Technical Aspects of Waterflooding
October 23rd Long Beach, California

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Oil Operations Bureau
Department of Gas and Oil

Part I
SPE 153810

An analytical methodology to determine oil in place, aquifer influx, and ultimate sweep efficiency of a mature heavy oil waterflood in the Wilmington Basin

Part II
Waterflood on Reservoir on Chip (ROC)

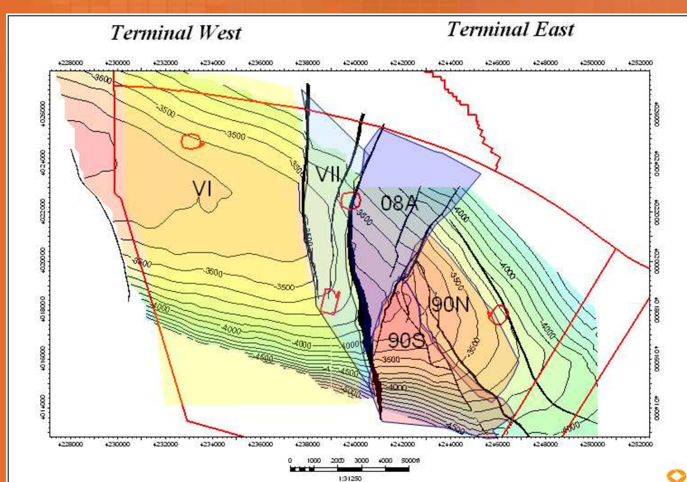
2011 Research Highlight from Royal Society of Chemistry
Bera et al., *Lab Chip*, **11**, 3785, 2011 (***Cover Article***)

SPE 153810 : Author Baldev S. Gill

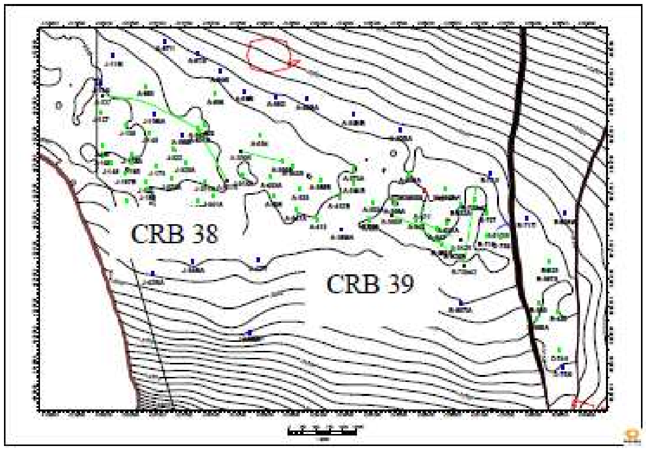
Outline

1. **Field overview**
2. **Determine tank size (OOIP)**
3. **Determine water influx**
4. **Recovery efficiency as a function of sweep efficiency**
5. **Injection performance for different Reservoirs**
6. **Conclusions**

Terminal West VI



Terminal West CRB 38/39



Terminal West CRB 38/39

Table 1. Average Reservoir Properties for Terminal

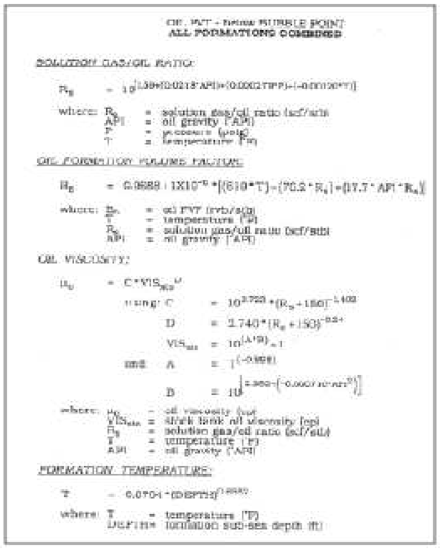
Reservoir Property	Terminal Zone
Depth (ft)	3200
Temperature	135
Oil Gravity (API)	20
Viscosity at Res Temp (cp)	17
Gross Thickness (ft)	1000
Pay Thickness (ft)	300
Porosity (%)	25
Initial Water Sat (%)	35
Permeability (md)	10-200
Current Flood Config	Peripheral

Table 2. Upper Terminal Sub-Zones

<table>
<tr><th>AGE (STAGE)</th><th>FORMATION</th><th>ZONE WEST</th><th>ZONE EAST</th><th>SUB-ZONES</th></tr>
<tr><td>Pleistocene</td><td>San Pedro</td><td></td><td></td><td></td></tr>
<tr><td>Upper Pliocene</td><td>Upper Pico</td><td></td><td></td><td>JF
JK</td></tr>
<tr><td rowspan="2">Lower Pliocene (Repettian)</td><td rowspan="2">Lower Pico (Repetto)</td><td>Tar</td><td>Tar</td><td>So
S
T
U
DU</td></tr>
<tr><td>Upper Ranger</td><td>Upper Ranger</td><td>F1
FO
F
H
M1
H1
X</td></tr>
<tr><td rowspan="4">Miocene/ Pliocene</td><td rowspan="4">Puente</td><td>Lower Ranger</td><td rowspan="2">Lower Ranger</td><td>G
G4
G5
G6</td></tr>
<tr><td rowspan="2">Upper Terminal</td><td>HX1
HXO
HX
HXB
HXC
J</td></tr>
<tr><td rowspan="2">Terminal East</td><td>Y
Y4
K
Z
W
A</td></tr>
<tr><td>Lower Terminal</td><td>AA
AB
AC
AD
ADL</td></tr>
</table>

Oil Field PVT Properties

Table 4. Oil PVT Below Bubble Point



OIL PVT – below BUBBLE POINT
ALL FORMATIONS COMBINED

SOLUTION GAS/OIL RATIO:

where: R_s = solution gas/oil ratio (scf/stb)
API = oil gravity (°API)
P = pressure (psig)
T = temperature (°F)

OIL FORMATION VOLUME FACTOR:

where: B_o = oil FVF (rvb/stb)
T = temperature (°F)
R_s = solution gas/oil ratio (scf/stb)
API = oil gravity (°API)

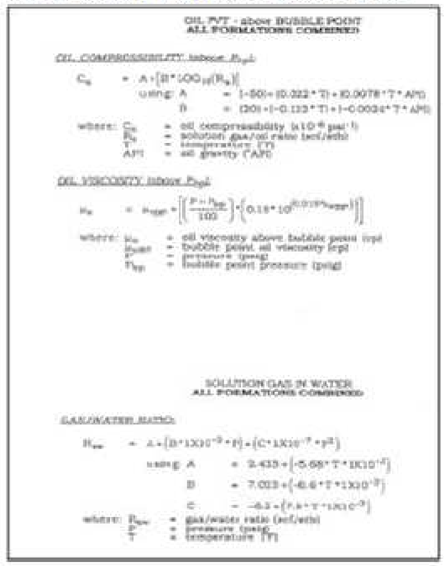
OIL VISCOSITY:

where: μ_o = oil viscosity (cp)
VIS_{stk} = stock tank oil viscosity (cp)
R_s = solution gas/oil ratio (scf/stb)
T = temperature (°F)
API = oil gravity (°API)

FORMATION TEMPERATURE:

where: T = temperature (°F)
DEPTH = formation sub-sea depth (ft)

Table 5. Oil PVT above Bubble Point



OIL PVT – above BUBBLE POINT
ALL FORMATIONS COMBINED

OIL COMPRESSIBILITY (above P_{bp}):

where: C_o = oil compressibility (x10⁻⁶ psi⁻¹)
R_s = solution gas/oil ratio (scf/stb)
T = temperature (°F)
API = oil gravity (°API)

OIL VISCOSITY (above P_{bp}):

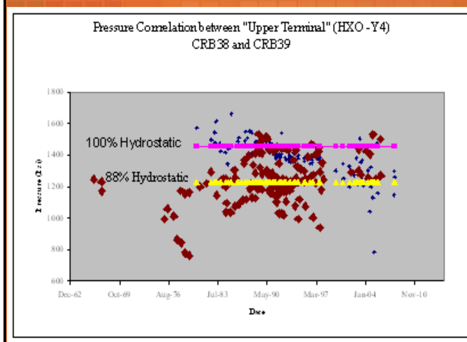
where: μ_o = oil viscosity above bubble point (cp)
μ_{obp} = bubble point oil viscosity (cp)
P = pressure (psig)
P_{bp} = bubble point pressure (psig)

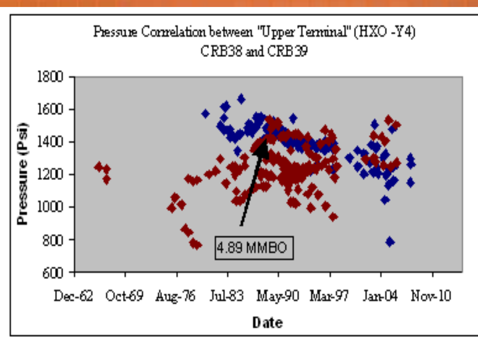
SOLUTION GAS IN WATER
ALL FORMATIONS COMBINED

GAS/WATER RATIO:

where: R_{sw} = gas/water ratio (scf/stb)
P = pressure (psig)
T = temperature (°F)

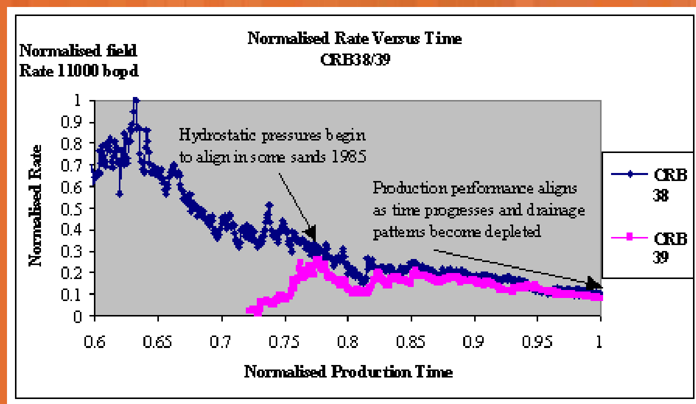
Hydrostatic Correlation Between the Cut Recovery Blocks 38 and 39





CRB	Avg Oil (B/D)	AVG Gross (M B/D)	Cum Oil (MMbbl)	Cum Gross (MMbbl)	WOR	Avg Inj (M B/D)	Cum Inj (MMbbl)	Voidage Injection (MMbbl)	Cum I/G	% Hydro
38	961	52	63	566	54	58	619	+53	1.09	84
39	879	27	17.0	169	30	28	125	- 42	0.74	86
38/39	1841	79	80	735	42	87	745	10	1.01	85

Normalized Rate Versus Time Plot



Determine Tank Size (OOIP)

General Material Balance Equation:

Np (Bo+(Rp-Rs))Bg + WpBw – WiBw – GiBgi = N[(Bo-Boi)+(Rsi-Rs)Bg + mBoi ((Bg/Bgi-1)) + (1+m) Boi ((CwSwc +Cf)/(1-Swc))ΔP] + We 1

F= Np {Bo+(Rp-Rs)*Bg} +WpBw –WiBw 2

E_o = (Bo – Boi) + (Rsi-Rs)Bg 3

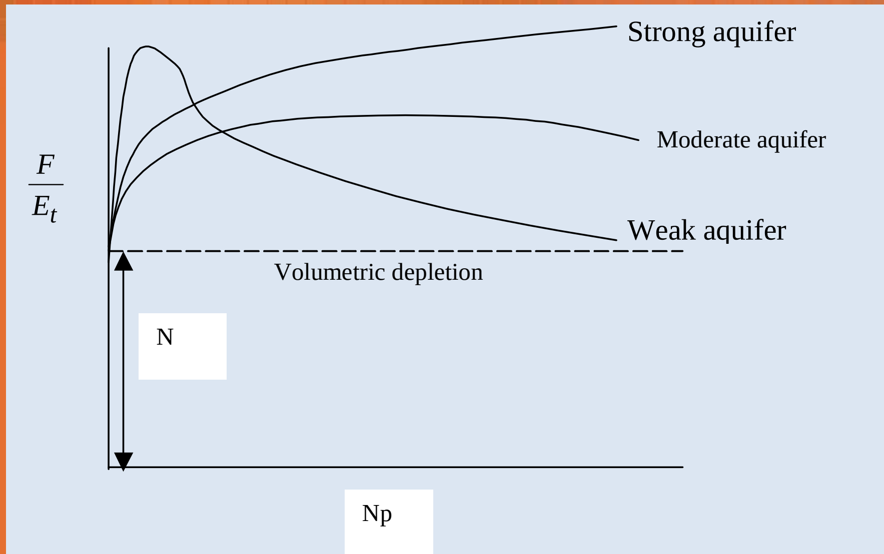
Eg = Boi (Bg/Bgi – 1) 4

E_{fw} = Boi [(CwSw + Cf)/(1-Swc)] ΔP 5

if we let $E_t = (E_o + mE_g + E_{fw})$ 6
Then the MBE is simplified to the form:

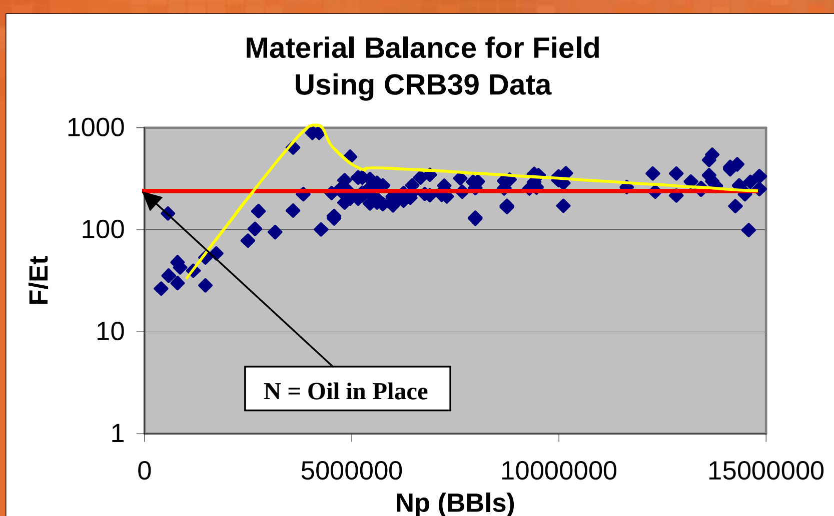
F = N (E_t) + We 7

Determine Tank Size



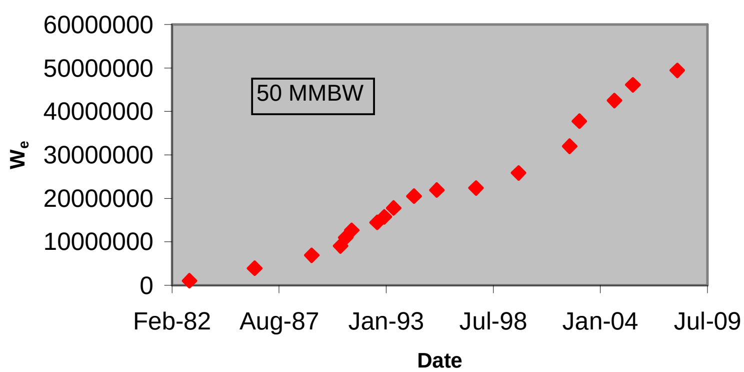
Determine Tank Size

N = ~ 250 MMBO from analytical plot versus 245 MMBO from independent Study



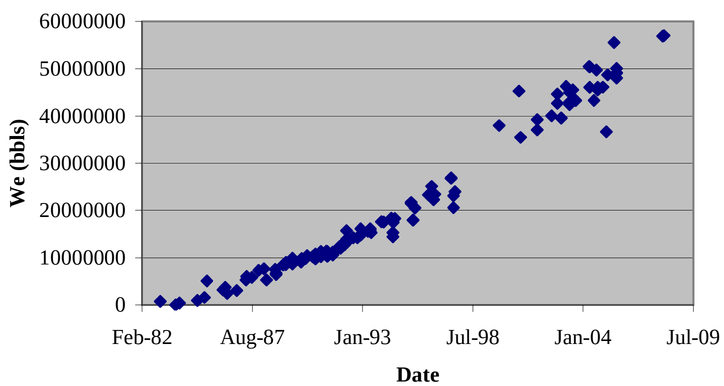
Determine Water Influx Via HVE and MBE Equation

Water Influx (W_e) using the Hurst Van Everdingen Technique Linear Aquifer Geometry

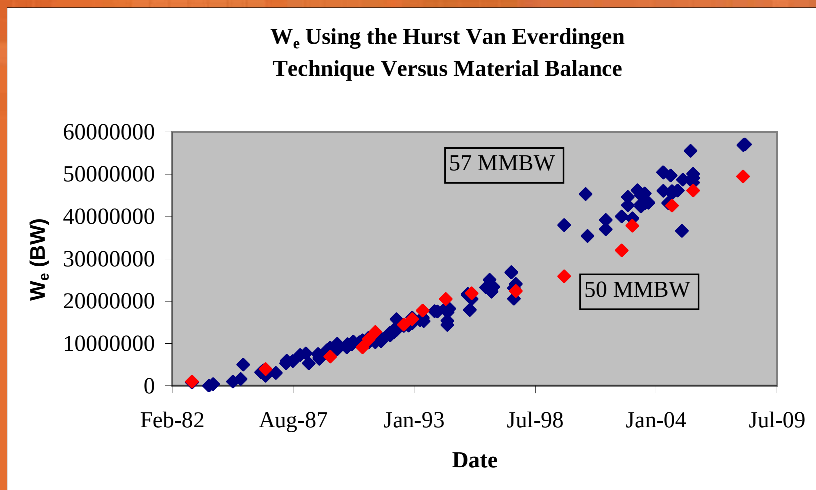


Determine Water Influx Via HVE and MBE Equation

Material Balance Method to Derive Cumulative Water Influx W_e



Determine Water Influx Via HVE and MBE Equation



Recovery Efficiency as a function of Sweep Efficiency

The Volumetric Sweep Efficiency is defined as:

$$E_v = E_a E_i = [(W_i - W_p)B_w] / V_{pHD}$$

where V_{pHD} is the displaceable pore volume = AH ϕ $(1-S_{wc} - S_{or})$

And the cumulative recovery efficiency is defined as;

$$E_r = N_p/N$$

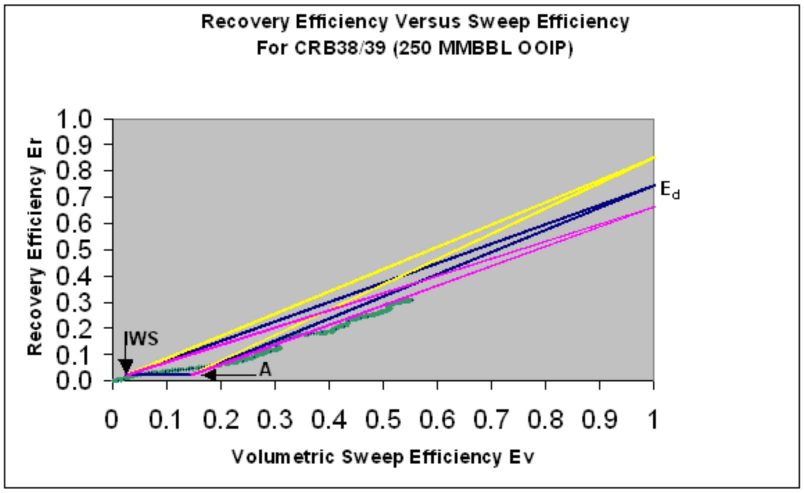
At a volumetric sweep of 1.0 we assume that all displaceable pore volume has been displaced and therefore this would theoretically be the maximum recovery efficiency possible, which equates to the displacement efficiency (Ed).

$$E_d = (S_{oi} - S_{or})/S_{oi}$$

IWS and E_d form two of the vertices of an obtuse triangle. The third leg of the triangle is the net dimensionless injection required to displace the gas saturation present at the start of the flood. This is defined as (point A) :

$$A = S_{gx} / (S_{oi} - S_{or})$$

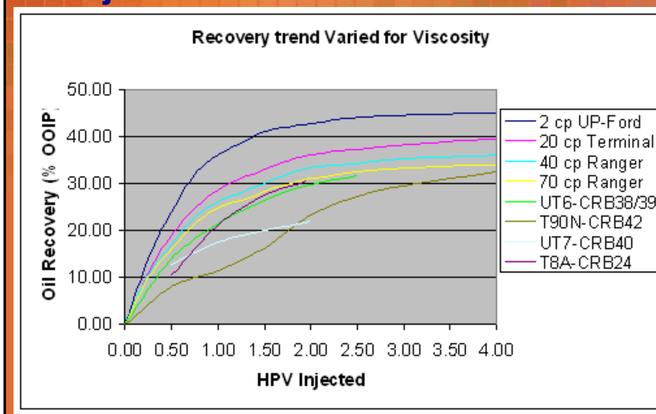
Recovery Efficiency as a function of Sweep Efficiency



Sweep efficiency of 55% and a recovery efficiency of about 32%

	So_i	So_r	E_d
AVG	65.7	24.4	0.64
AVG HX-J	70.1	31.6	0.56
AVG Y-A	61.8	18.2	0.71

Injection Performance for Terminal Reservoirs



OOIP numbers of 53.2 MMBO, 24.6 MMBO and 245 MMBO for CRBs' 24, 42 and 38/39 respectively

CRB	Assuming 32% Recovery Ideal	Assuming 32% Recovery Actual	Injection Efficiency %	Over Injection MMBW
38/39	1.375	2.5	55	270
42	1.375	3.5	39	53
24	1.375	1.96	70	31

CONCLUSIONS

- "*Tank Size*": One reservoir with an original oil in place number of approximately 250 MMBO

- "*Water Influx*": Size of the water influx small (54 MMBW) compared to the relative size of water injection (745 MMBW)

- "*Sweep Efficiency*": Injector sweep efficiency was determined to be approximately 55%

"*Future Work*": Determine the optimum injection alignment and distance to the producers with further studies.

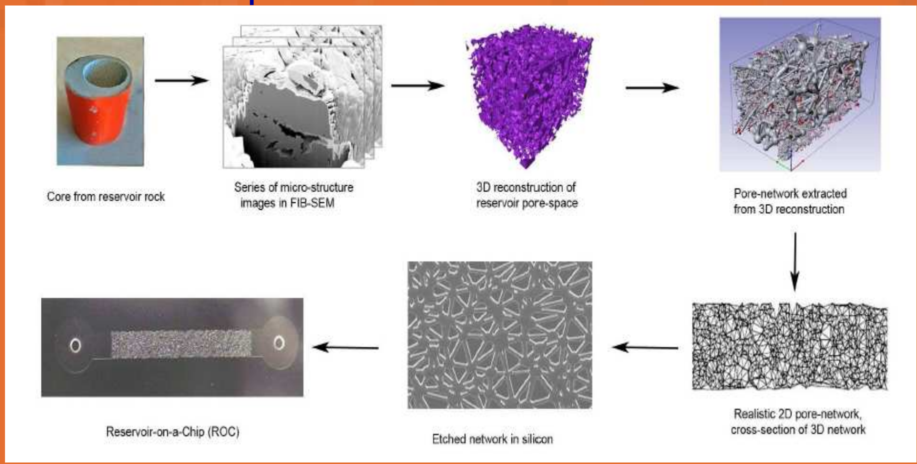
Part II
Waterflood on Chip

Department of Mechanical Engineering
MNT Lab, University of Alberta

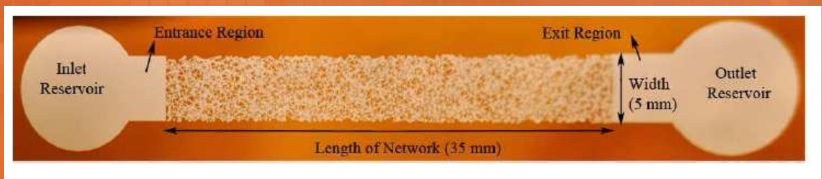
2011 Research Highlight from Royal Society of Chemistry
Bera et al., *Lab Chip*, **11**, 3785, 2011 (***Cover Article***)

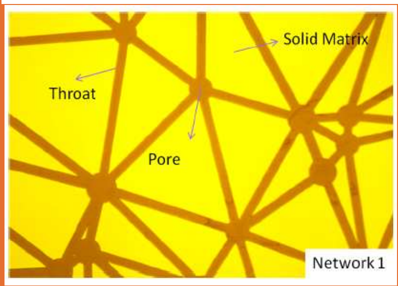
Reservoir-on-a-Chip (ROC)

- Prefab Chip Flow Process

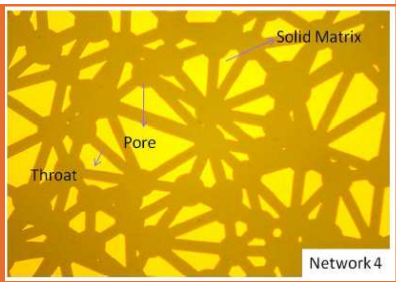


Pore Network Design



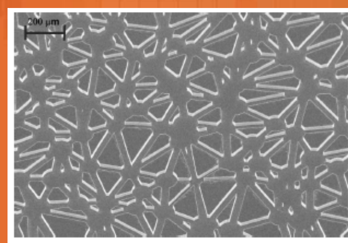


2000 pores, 6000 throats, mean pore size=40 µm

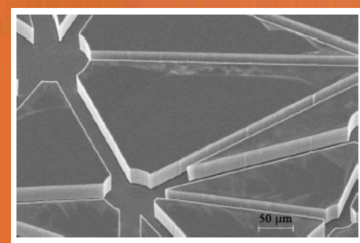


6000 pores, 20000 throats, mean pore size=50 µm

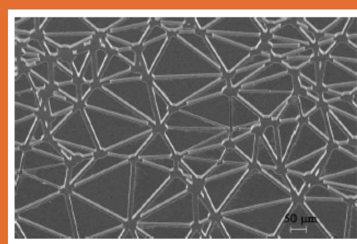
SEM Images: Network Etched on Silicon



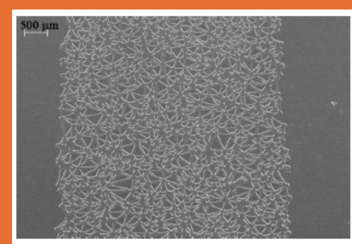
(a)



(b)



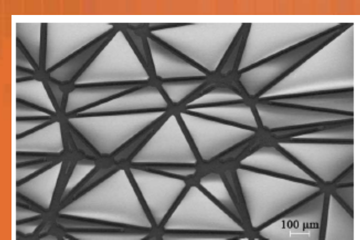
(c)



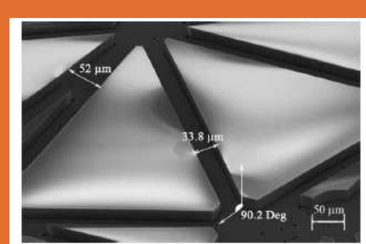
(d)

SEM Images: Network Etched on Quartz

(a)

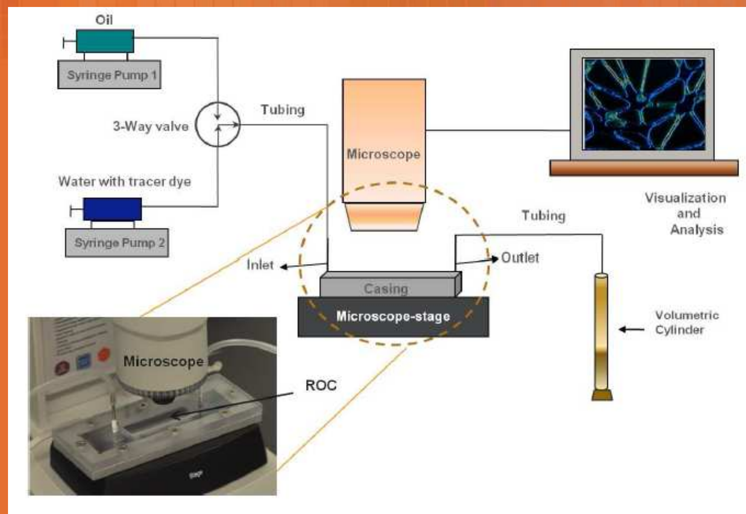


(b)

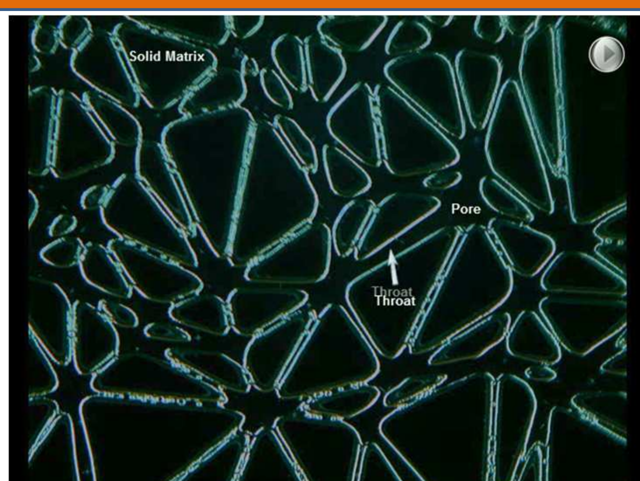


(c)

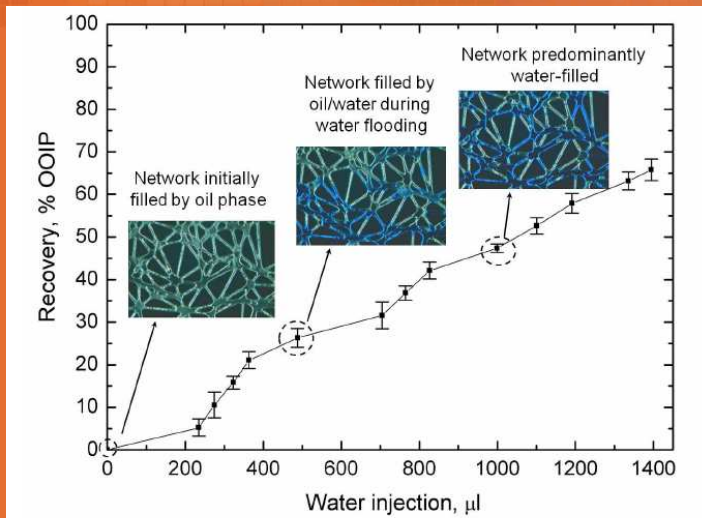
Waterflooding with ROC



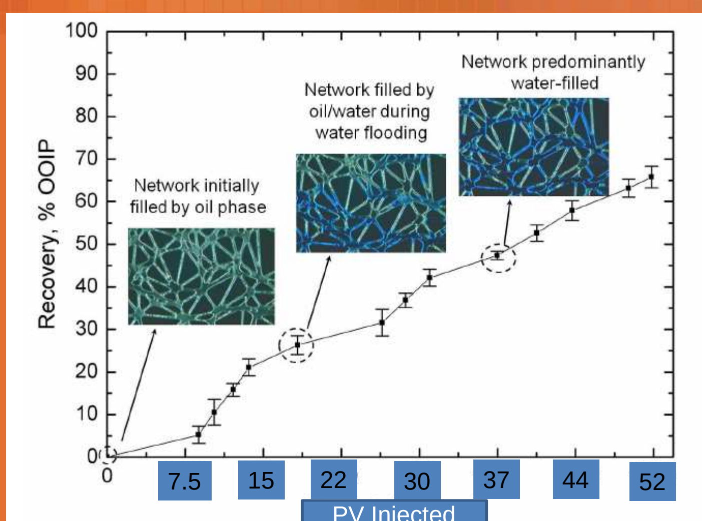
Waterflooding with ROC



Recovery Curve for ROC



Recovery Versus PV Injected



What's Next!

- Evaluate the impact of Injection Rate to Ultimate Recovery
- Look at Changes to Wettability and influence on recovery with Mixed-Wet and Oil-Wet CHIPs
- Look at the impact of effective permeability to flow streamlines as oil cut changes with rate variance

Acknowledgments!

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Questions……..