“What Makes An Oil Well Tick?”

Back to Basics

(SPE Los Angeles Basin Section)

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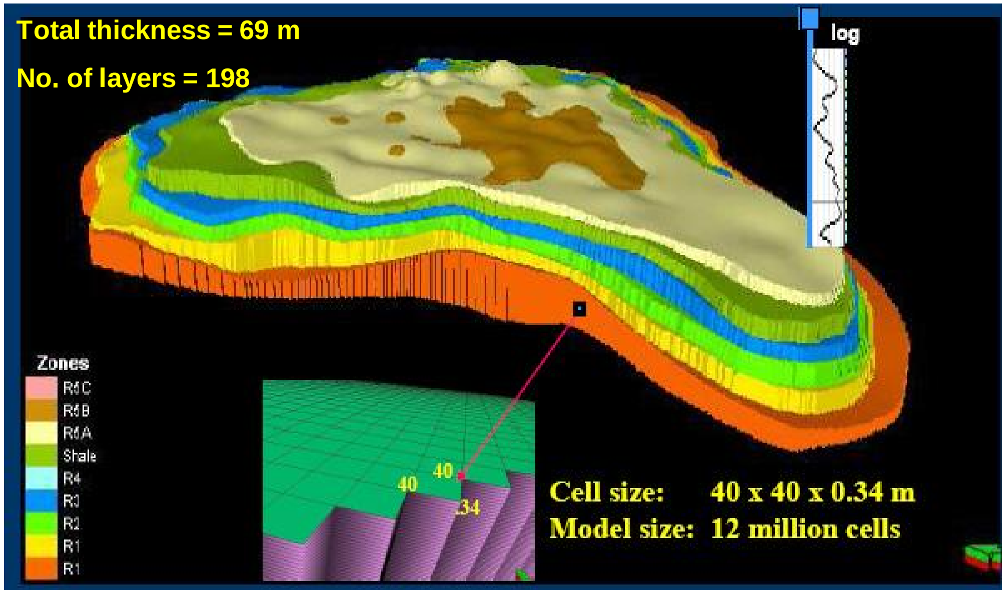
Presentation Outline – 'Back to Basics'

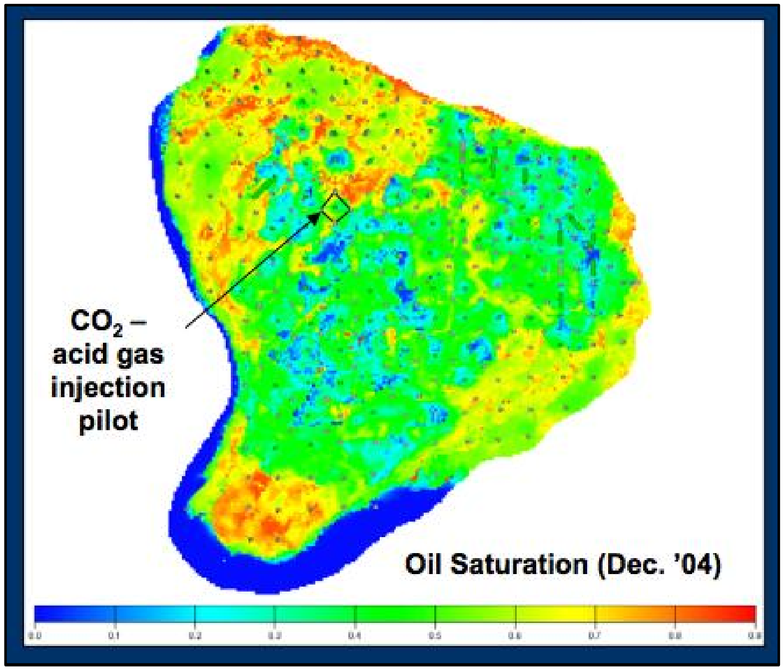
- Need for Realistic Oil Rate Estimation
- Special Core Analysis, Relative Permeability
- Recoverable Oil, Sweep Efficiencies
- Radial Flow Equation
- Production & Injection Rate Estimation

Realistic Oil Rate Estimation for Investment Decisions

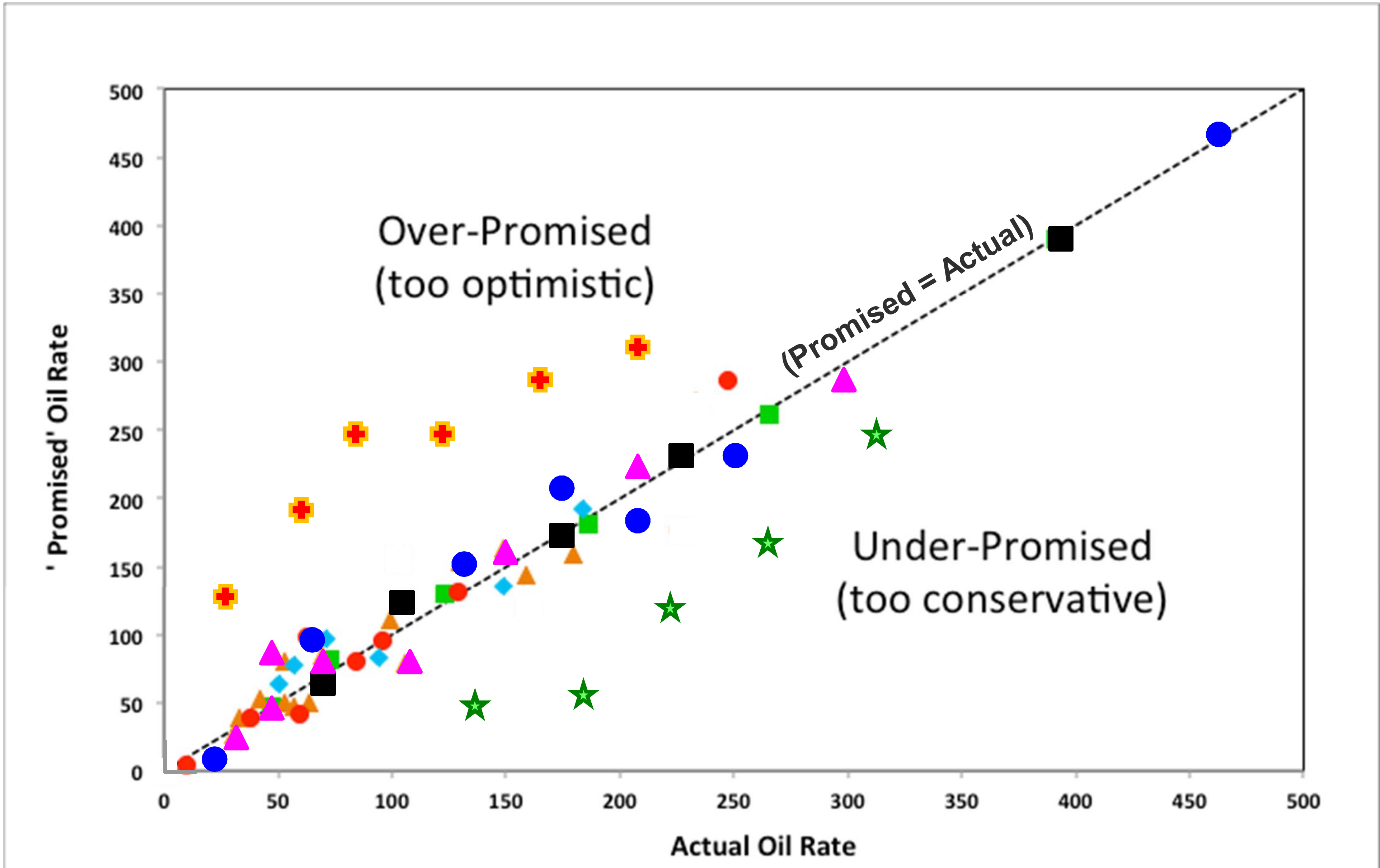
- Well workovers (acid, fracture, pump upsize)
- Infill producers
- Producer to water injector conversions
- Asset acquisition – oil well production upsides



• Honoring the back-stepping geometry.

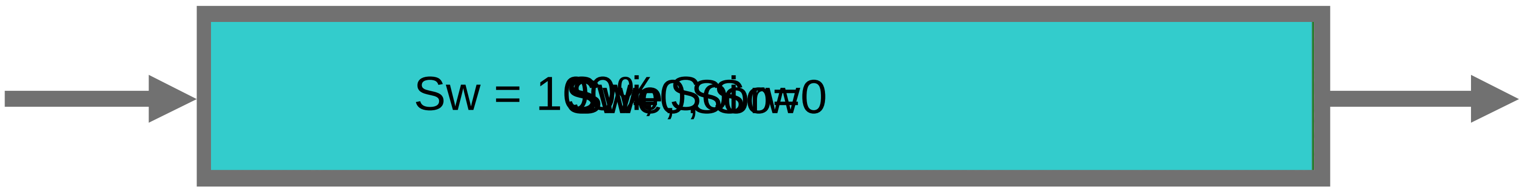


Example: Promised vs. Actual Oil Rate



Special Core Analysis

Water-Oil Relative Permeability



1) Core is cleaned of fluids, then dried.

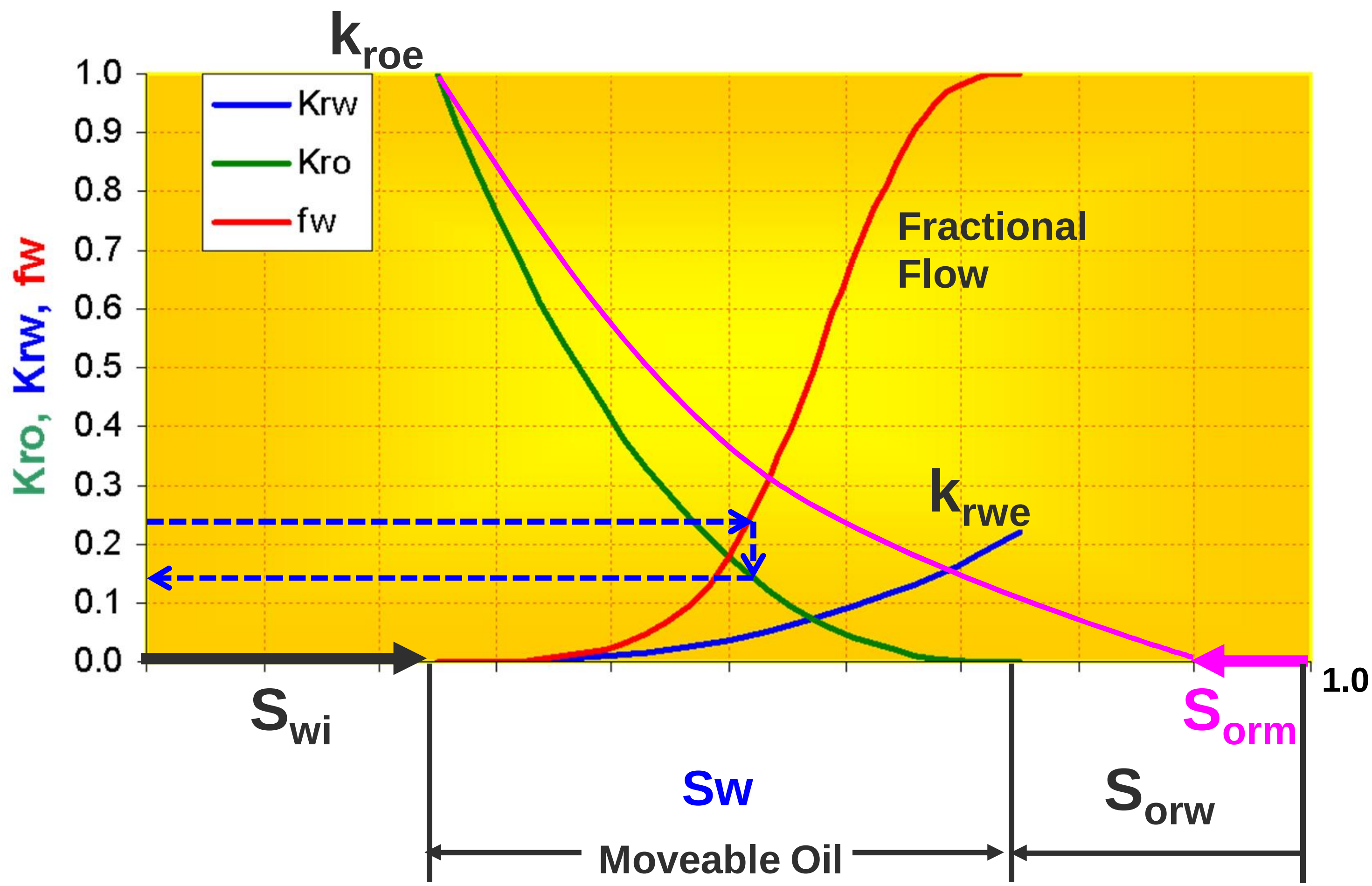
2) Water is injected to saturate core to 100% S_w.

3) Oil is injected through core, until no water at effluent to establish S_{wi}. Core is then aged for a period of time.

4) Special core analysis is then conducted by injecting water into core, and measuring effluent oil and water quantities. Relative permeability curves are then established.

Determine saturation end points and curves (Swi, Sorw, Kro, Krw).

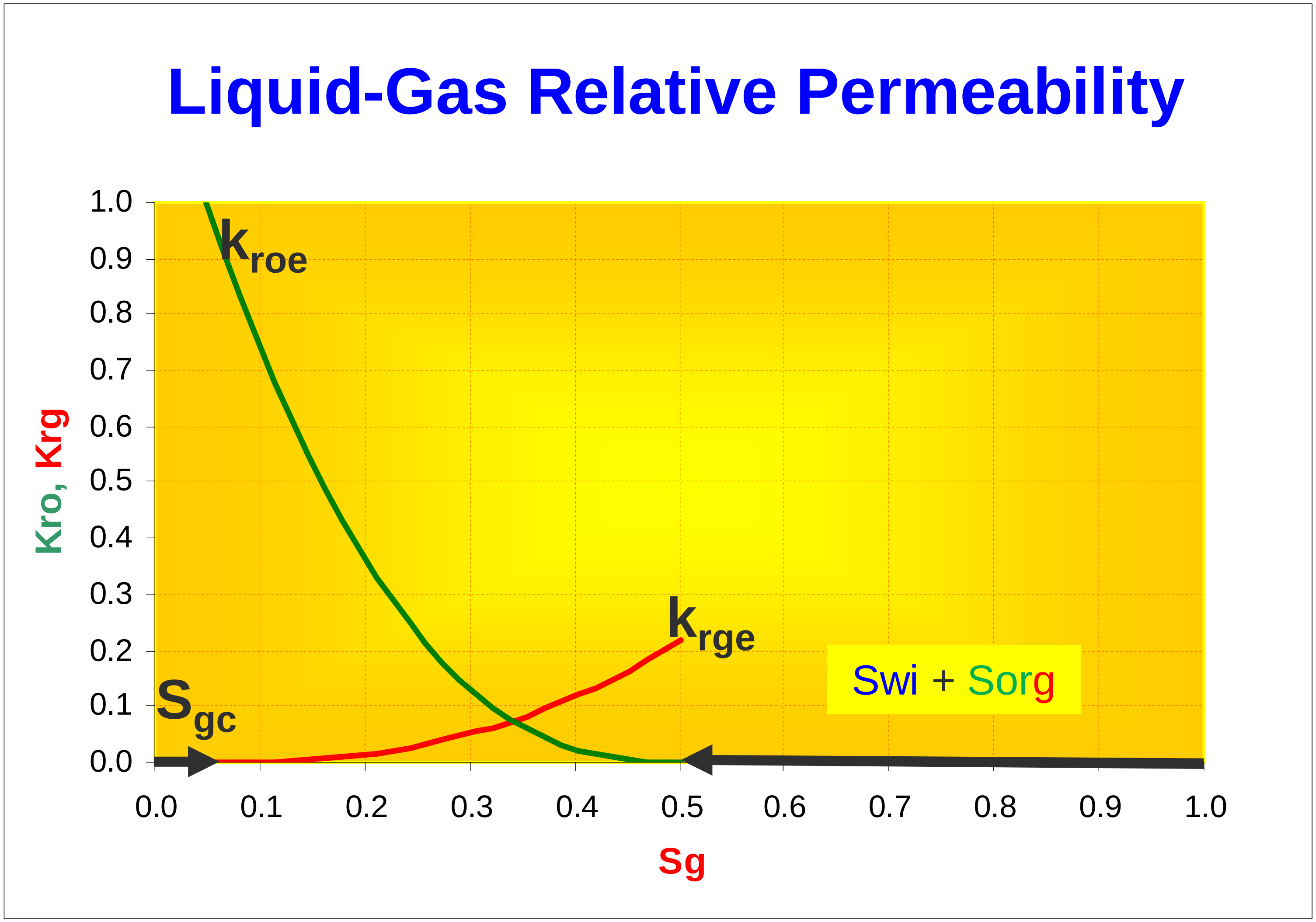
Relative Permeability Concept
Oil-Water



Fractional flow in reservoir units. Could use surface water cut to approximate.

Relative Permeability Concept

Liquid-Gas (with S_{wi})



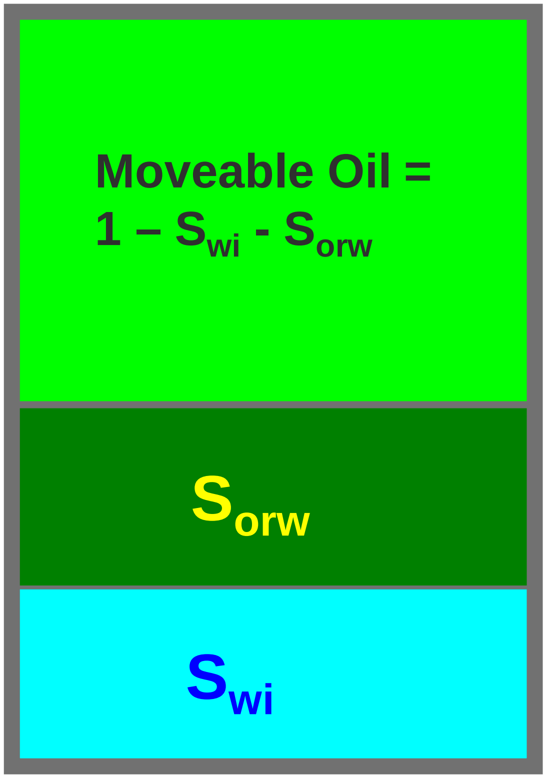
Presence of gas (>Sgc) reduces effective oil permeability.

Moveable Oil, Sweep, Recovery Factor

Oil-Water System

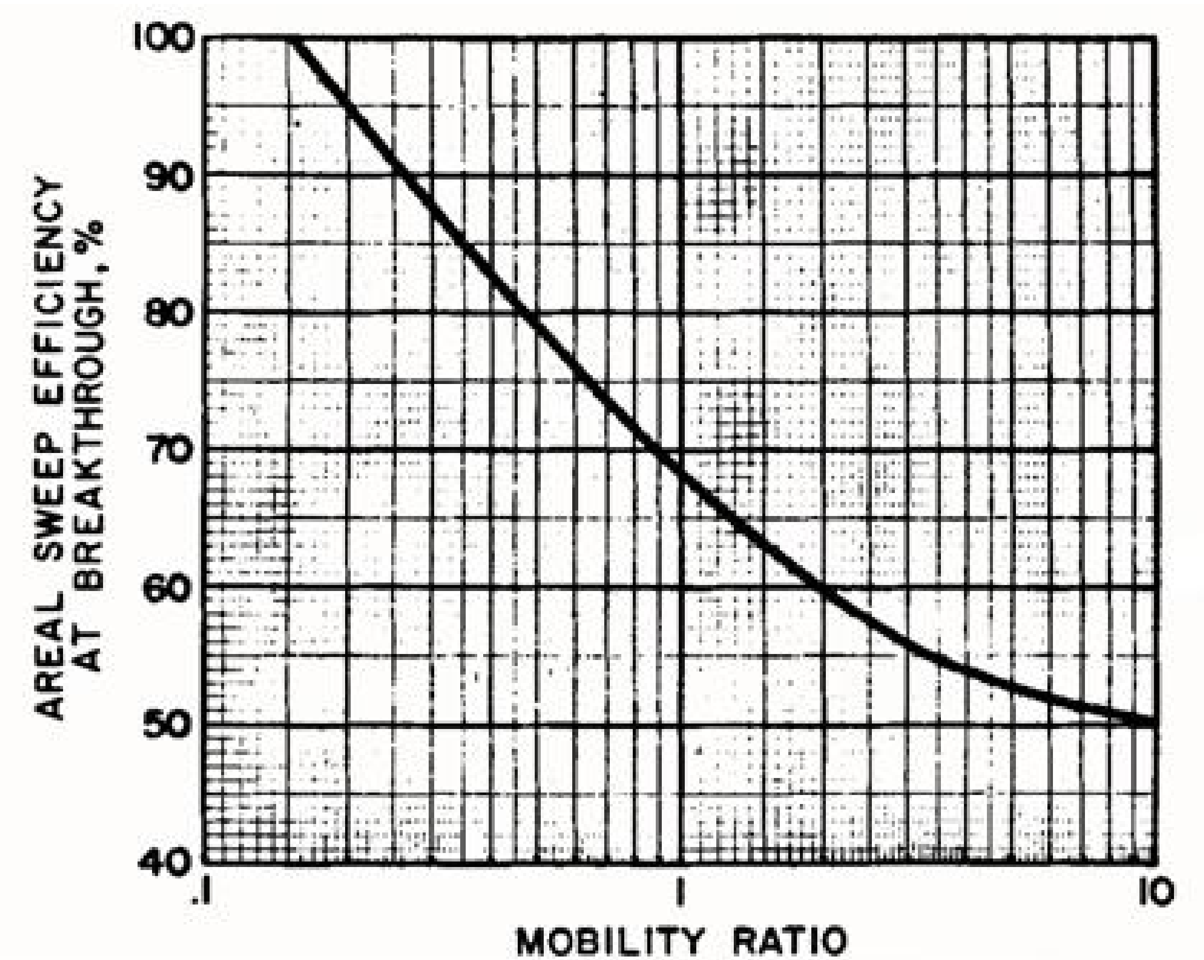
- Oil-in-place = $1 - S_{wi}$
- Residual oil after waterflood = S_{orw}
- Moveable Oil = $1 - S_{wi} - S_{orw}$
- Displacement Efficiency, E_d

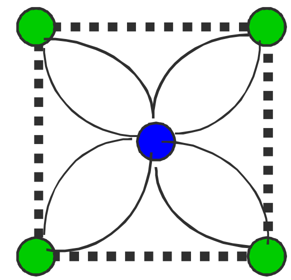
  = $(1 - S_{wi} - S_{orw}) / (1 - S_{wi})$
- Vertical Sweep Efficiency = E_v
- Areal Sweep Efficiency = E_a
- **Recovery Factor = $E_d * E_v * E_a$**



Note: areal and vertical sweep efficiencies are different for vrt. vs. hrz. flood.

Areal Sweep Efficiency at Breakthrough,
Inverted 5-Spot Waterflood Pattern

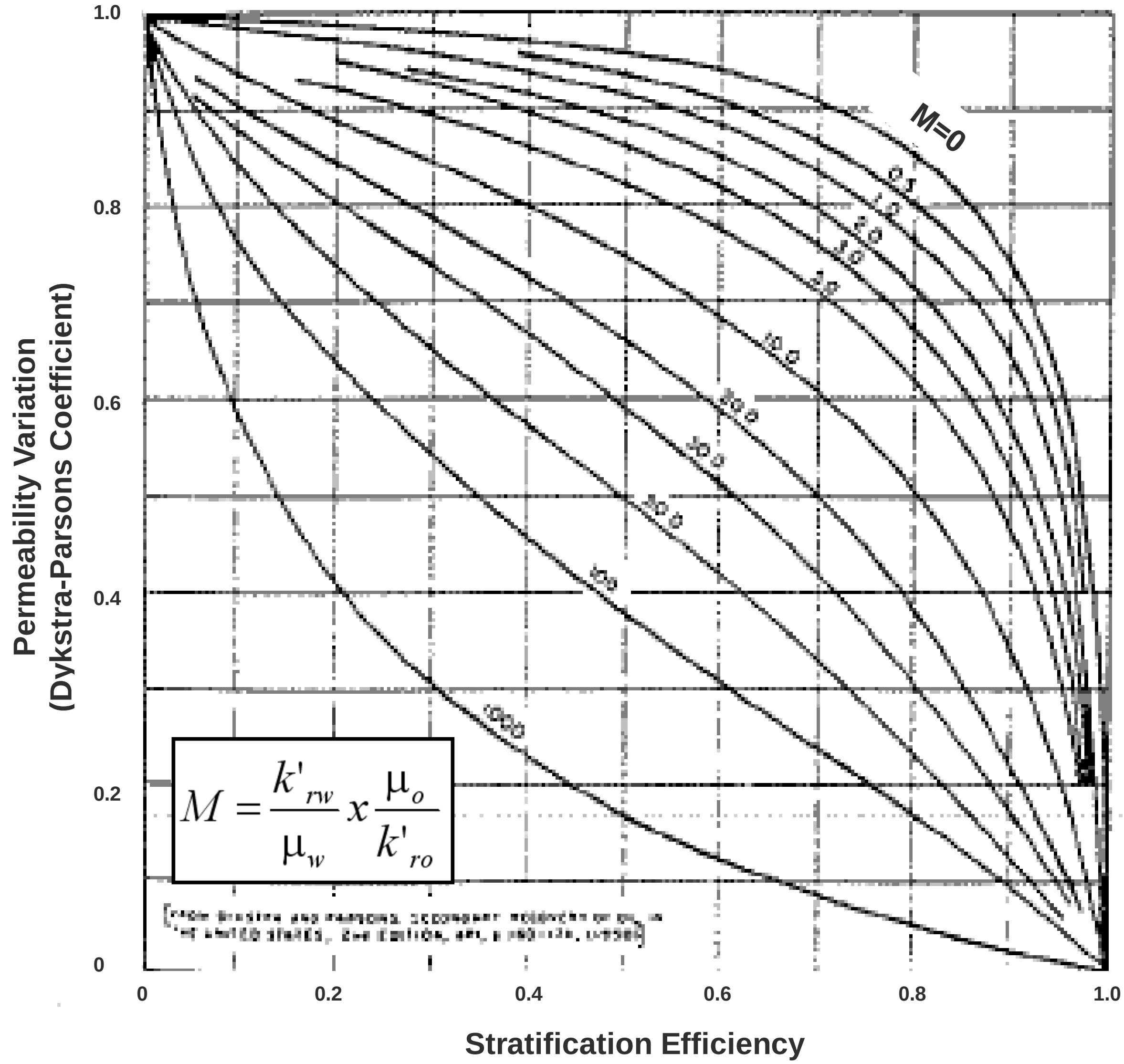




$$M = \frac{k'_{rw}}{\mu_w} x \frac{\mu_o}{k'_{ro}}$$

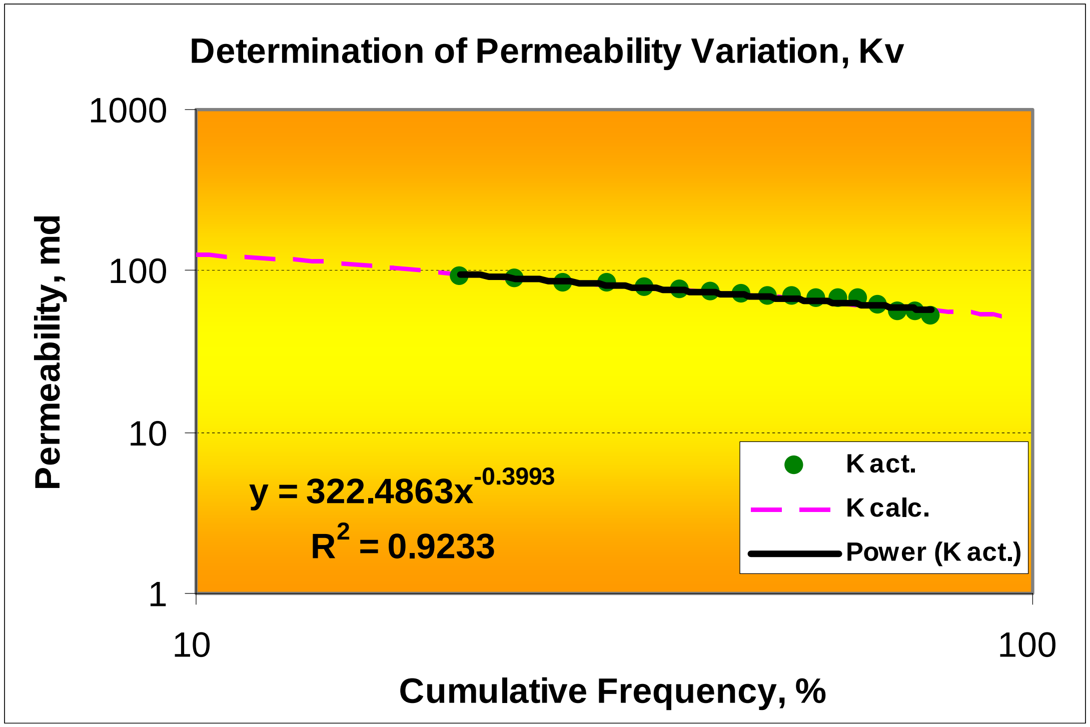
Areal sweep ~68% with M=1.0. Parallel hrz well drive could sweep better.

Vertical Sweep @ WOR=25 (96.15% Water Cut)



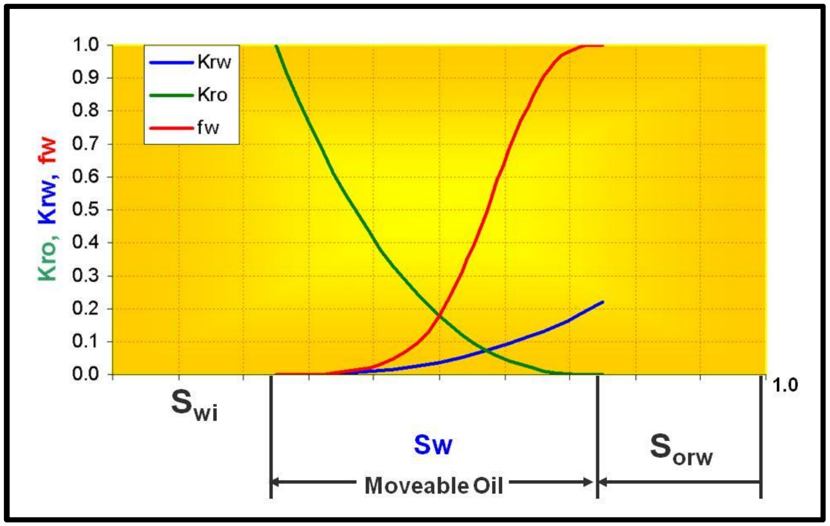
Dykstra-Parsons Coefficient

- A measure of overall permeability stratification / zonation in each well.
- Assume no cross-flow between layers.
- List core permeability values in descending order, and calculate for each value percentage of samples having higher permeability values. (0% for the highest permeability, and ~100% for the lowest).
- Permeability variation, Dykstra-Parsons Coefficient, $k_v = (k_{50\%} - k_{84.1\%}) / k_{50\%}$.
- **K_v = 0 (homogeneous); K_v = 1 (heterogeneous)**



Power relationship: $y=cx^b$			
c =	322.4863	b =	-0.3993
$k_{50\%}$ =	67.63	$k_{84.1\%}$ =	54.95
k_v =	0.19		

Waterflood Recovery Factor Estimation Example



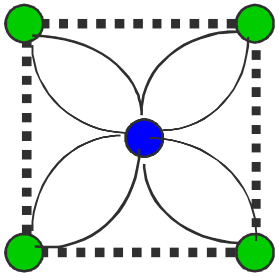
Given:

S_{wi} = 0.25, S_{orw} = 0.30

If:

Areal Sweep Efficiency = 70%

Vertical Sweep Efficiency = 80%



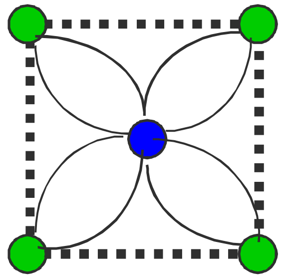
Then:

Moveable Oil = 1 – 0.25 – 0.30 = 0.45

Displacement Efficiency = 0.45 / 0.75 = 60%

Total Recovery Factor = 60% x 70% x 80% = **34%**

CO_2 Flood Recovery Factor Estimation Example



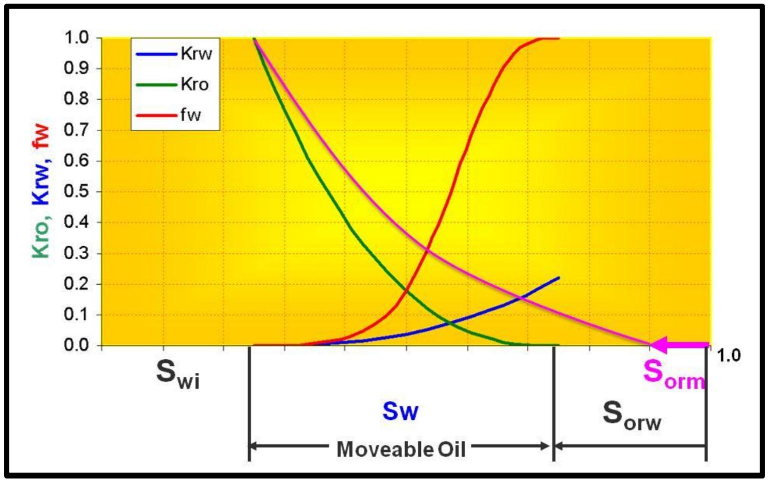
<u>Given:</u>

$S_{wi} = 0.25$, $S_{orw} = 0.30 \rightarrow S_{orm} = 0.10$

<u>If:</u>

Areal Sweep Efficiency = 70%

Vertical Sweep Efficiency = 80%



<u>Then:</u>

Moveable Oil = 1 – 0.25 – 0.10 = 0.65

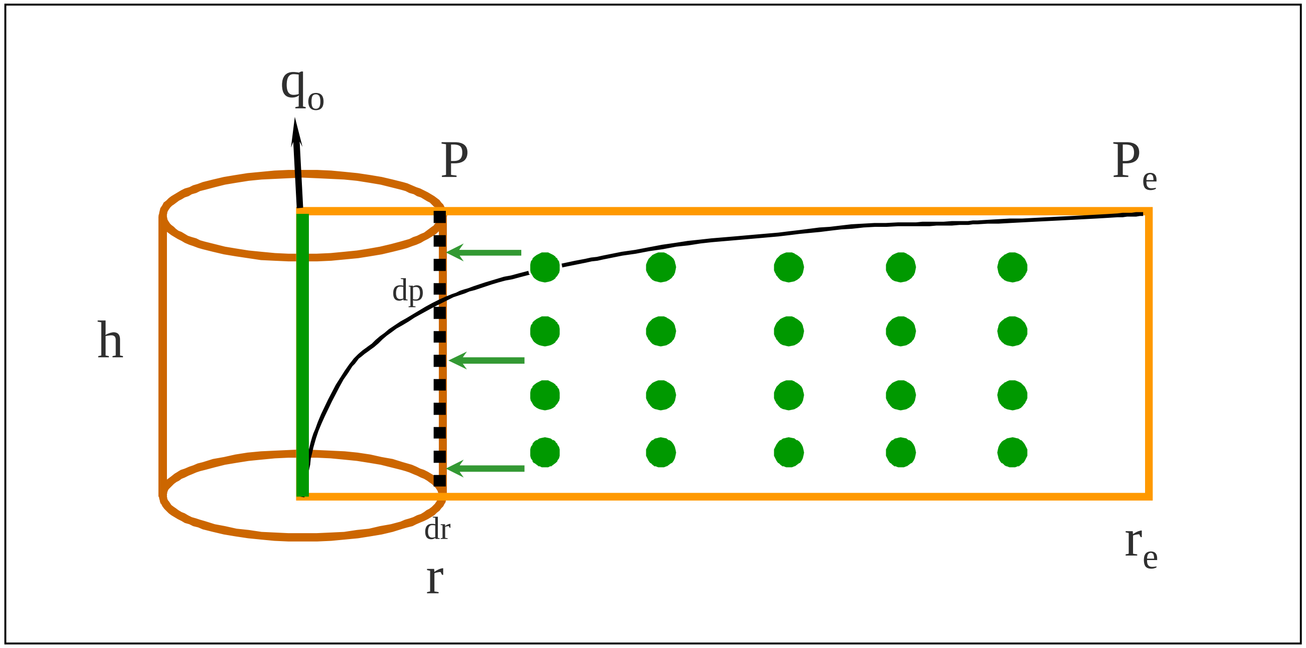
Displacement Efficiency = 0.65 / 0.75 = 87%

Total Recovery Factor = 87% x 70% x 80% = **49%**

Incremental RF over Waterflood = 49% - 34% = **15%**

Darcy’s Law – Fluid Flow into a Cylindrical Surface

oil well example



Simplified Darcy’s Law of Fluid Flow:

Flow rate = **Permeability** * **Pressure Gradient** * **Area**

Consider oil flow across an infinitesimally small cylindrical element:

$$dq_o = \frac{k \; k_{ro}}{B_o \mu_o} * \frac{dp}{dr} * (2\pi \; r \; h)$$

Derivation of Darcy's Oil Flow Rate Equation

$$dq_o = \frac{k\ k_{ro}}{B_o \mu_o} * \frac{dp}{dr} * (2\pi\ r\ h)$$

$$q_o = \int_{r_w}^{r_e} \int_{P_{wf}}^{P_e} dq_o$$

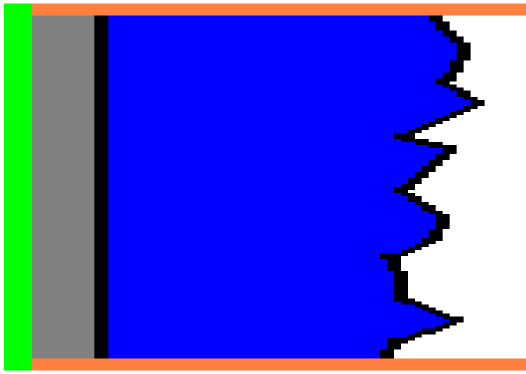
$$q_o = (2\pi k k_{ro} h / B_o \mu_o) \int_{r_w}^{r_e} \int_{P_{wf}}^{P_e} dp\ r/dr$$

$$q_o = \frac{2\pi\ k k_{ro}\ h\ (P_e - P_{wf})}{B_o \mu_o \ln(r_e/r_w + s)}$$

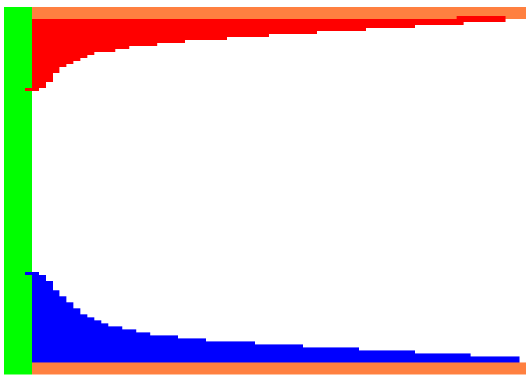
or

$$q_o = \frac{0.00708\ k k_{ro}\ h(P_e - P_{wf})}{B_o \mu_o \ln(r_e/r_w + s)} \quad \text{in field units}$$

Factors Affecting Production Rates



- Wellbore & Drainage:
  - h, r_w, P_{wf}, r_e, P_e
- Stimulation & Damage:
  - r_w', S



- Rock & Fluid Properties:
  - P, T, S_w, S_o, S_g
  - k, k_{ro}, k_{rg}, k_{rw}, B_o, B_g, B_w, μ_o, μ_g, μ_w

Winning Conditions

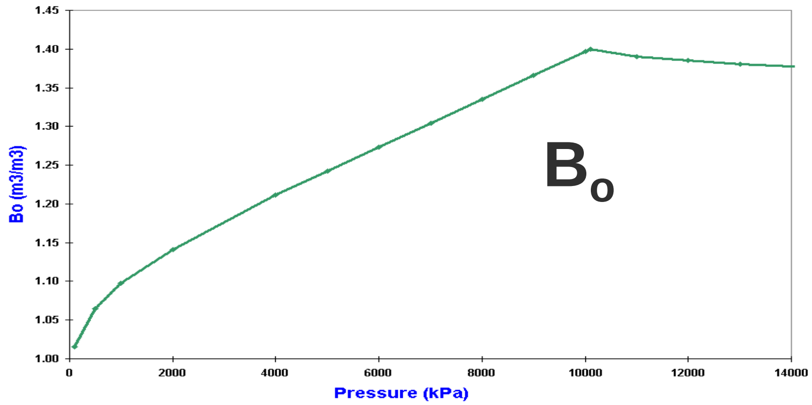
Where to drill?

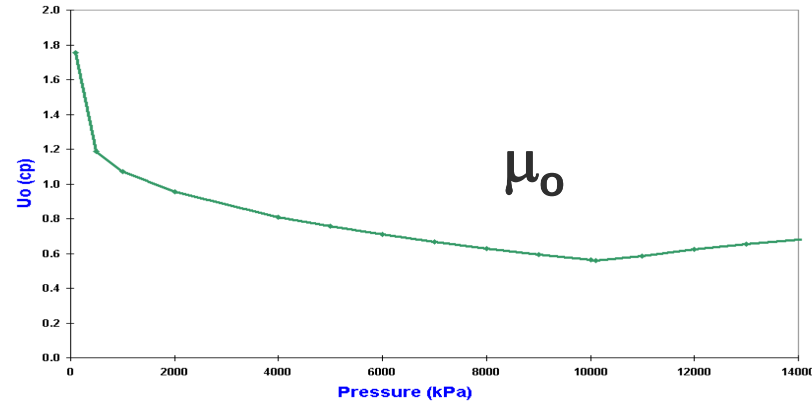
- ✓ No/low water, no/low gas (Sw↓, Sg↓ => kro↑)
- ✓ High permeability (k↑), thick pay (h↑)

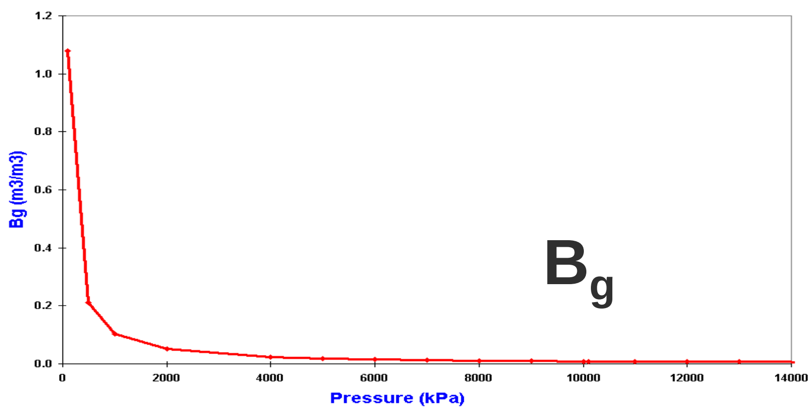
How to complete & operate?

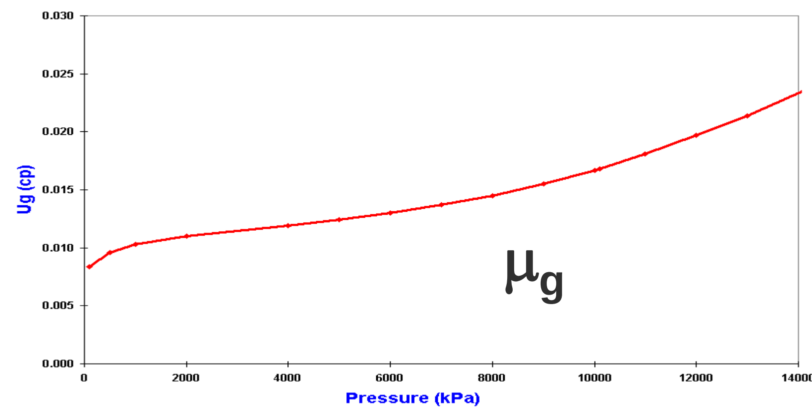
- ✓ Long prod. interval, large wellbore (h↑, rw'↑)
- ✓ No/low formation damage (S↓)
- ✓ High differential pressure (Pe↑-Pwf↓)

Fluid Properties (PVT) – Pressure Dependent









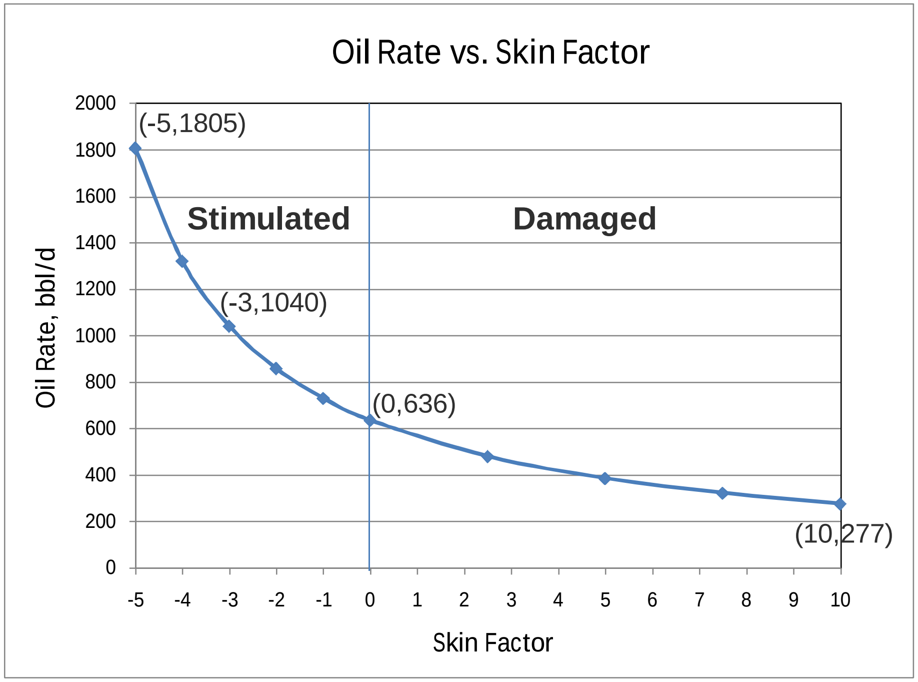
Permeability/porosity may also be pressure (effective stress) dependent.

Vertical Well - Oil Production / Water Injection Rate Estimation Examples

Input :	**Pool :**	**Vertical Well**							
Productivity					**5-Spot Injection Rate**			(rw=L/4 for fracture)	
Kro	**0.9**				Krw(or)	**0.35**			
K	**77**	md			K	**77**	md		
h	**10.5**	m	34.45	ft	h (net)	**10.5**	m	34.45	ft
Pe	**14000**	kPa	2030.52	psi	Piwf	**20000**	kPa	2900.74	psi
Pwf	**12600**	kPa	1827.46	psi	Ppwf	**12600**	kPa	1827.46	psi
Bo	**1.30511**	Rm3/m3			Uw	**0.5**	cp		
Uo	**0.536**	cp			d	**400**	m	1312.34	ft
re	**200**	m	656.17	ft	rw	**0.0889**	m	0.29	ft
rw	**0.0889**	m	0.292	ft	s	**0**			
s	**0**				Bo	**1.30511**			
					Uo	**0.536**	cp		
					Kro	**0.9**			
					J	**0.0722**	m3/d/kPa	3.13	STB/d/psi
Output :									
qo =	635.6	bbl/d			**iw =**	905.5	bbl/d		
	101.1	m3/d				**144.0**	m3/d		
					(conversion)				
J =	3.1303	STB/d/psi			**iw =**	914.2	bbl/d		
	0.0722	m3/d/kPa				**145.3**	m3/d		

Stimulation / Damage – Vertical Well Rate Estimation Examples

Input :	Pool :	Vertical well		
Productivity				
Kro	0.9			
K	77	md		
h	10.5	m	34.45	ft
Pe	14000	kPa	2030.52	psi
Pwf	12600	kPa	1827.46	psi
Bo	1.30511	Rm3/m3		
Uo	0.536	cp		
re	200	m	656.17	ft
rw	0.0889	m	0.292	ft
s	-3			
Output :				
qo =	1039.7	bbl/d		
	165.3	m3/d		
J =	5.1206	STB/d/psi		
	0.1181	m3/d/kPa		



Acid Stimulation
(Skin Adjustment)

Fracture Stimulation – Vertical Well Rate Estimation Examples

Input :	Pool :	Vertical well		
Productivity				
Kro	0.9			
K	77	md		
h	10.5	m	34.45	ft
Pe	14000	kPa	2030.52	psi
Pwf	12600	kPa	1827.46	psi
Bo	1.30511	Rm3/m3		
Uo	0.536	cp		
re	200	m	656.17	ft
rw	0.0889	m	0.292	ft
s	-5			
Output :				
qo =	1804.7	bbl/d		
	287.0	m3/d		
J =	8.8877	STB/d/psi		
	0.2050	m3/d/kPa		

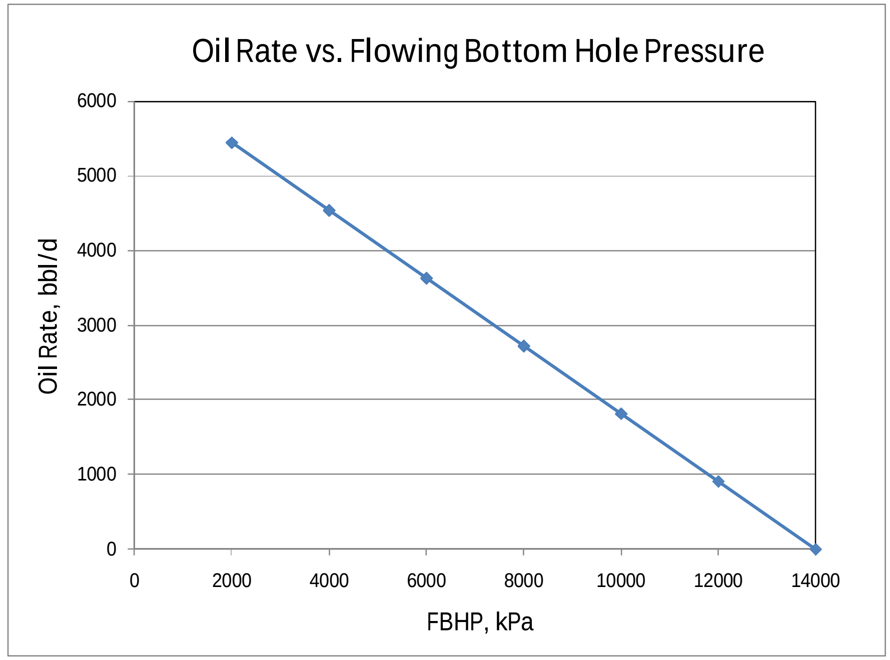
Fracture Stimulation
(Skin Adjustment)

Input :	Pool :	Vertical well		
Productivity				
Kro	0.9			
K	77	md		
h	10.5	m	34.45	ft
Pe	14000	kPa	2030.52	psi
Pwf	12600	kPa	1827.46	psi
Bo	1.30511	Rm3/m3		
Uo	0.536	cp		
re	200	m	656.17	ft
rw	13.20	m	43.292	ft
s	0			
Output :				
qo =	1804.7	bbl/d		
	287.0	m3/d		
J =	8.8880	STB/d/psi		
	0.2050	m3/d/kPa		

Fracture Stimulation
(Wellbore Radius Adjustment)
(½ x Half-Length)

Artificial Lift – Vertical Well Rate Estimation Examples

Input :	**Pool :**	**Vertical Well**		
Productivity				
Kro	**0.9**			
K	**77**	md		
h	**10.5**	m	34.45	ft
Pe	**14000**	kPa	2030.52	psi
Pwf	**2000**	kPa	290.07	psi
Bo	**1.30511**	Rm3/m3		
Uo	**0.536**	cp		
re	**200**	m	656.17	ft
rw	**0.0889**	m	0.292	ft
s	**0**			
Output :				
qo =	5448.2	bbl/d		
	866.4	m3/d		
J =	3.1303	STB/d/psi		
	0.0722	m3/d/kPa		



Pump Installation

(Flowing BHP Adjustment)

Vertical Well Rate Estimation Examples - Summary

	Oil Rate	Incr. Rate	% Change
Base	636	--	
Acid (Skin=-3)	1040	404	64
Damaged (Skin=10)	277	(359)	(56)
Fractured (Skin=-5)	1805	1169	184
Pump (Pwf=2000 kPa)	5448	4812	757

Horizontal Well - Oil Rate Estimation Example

Drainage Volume, Well Placement

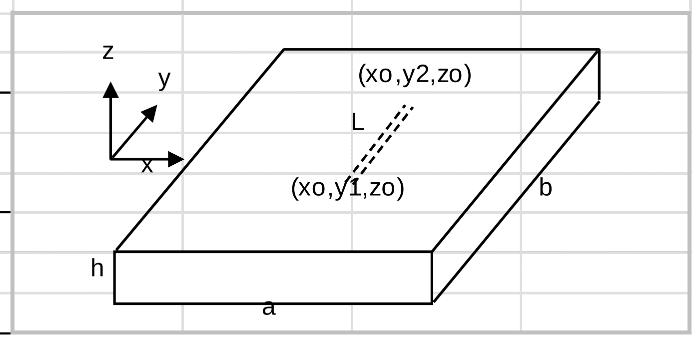
Differential Pressure

Effective Permeability

Input :	**Pool :**				
a =	**200**	m	656.17	ft	(extension of drainage volume of hrz.well in x direction)
b =	**600**	m	1968.50	ft	(extension of drainage volume of hrz.well in y direction)
h =	**5**	m	16.40	ft	(extension of drainage volume of hrz.well in z direction)
xo =	**100**	m	328.08	ft	(x coordinate of center of well)
zo =	**2.5**	m	8.20	ft	(z coordinate of center of well)
y1 =	**100**	m	328.08	ft	(y coordinate of beginning of well)
L =	**400**	m	1312.34	ft	(length of hrz.well)
kx =	0.6	md		**Kro*K**	(permeability in x direction)
ky =	0.6	md			(permeability in y direction)
kz =	0.3	md			(permeability in z direction)
Pr =	**9390.72**	kPa	1362.00	psi	(average pressure in drainage volume of well)
Pwf =	**2000**	kPa	290.07	psi	(average flowing bottomhole pressure)
B =	**1.169**	Rm3/m3		RB/STB	(formation volume factor)
U =	**1.196**	cp			(viscosity)
rw =	**0.0899**	m	0.2949	ft	(wellbore radius)
Sf =	**0**				(skin resulting from change in formation permeability)
Krlg =	**1**				(liquid relative permeability at 10% gas saturation)
Kabs =	**17.86**	md			(absolute permeability)
kz/kx =	**0.42**				(vertical to horizontal permeability ratio)
Kro=	**0.03404**				(current oil relative permeability)

Output :

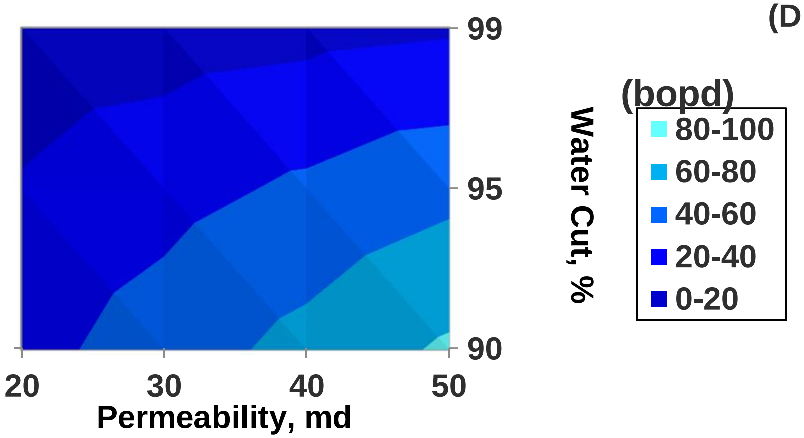
Flow rate, q =	82.44	STB/d
	13.11	m3/d
Prod. Index, J =	0.0769	STB/(d.psi)
	0.0018	m3/(d.kPa)



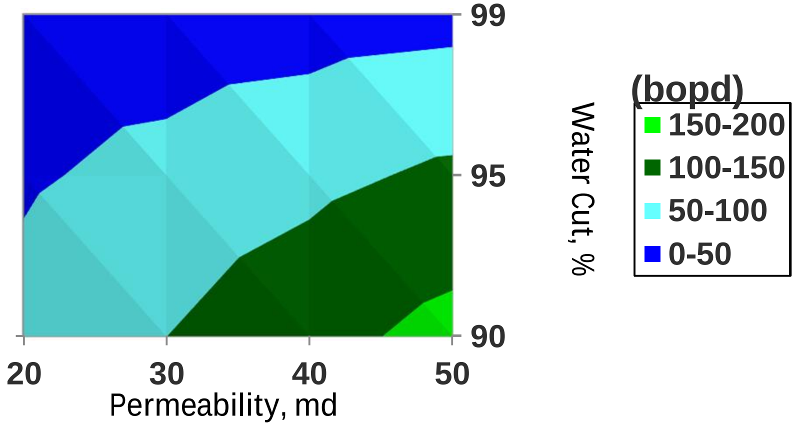
[Babu, D.K. & Odeh, A.S., SPE Reservoir Engineering, Nov. 1989, pp.417-421]

Horizontal Well - Oil Rate Variation Example

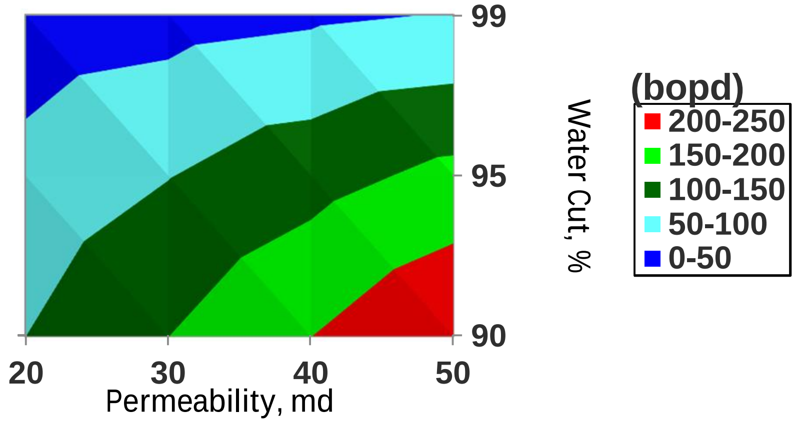
(Drainage volume: length=780m, width=200m, height=6m)



(Res.Press - FBHP = 2,000 kPa)				
Wcut \ Kmax	20	30	40	50
90	33	50	67	83
95	22	33	44	55
99	7	10	14	17



(Res.Press - FBHP = 4,000 kPa)				
Wcut \ Kmax	20	30	40	50
90	67	100	133	166
95	44	66	87	109
99	14	21	28	35



(Res.Press - FBHP = 6,000 kPa)				
Wcut \ Kmax	20	30	40	50
90	100	150	200	249
95	66	98	131	164
99	21	31	42	52

Oil Production / Water Injection Rate Estimation
Practical Use

- Estimate oil rate improvement from acidizing (-S).
- Estimate oil rate reduction from formation damage (+S).
- Estimate oil rate improvement from fracturing (-S, effective r_w).
- Estimate oil rate change with pay thickness or horizontal well length.
- Estimate water injection rate if producer is converted to become an injector.
- Estimate effects of pressure (P_e, P_{wf}) & fluid property (μ_o, B_o) changes on oil rate.
- Estimate effects of fluid saturation (k_{ro}) changes on oil rate.

Conclusions – What Makes an Oil Well Tick?

- Effective Oil Mobility
- Differential Pressure
- Drainage Volume, Well Placement, Skin