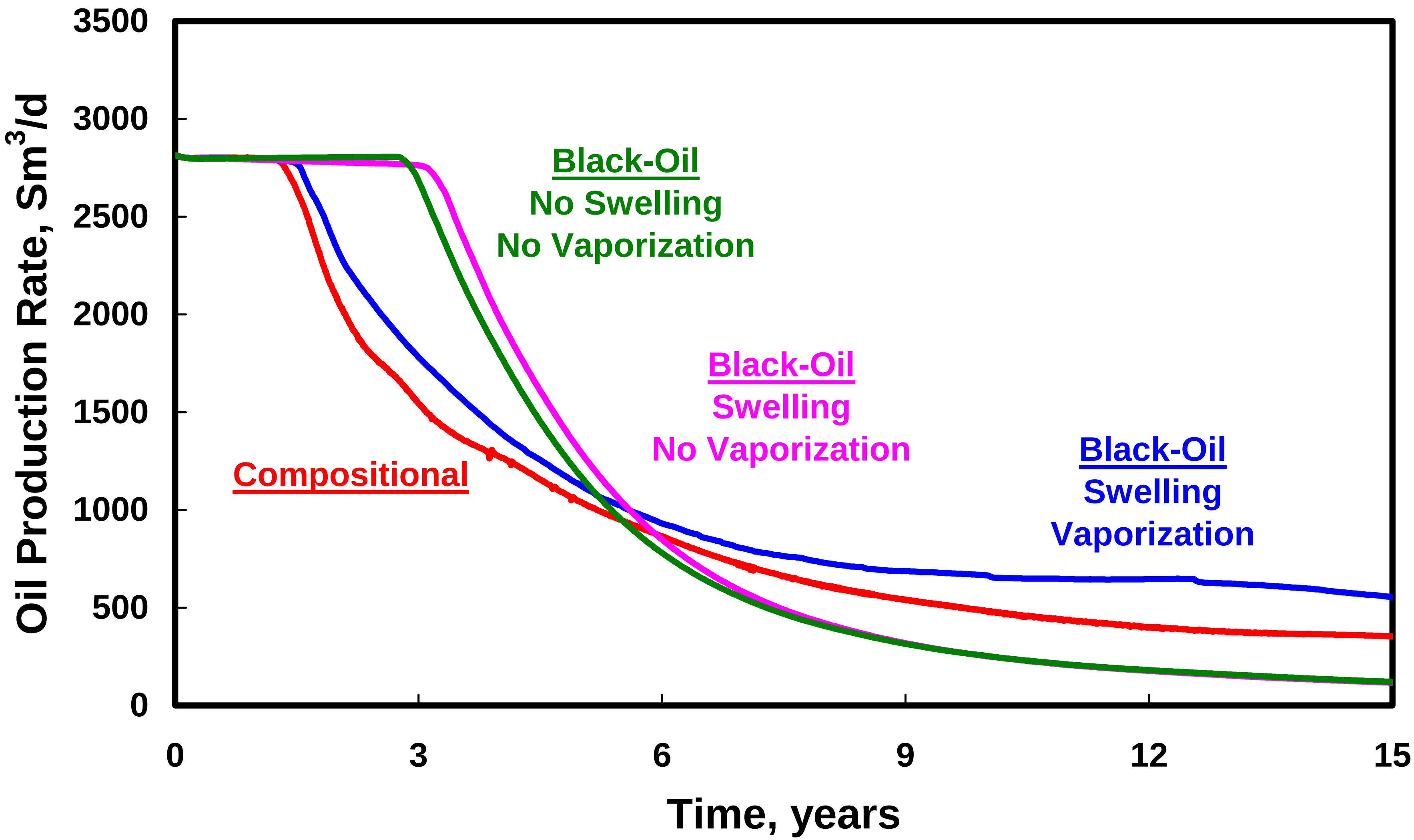


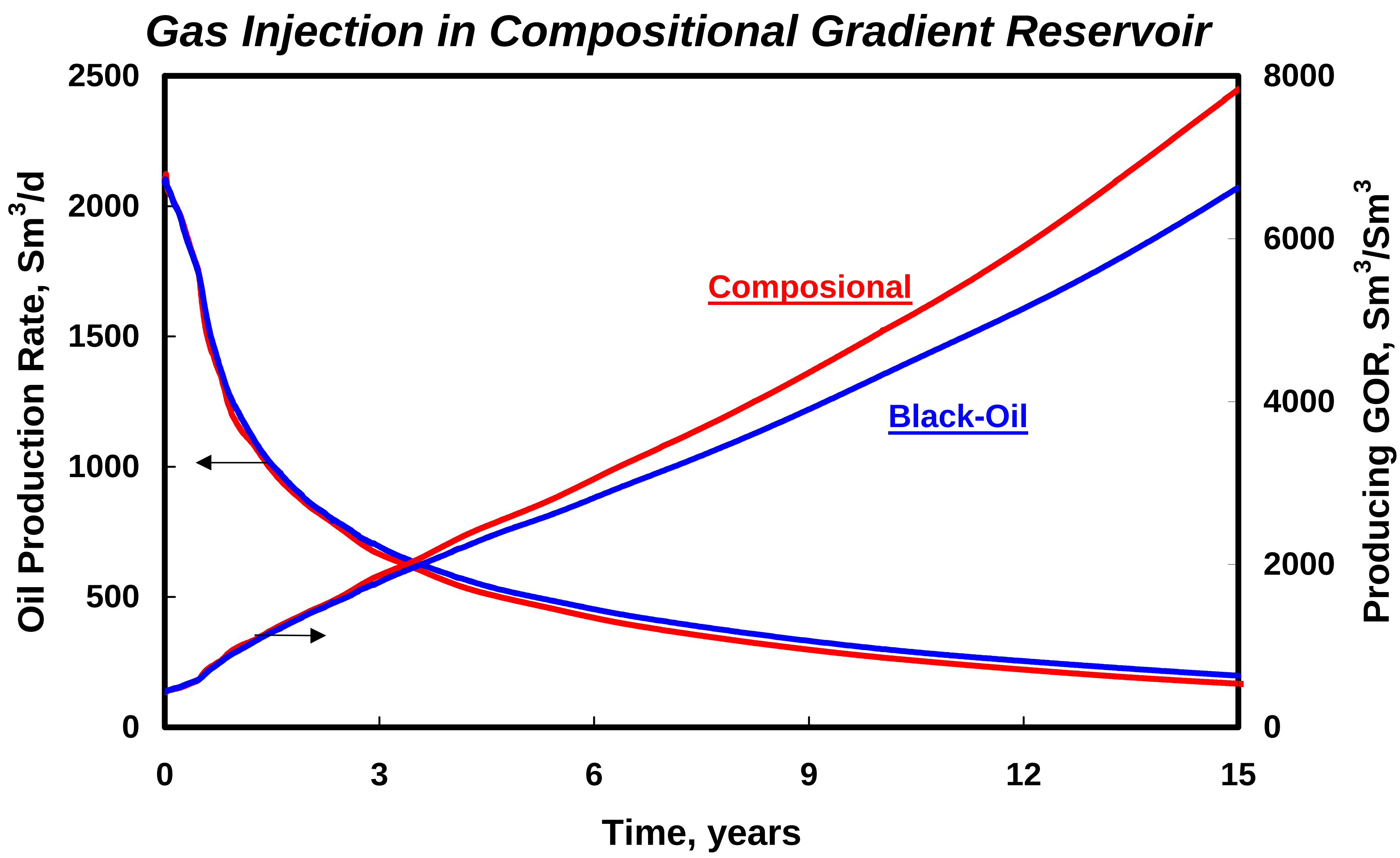
Gas Injection in Slightly Volatile Oil
Oil Production Rate, Sm3/d
3500
3000
2500
2000
1500
1000
500
0
0
3
6
9
12
15
Time, years
Black-Oil
No Swelling
No Vaporization
Compositional



Gas Injection in Slightly Volatile Oil
Oil Production Rate, Sm³/d
3500
3000
2500
2000
1500
1000
500
0
0
3
6
9
12
15
Time, years
Black-Oil
No Swelling
No Vaporization
Black-Oil
Swelling
No Vaporization
Compositional

Gas Injection in Slightly Volatile Oil




Gas Injection in Compositional Gradient Reservoir
Oil Production Rate, Sm3/d
2500
2000
1500
1000
500
0
Producing GOR, Sm3/Sm3
8000
6000
4000
2000
0
Composional
Black-Oil
0
3
6
9
12
15
Time, years

Main Conclusions
Depletion Cases

- **Black-Oil models are always OK**

… if black-oil tables
are generated properly

Main Conclusions
Gas Injection Cases

- Black-Oil is not recommended in general.

- A few exceptions where black-oil is OK:
  - Minimal vaporization effects (r_s ~ 0)
    - Swelling + viscosity reduction only
  - Gas cycling gas condensate above dew point for lean to medium-rich gas condensate reservoirs

Main Conclusions
Initialization - IFIP

- **EOS model**
  - **Calculate compositional gradient from the original EOS model.**

- **Black-Oil model**
  - **Use solution GORs and OGRs versus depth**
  - **Generate black-oil PVT data from properly selected fluid.**

Main Conclusions
Pseudoization

- Split C_{7+} (or C_{10+}) fraction into 3-5 fractions
- Pseudoize down to as few as 6 to 8 components
- while pseudoization, adjust key component properties to minimize the difference between the pseudoized and the original EOS

Acknowledgements

Conoco

Elf Petroleum Norge

Mobil Exploration Norway Inc.,

Neste Petroleum

Norsk Hydro

Norwegian Petroleum Directorate

Statoil

Different Fluid Systems

- Gas-to-oil gradient throughout
- Gas gradient only
- Oil gradient only
- Constant gas composition throughout
- Constant oil composition throughout
  - undersaturated
  - saturated
- Low-GOR oil constant composition throughout
  - somewhat undersaturated
  - highly undersaturated

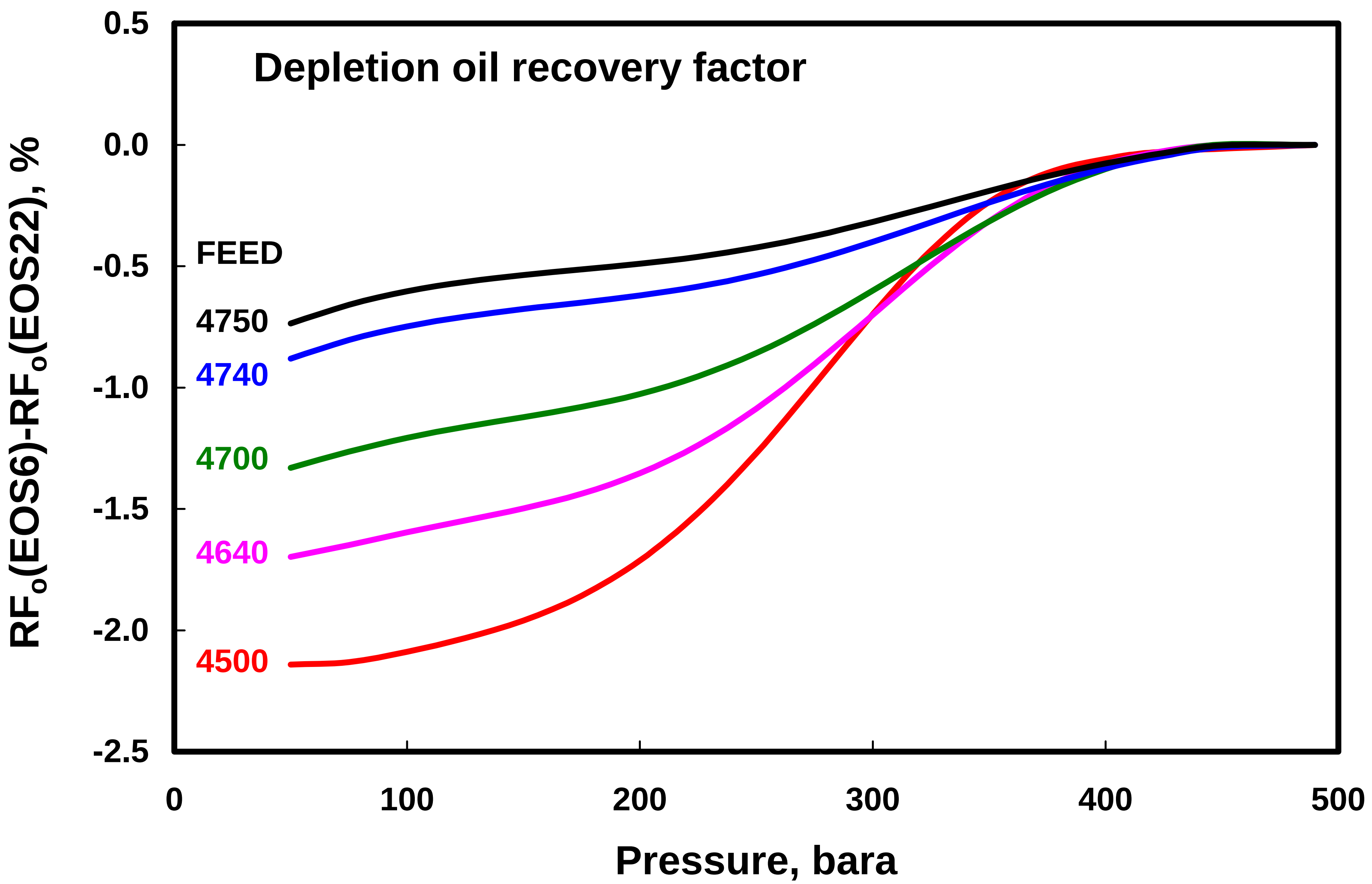
Simulation Model Initialization

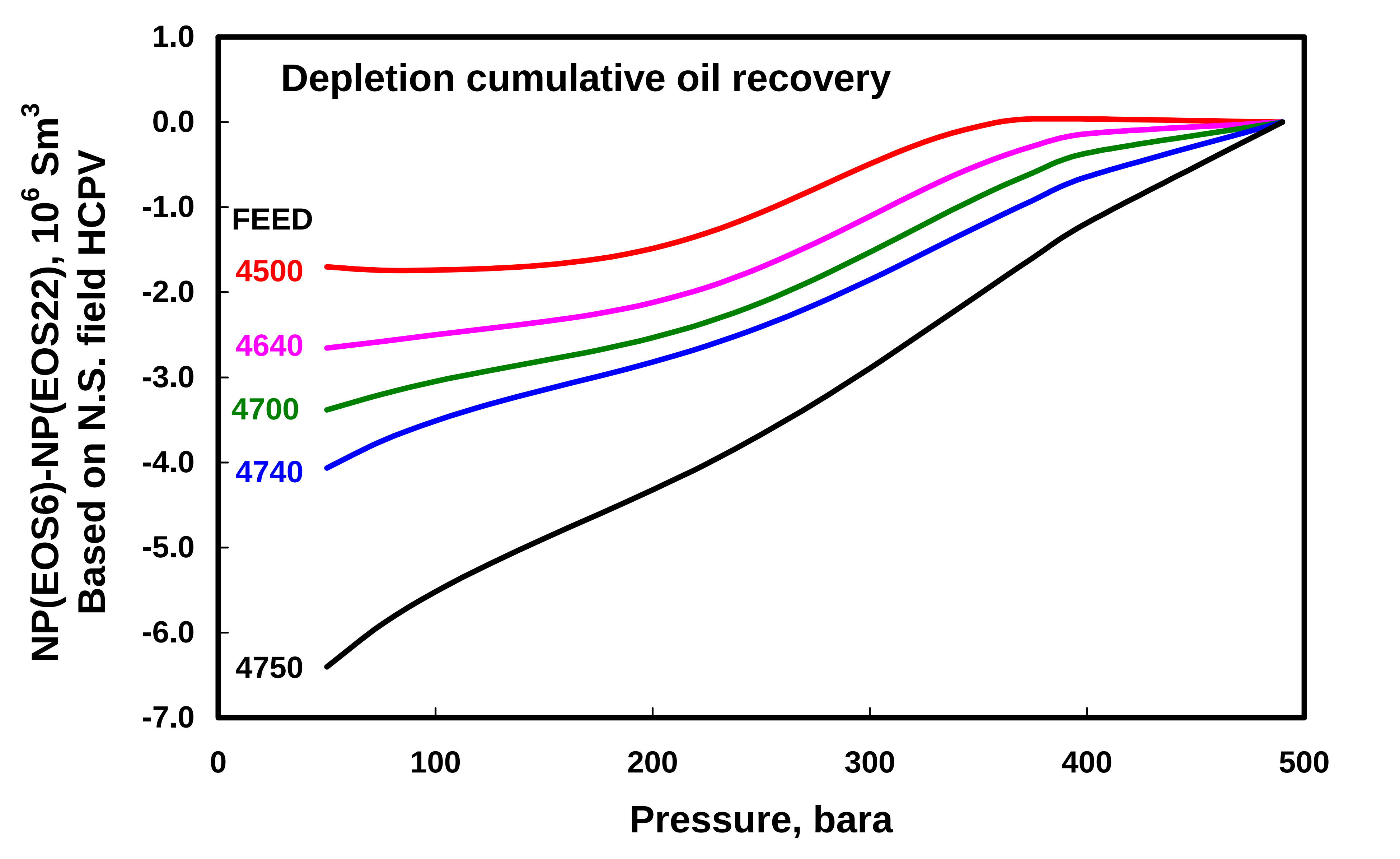
CASE	IOIP (10^6 Sm^3)	IGIP (10^9 Sm^3)	ΔIOIP[a] (%)	ΔIGIP[a] (%)
EOS22	13.22	11.02	-	-
BO 22 (GOR vs D)	13.15	11.08	-0.55	0.51
BO 22 (Psat vs D)	14.78	10.74	11.82	-2.53
EOS6	13.10	11.08	-0.88	0.56

(a) Deviations relation to EOS22 values

EOS and Viscosity Models

- **SRK model**
- **Pedersen et al. viscosity correlation for viscosity**
- **Tuned LBC correlation to match Pedersen et al. viscosity**
- **Generated higher oil viscosities (>0.5 cp) using mixtures of the reference fluid and Methane and then flashing in the range of 100 to 300 bara**


Depletion oil recovery factor
FEED
4750
4740
4700
4640
4500
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
0
100
200
300
400
500
Pressure, bara
RFo(EOS6)-RFo(EOS22), %



Depletion cumulative oil recovery
NP(EOS6)-NP(EOS22), 10^6 Sm^3
Based on N.S. field HCPV
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
FEED
4500
4640
4700
4740
4750
0
100
200
300
400
500
Pressure, bara

Generating Original EOS22 PVT "Data"

- Simulate a set of experiments with many feeds
  - CCE, CVD, DLE, SEP, MCV
- Weigh individual data and types of data to emphasize key properties for a given reservoir recovery process

Stepwise Pseudoization

Reducing Number of Components

- Group components to form new pseudocomponents
- Regress on newly-formed pseudocomponent EOS properties to get best fit of original EOS model "data"
- Evaluate pseudo-EOS with original-EOS using "key" PVT properties including equilibrium compositions
- Accept new pseudo-EOS model, or return to start with a different selection of new pseudocomponents