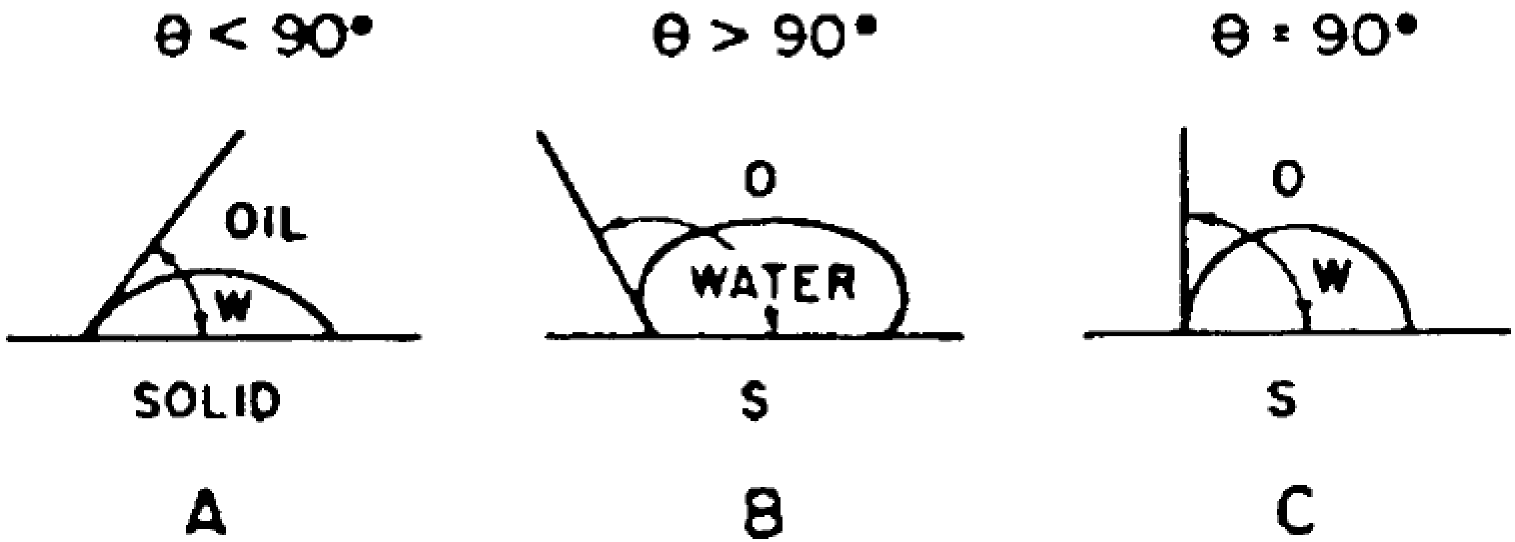
Naturally Fractured Reservoirs
Evaluation of Matrix-Fracture Fluid Exchange (a)

Shahab Gerami, Fall 2010

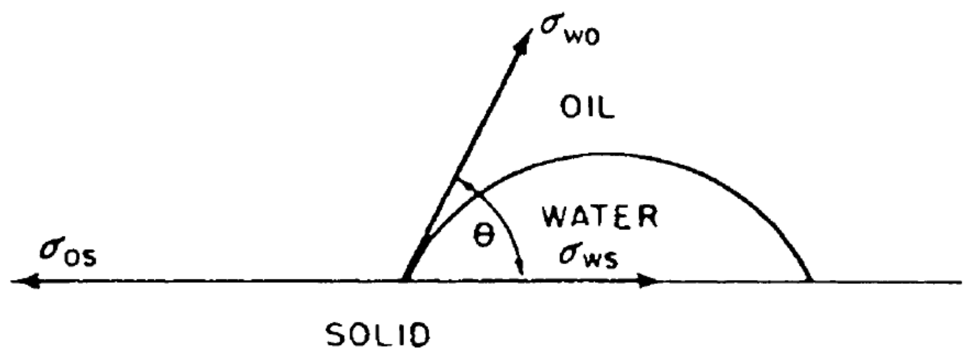
FUNDAMENTALS OF SURFACE AND CAPILLARY FORCES

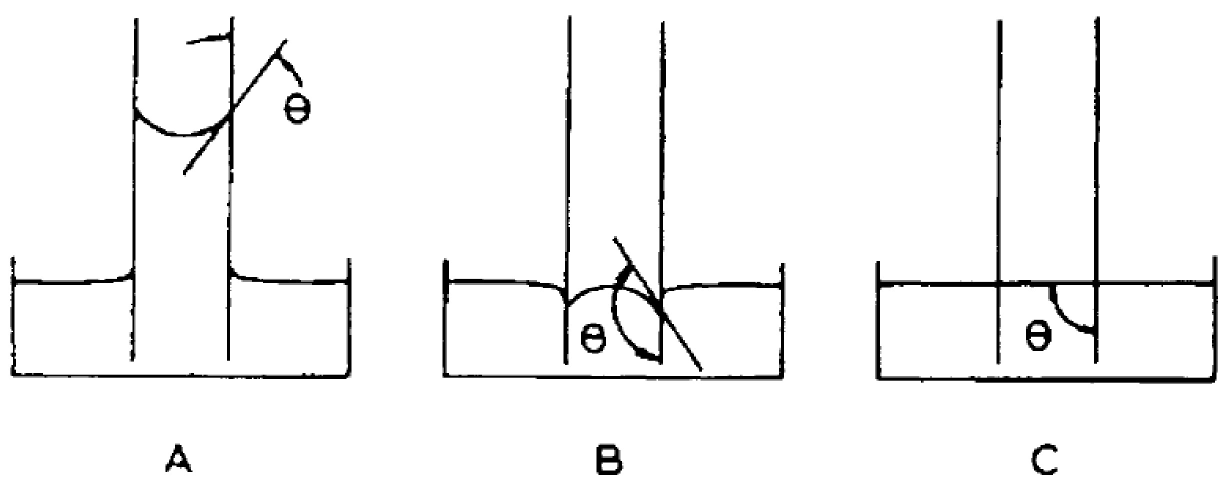
Wettability may be defined as the ability of the liquid to "wet", or spread over, a solid surface.



INTERFACIAL TENSION AND CONTACT ANGLE

The angle which the liquid interface makes with the solid is called the contact angle, **θ**. Usually, it is measured from the solid through the liquid phase (if the other phase is a gas) and through the water phase if oil and water are both present.



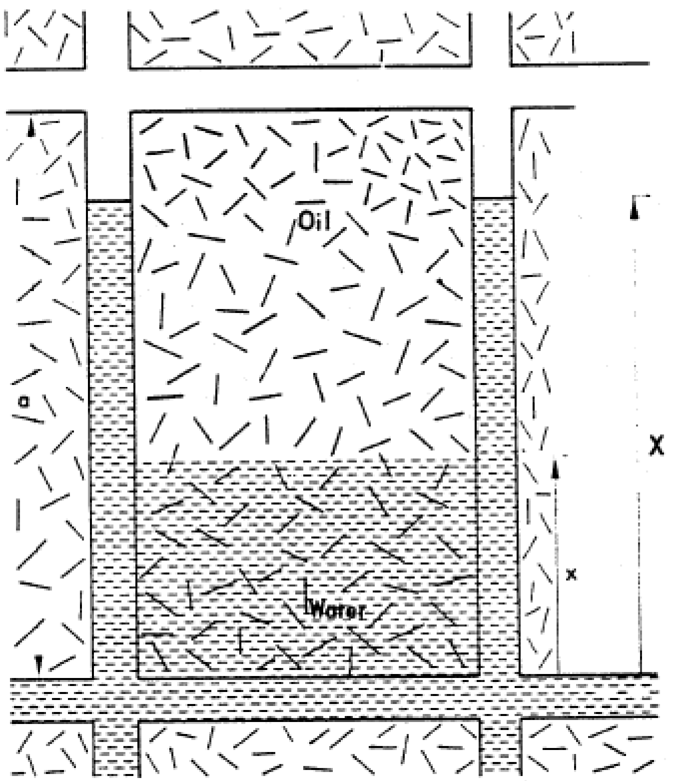


Fluid Distribution in Fractured Reservoirs

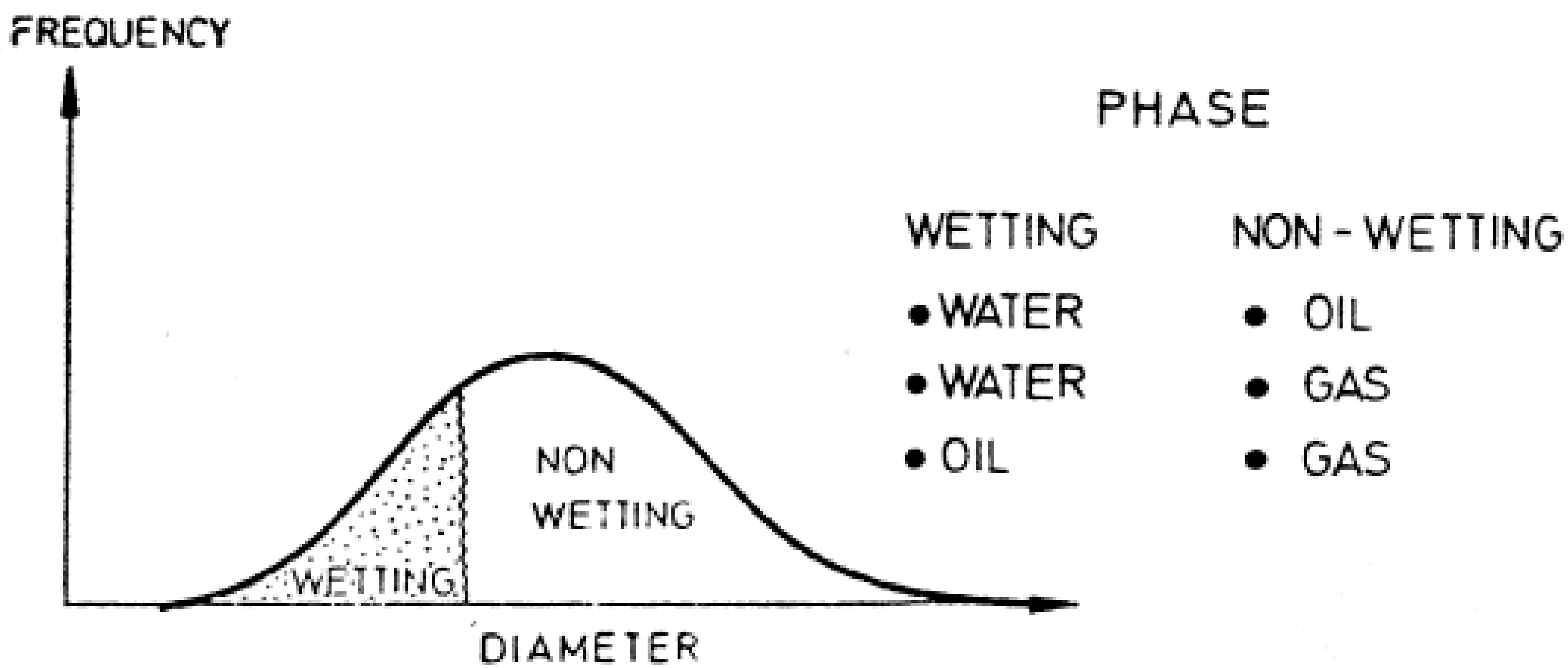
•The discontinuity of the matrix caused by the fracture network explains why the water table is only related to the fracture network.

• Capillary and gravitational forces control the static and dynamic equilibrium of each matrix block.

•The basic element which relates individual block behaviour to reservoir behaviour is the water-oil contact in fractures and is called **water table level**.

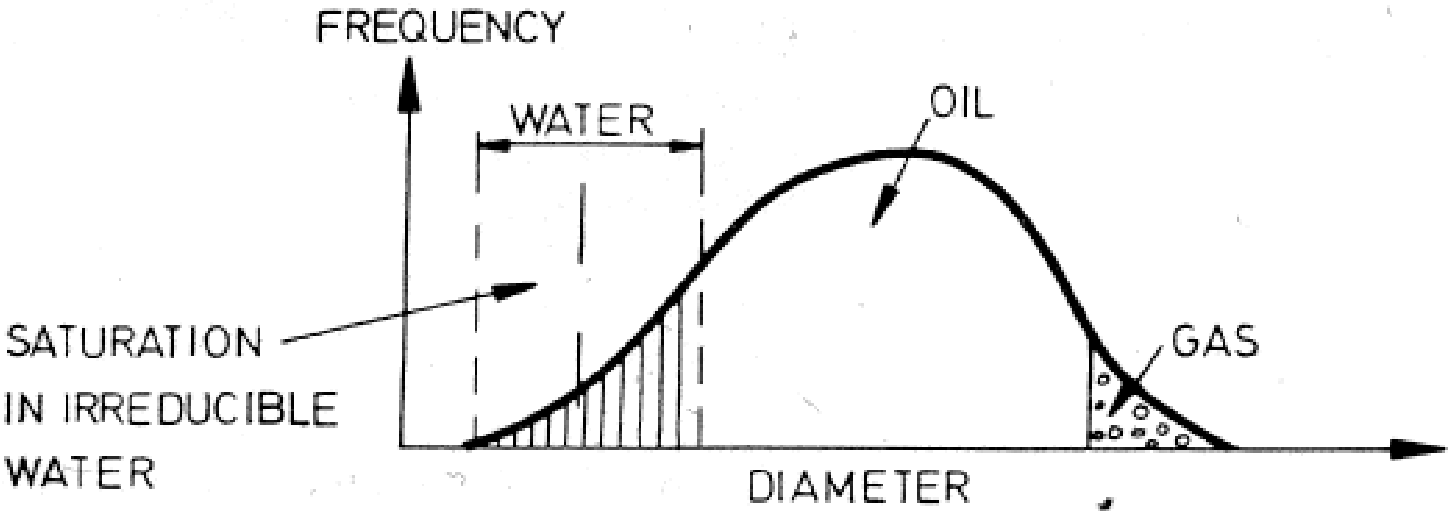


If a pore size frequency curve is available, distribution of the wetting and non-wetting phases will be as shown in figure 4.35 where the wetting phase fills small pores and the non-wetting phase fills the large pores. Thus, saturation in the irreducible wetting phase will depend on the average pore size. Saturation in irreducible water will be greater in small pores than in large pores (as shown in figure 4.36 where $d_1 < d_2$).



4.35 – Pore size frequency curve and fluid saturation

If all three phases, water, oil and gas, coexist simultaneously in the reservoir, their distribution will follow the same pattern. According to the degree of wettability, water will fill the smallest pores and gas the largest pores, leaving the intermediate pores for oil (figure 4.37).



4.37 – Three-phase saturation distribution.

Parameter	water wet	oil wet
S_{wir}	>0.2	<0.15
S_w at $k_{rw}=k_{ro}$	>0.5	<0.5
k_{rw} at $1-S_{or}$	<0.3	>0.5

Capillary Pressure

$$S_w = f\,(P_c)$$

Fluid Property

Wettability
Rock-Fluid Property

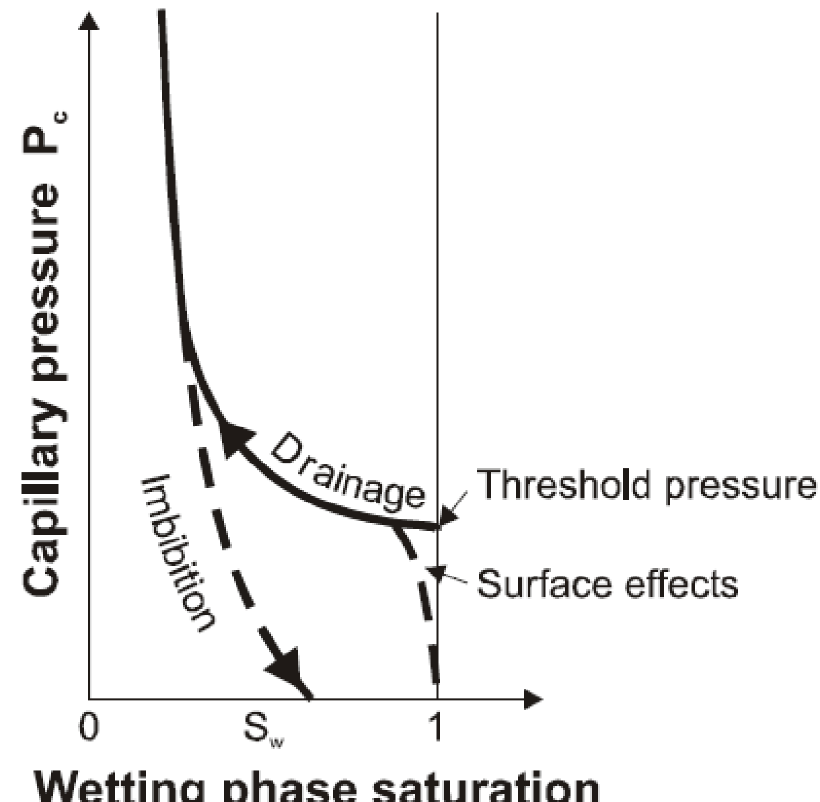
$$P_c = \frac{2\,\sigma\,\cos\theta}{r}$$

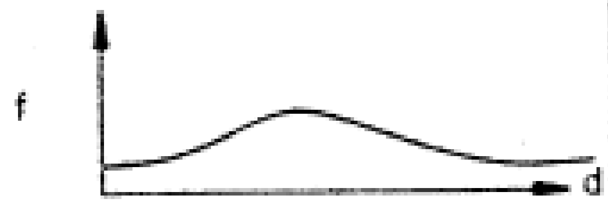
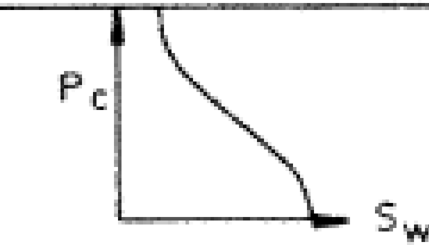
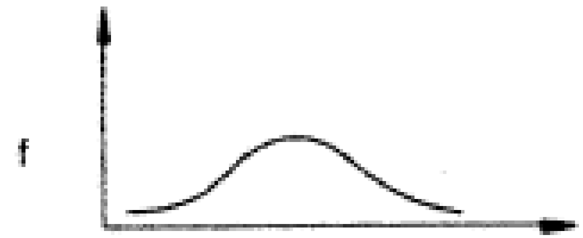
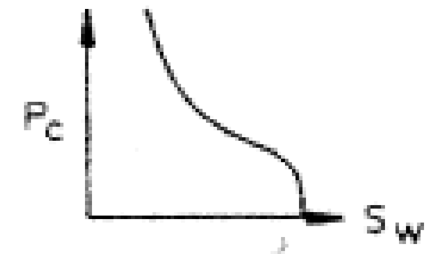
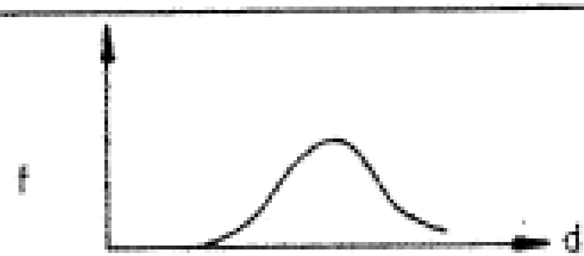
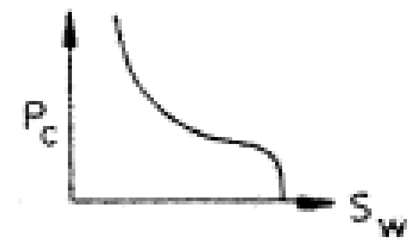
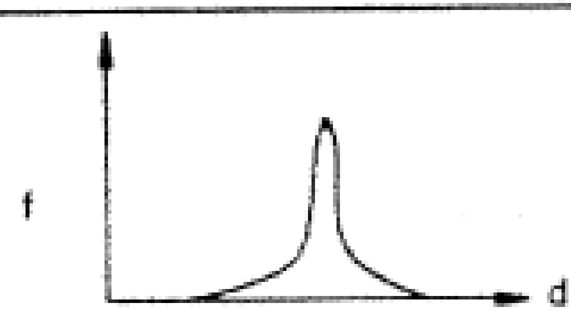
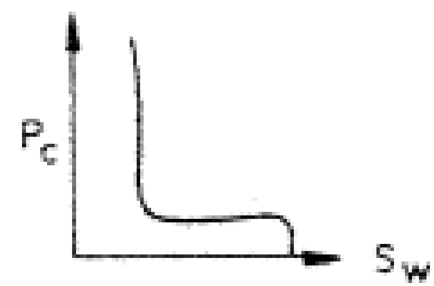
Rock Property
(K&ϕ)

$$P_c = p_e\left(\frac{S - S_{wr}}{1 - S_{wr}}\right)^{-1/\lambda}$$

$$P_c = p_e\left(S_{eff}^{\ -1/\lambda} - 1\right)$$

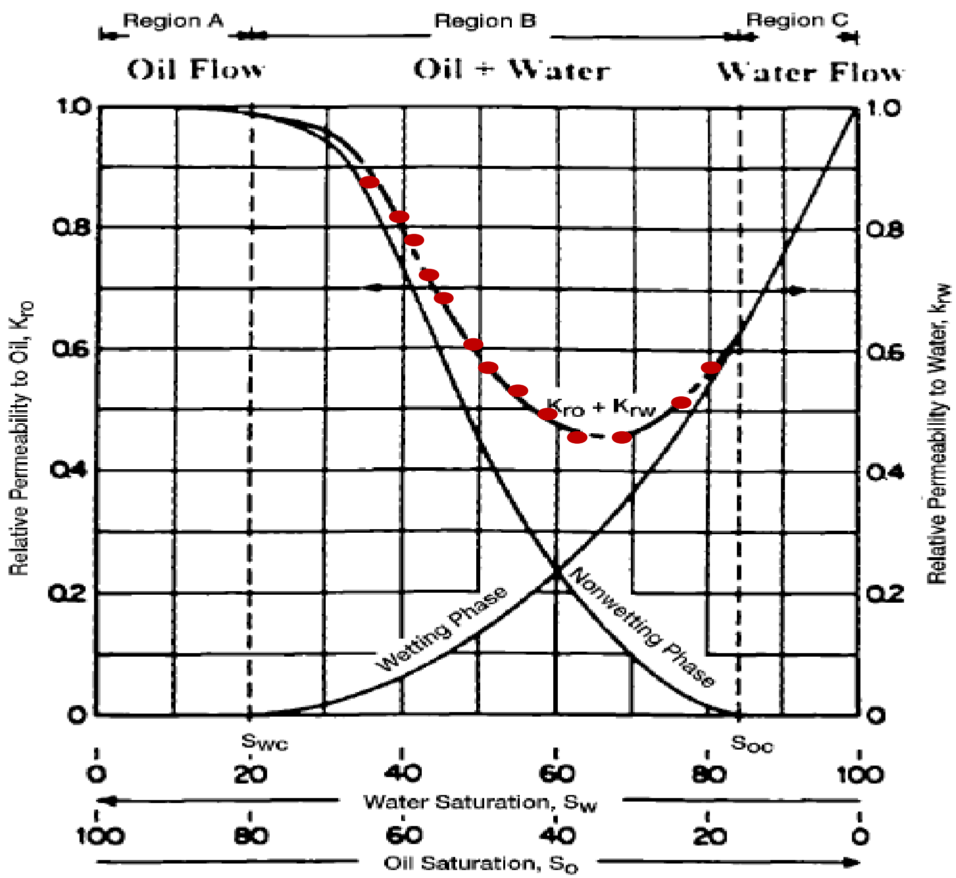
$$S_{eff} = \frac{S_w - S_{wr}}{1 - S_{wr} - S_{nwr}}$$



PORE SIZE RANGE DISTRIBUTION	FREQUENCY DISTRIBUTION	CAPILLARY PRESSURE CURVE	λ
VERY WIDE			0.5
WIDE			2
MEDIUM RANGE			4
UNIFORM			∞

Factors Affecting Relative Permeabilities

- Fluid saturations
- Geometry of the pore spaces and pore size distribution
- Wettability
- Fluid saturation history (i.e., imbibition or drainage)



Capillary Pressure Curve

- In a fractured matrix system, the capillary pressure curve plays a much more important role than in a conventional reservoir. In fact, in a single-porosity reservoir the role of capillary pressure at static conditions is associated with the transition zone, whereas at dynamic conditions the capillary forces (and thus the capillary pressure curve shape and magnitude) play a more limited role because the fluid displacement process in all conventional reservoirs is mainly controlled by viscous forces.

- On the contrary, in a fractured reservoir where the displacement process is essentially controlled by gravity and capillary pressure forces, the examination of capillary pressure curve behavior becomes essential for a correct understanding of the displacement process. Capillary pressure behavior with both "drainage" and "imbibition“ displacement processes, if combined with gravity displacement behavior (through similar relationship), make possible evaluation of matrix-fractures fluid exchange.

Wettability Role

- Wettability is the result of interaction of the solid / fluid under given temperature and pressure conditions where one fluid which is preferentially wetting the solid represents the "wetting phase" and the other fluid wetting the solidless is called the "non-wetting-phase".
- There are a series of conditions which contribute to increasing or decreasing preferential wettability of one or the other of the phases:
  (1) higher temperature increases the wettability for water phase; and
  (2) Certain compounds, such as asphaltene, reduce the wettability for water and increase the wettability for oil.
- The various phases encountered in a hydrocarbon reservoir under preferential wettability for one phase compared with other are:

Wetting	Wetting phase	Non-wetting phase	Number of phases
Water-wet case	Water	Oil and gas	three
Water-wet case	Water	Oil	two
Water-wet case	Water	Gas	two
Oil-wet case	Oil	Water and gas	three
Oil-wet case	Oil	Gas	two

Capillary Displacement vs. Wettability

The displacement of oil from the matrix, and the role of capillary pressure, are dependent on fluid saturations in the fracture/matrix system, as well as on fluid wettability and saturation history. In fact, the displacement process could be a drainage or an imbibition process if the behavior of saturation variation in the matrix and fractures is similar to those described in Table 7-V

Initial conditions of drainage / imbibition displacement.

TIME	FRACTURE	MATRIX	DISPLACEMENT PROCESS
at $t = 0$	$S_{WETT} = 0$	$S_{WETT} = 1$	DRAINAGE
	P_{fr} >	P_{Matrix}	
$t > 0$	$S_{WETT} = 0$	$S_{WETT} < 1$ (decreases)	
at $t = 0$	$S_{WETT} = 1$	$S_{WETT} = 0$	IMBIBITION
	P_{fr} =	P_{Matrix}	
$t > 0$	$S_{WETT} < 1$	$S_{WETT} > 0$ (increases)	

TIME	FRACTURE	MATRIX	DISPLACEMENT PROCESS
at $t = 0$	$S_{WETT} = 0$	$S_{WETT} = 1$	<u>DRAINAGE</u>
	P_{fr} >	P_{Matrix}	
$t > 0$	$S_{WETT} = 0$	$S_{WETT} < 1$ (decreases)	

➢Initially (@ t = 0) the matrix blocks are fully saturated with the "wetting-phase“ (S_{WET}=1) and the surrounding fractures fully saturated with "non-wetting-phase " (S_{WET}= 0). The displacement of "wetting-phase" (contained in matrix blocks) by "nonwetting-phase" (contained in fractures) requires a higher pressure in fractures than in matrix (P_f > P_{matrix}) and is called "drainage displacement". The resulting capillary pressure vs. saturation relationship is known as the "drainage capillary pressure curve“ .

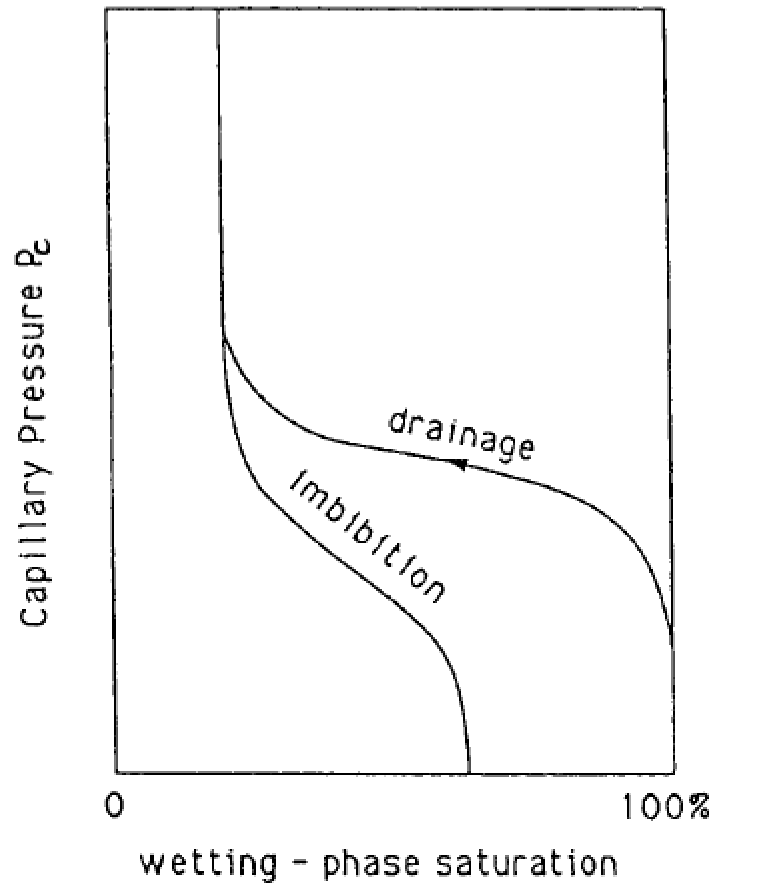


Fig. 7-32. Drainage and imbibition capillary pressure curves.

TIME	FRACTURE	MATRIX	DISPLACEMENT PROCESS
at t = 0	$S_{WETT} = 1$	$S_{WETT} = 0$	IMBIBITION
	P_{fr} =	P_{Matrix}	
t > 0	$S_{WETT} < 1$	$S_{WETT} > 0$ (increases)	

Inversely, if initially (@ t = 0) the matrix block is saturated with a "nonwetting- phase" (S_{WET}= 0) , whereas the fractures are saturated with the "wetting-phase“(S_{WET}= 1), then an "imbibition displacement" drive mechanism takes place. This displacement is controlled by a capillary pressure vs. saturation relationship known as "imbibition capillary pressure" curve.

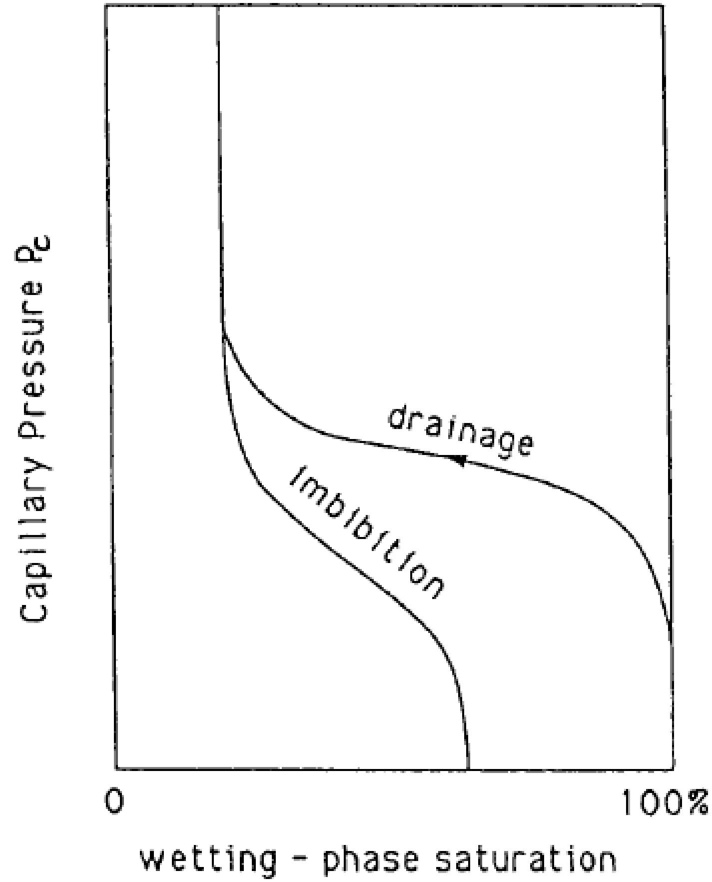


Fig. 7-32. Drainage and imbibition capillary pressure curves.

Description of Drainage and Imbibition Displacement Process

In order to describe the drainage and imbibition processes, the desaturation in a wetting-phase (drainage), and saturation increases in a wetting-phase (imbibition) are schematically illustrated between initial conditions (@ t= 0) and final conditions (t ~ ∞) in Fig. 7-33.

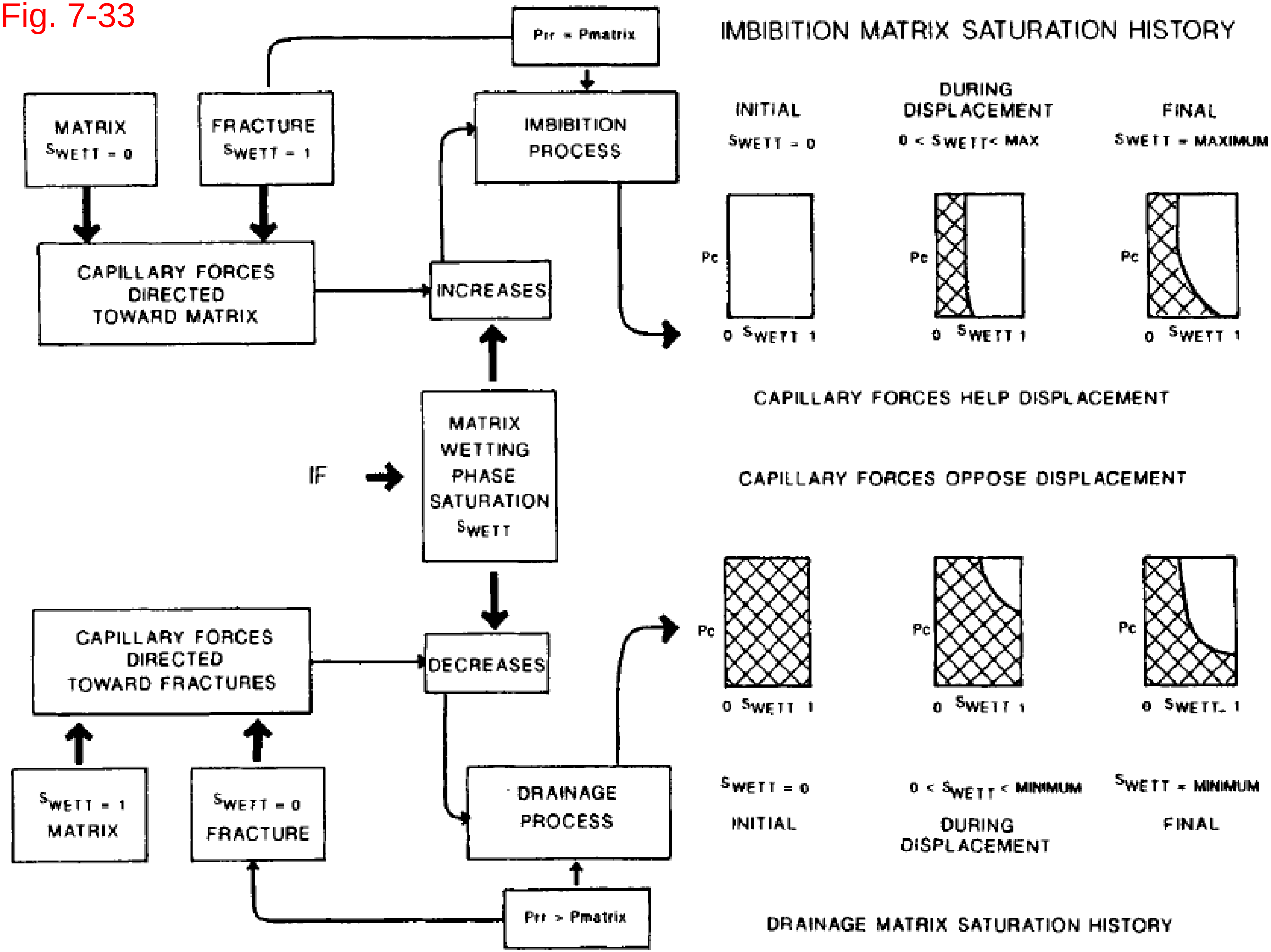
The essential characteristics obtained from the two driving histories, which resulted in two capillary pressure curves (drainage and imbibition) indicated in Fig. 7- 33, suggest the following:
(1) the minimum saturation of a wetting phase, which is the same in both processes and is called "irreducible saturation of wetting phase," corresponds to an infinitely large "displacing capillary pressure";
(2) the shape of a drainage capillary pressure curve shows the distribution of pores and reflects the homogeneity of pore dimensions;
(3) the existence of a residual saturation in the non-wetting phase is obtainable only in an imbibition displacement process, when the trapped non-wetting phase fills large-diameter pores which intersect with clusters of small-diameter pores;

(4) in the case of capillary and gravity forces controlling a drainage process, the displacement of a wetting phase by a non-wetting phase can take place only if the threshold height is smaller than the block height;

(5) the drainage process can start only if the pressure difference $P_f > P_m$ is higher than "threshold pressure" $P_{threshold}$ (which is very close to the pore throat pressure); and

(6) capillary forces are opposing the entrance of a non-wetting-phase in the matrix during the drainage process, whereas capillary forces help the entrance of the wetting phase in the matrix during imbibition.

Fig. 7-33



IMBIBITION MATRIX SATURATION HISTORY
Prr = Pmatrix
MATRIX
SWETT = 0
FRACTURE
SWETT = 1
IMBIBITION PROCESS
CAPILLARY FORCES DIRECTED TOWARD MATRIX
INCREASES
INITIAL
SWETT = 0
DURING DISPLACEMENT
0 < SWETT < MAX
FINAL
SWETT = MAXIMUM
Pc
0 SWETT 1
CAPILLARY FORCES HELP DISPLACEMENT
IF
MATRIX WETTING PHASE SATURATION SWETT
CAPILLARY FORCES OPPOSE DISPLACEMENT
CAPILLARY FORCES DIRECTED TOWARD FRACTURES
DECREASES
SWETT = 1
MATRIX
SWETT = 0
FRACTURE
DRAINAGE PROCESS
Prr > Pmatrix
SWETT = 0
INITIAL
0 < SWETT < MINIMUM
DURING DISPLACEMENT
SWETT = MINIMUM
FINAL
DRAINAGE MATRIX SATURATION HISTORY

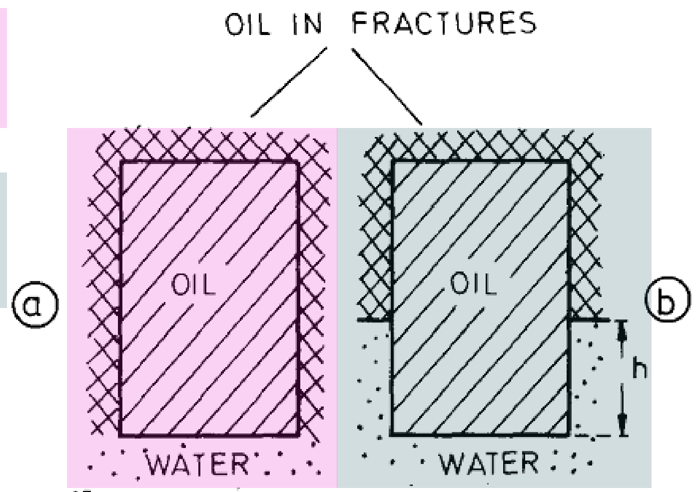
Composite Capillary Imbibition Curve

According to the relationship between fluids coexisting in matrix and fracture, the displacement process will be controlled by gravity (due to the difference in densities between oil and water) or capillary forces (due to the interaction of surface forces within the pores).

Sudation: combined effect of capillary and gravity forces

(a): the capillary forces imbibing the matrix displace the oil;

(b): the difference in level **h** will generate a displacement through gravity effect.



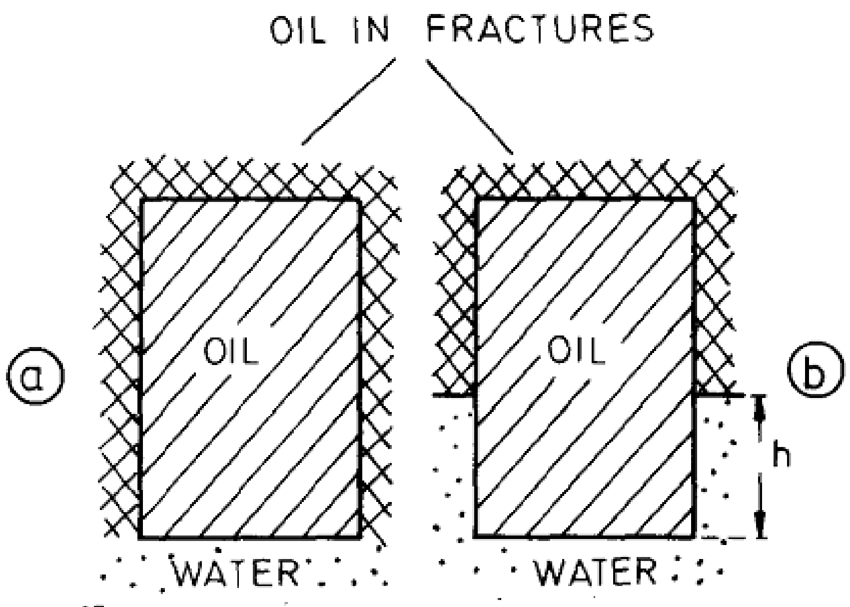
- ❑Gravity forces are working preferentially on larger pores.
- ❑Capillary forces are working preferentially on smaller pores.
- ❑The composite imbibition curve will take care of both forces working during imbibition.

a) Displacement under capillary forces

b) Displacement under capillary and gravity forces.

Composite Capillary Imbibition Curve

The presence of gravity forces is related to the existence of a level difference between water-oil contacts in fractures and in matrix.



$$P_G = h \times \Delta\gamma$$

$$P_c = h_c \times \Delta\gamma$$

$$h_c \cong \frac{1}{r_c, \text{avg}}$$

➢Capillary forces will be large if pore size is small while gravity forces will increase as the height of the matrix block increases.

- ❑ The gravity forces will govern the imbibition in the case of high blocks and large pore size
- ❑capillary forces will govern the imbibition in the case of small matrix blocks and reduced pore size.

Example

Considering a fractured reservoir with an average pore diameter of 4μ (microns) in which oil is displaced by water capillary imbibition one may compare the capillary and gravity forces of one block with a height of h_{BL}=0.3 m and with another of height, h_{BL} = 20 m.

System	θ Contact Angle (grades)	Cos Θ	σ Interfacial Tension (dynes/cm)	σ cos Θ
Laboratory				
Air-water	0	1.0	72	72
Oil-water	30	0.866	48	42
Air-mercury	140	0.765	480	367
Air-oil	0	1.0	24	24
Reservoir				
Water-oil	30	0.866	30	26
Water-gas	0	1.0	50*	50

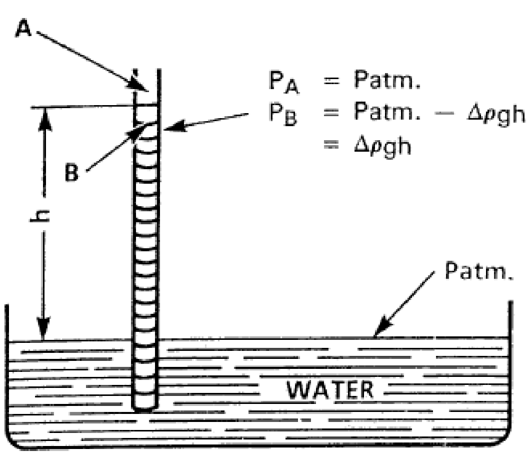
$$h_c = \frac{P_c}{\Delta\gamma} = \frac{1}{\Delta\gamma} \cdot \frac{\sigma\cos\theta}{2r} = \frac{1}{0.2 \times 10^{-3}} \cdot \frac{42 \times 10^{-6}}{4 \times 10^{-4}} = 525 \text{ cm} = 5.25\text{m}$$

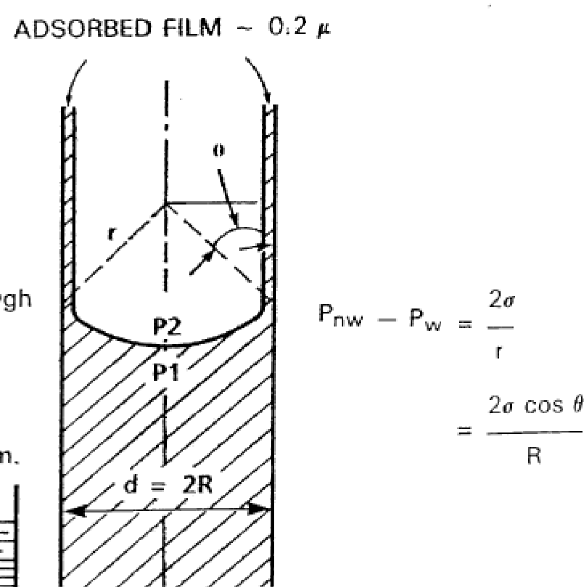
Comparing capillary height h_c = 5.25m with the block heights h_{Bl} = 0.3m and h_{Bl} = 20m, it results that in the first case the capillary pressure dominates the displacing process and in the second case the gravitational forces.

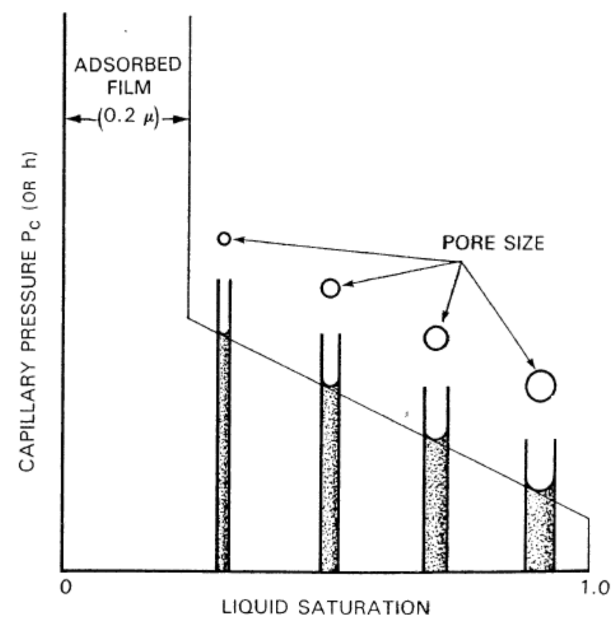
Capillary Height with Different Effective Pore Diameter

σ=5 dynes/cm
Θ=0
$\Delta(dp/dZ)_{o\text{-}w}$=0.2 psi/ft
R_1=1.45 microns
R_2=1.96 microns
R_3=2.90 microns
R_4=5.80 microns

h_1=3.30 ft
h_2=2.50 ft
h_3=1.67 ft
h_4=0.83 ft







Magnitude of Pores Displaced by P_C and P_G

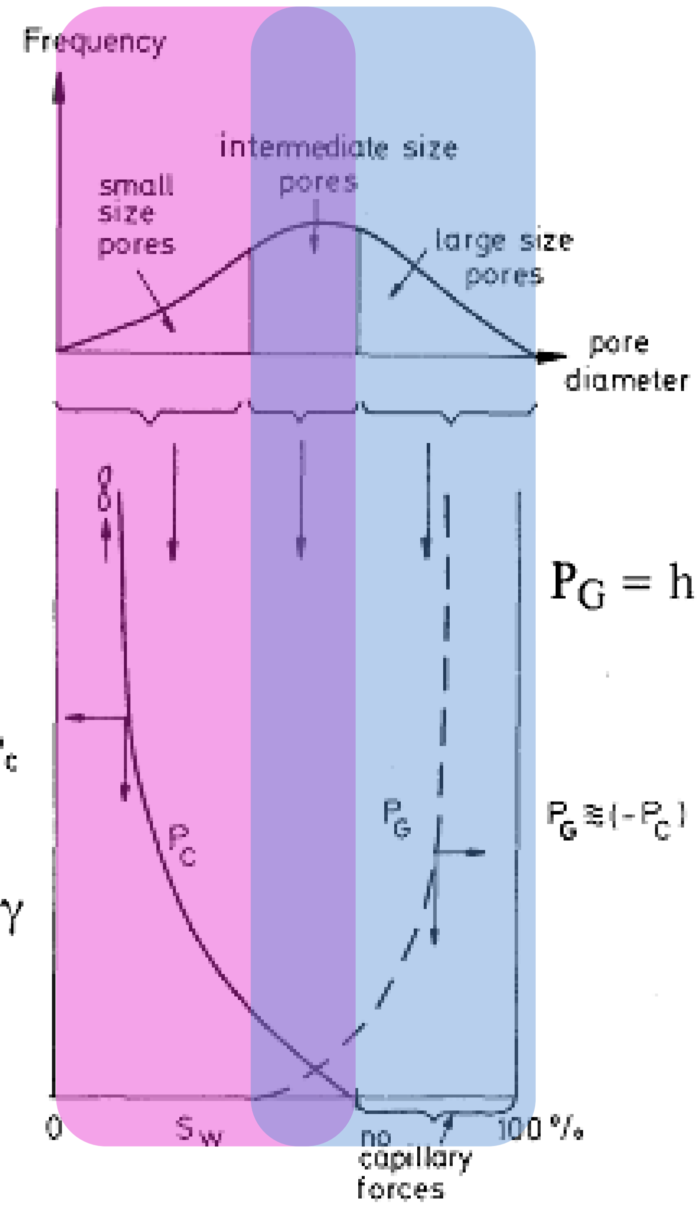
- small and very small pores are associated with capillary forces of various magnitudes.

- If pore size increases from small to intermediate, their magnitude will directly influence the P_c curve, which decreases from infinite to zero.

- But a number of pores (intermediate and large) between $P_c = 0$ and $S_w = 100\%$ may not show any capillary force and thus the displacement will be related to gravitational forces.

$$P_c = h_c \times \Delta\gamma$$

$$P_G = h \times \Delta\gamma$$



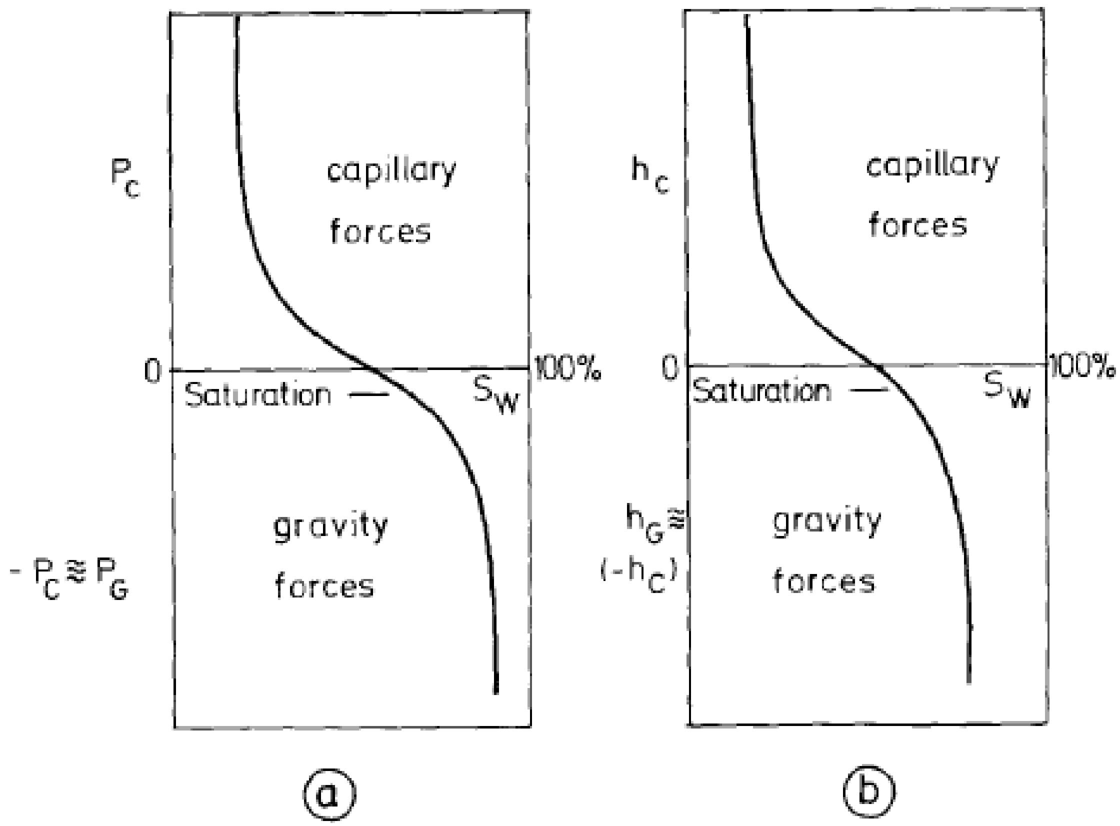
4.63 – Influence of pore size distribution on P_c vs S_w and on P_G vs S_w

The <u>gravity forces</u> which may be predominant forces of displacement in intermediate and large pores are limited in the displacement of oil by the interpenetration of small pores and large pores, which leads to the <u>blockage of oil</u> in the area of contrasting pore size. Thus the relationship P_G -S_w is dependent on <u>pore size distribution</u> and <u>pore intercommunication</u>.

Composite Imbibition Curve Approach

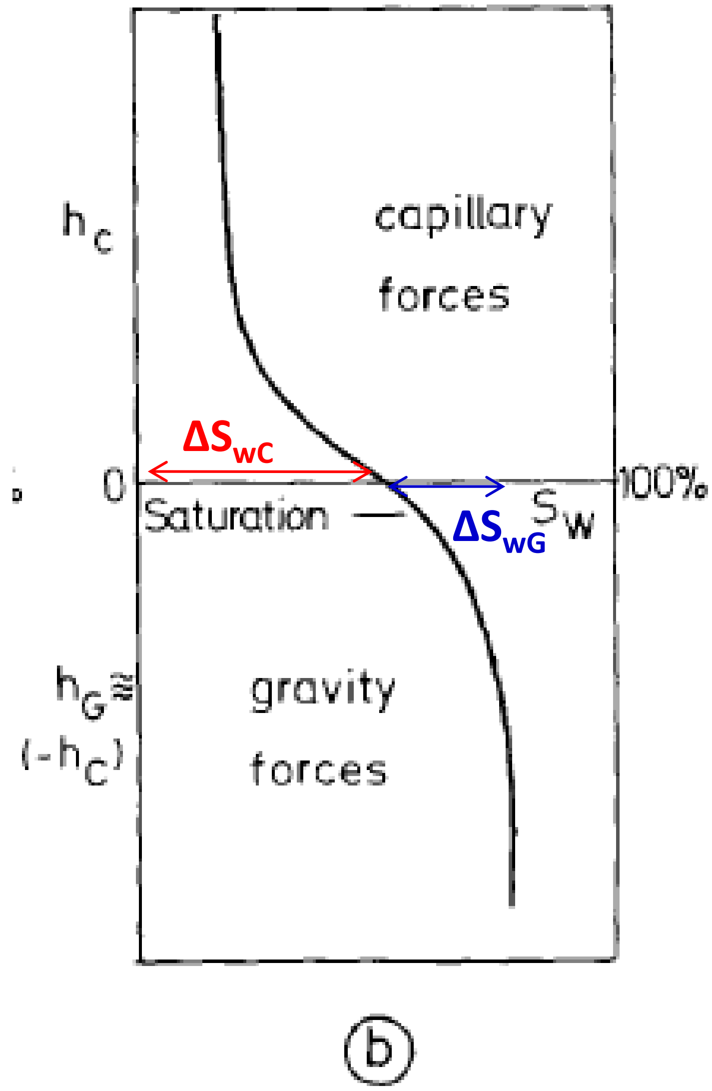
Due to the fact that the relationship P_G vs. S_w may be considered similar to a capillary curve, it is permissible to write P_G equivalent to a negative P_c where the negative sign of P_c is a conventional sign, since during imbibition both forces may displace the matrix fluid in the same direction.

The composite curve is thus presented as in figure 4.64, either as pressure (figure 4.64a) or height (h_G o r h_C, figure 4.64b).



4.64 – Composite curves: a) Pressure vs. S_W; b) height vs. S_W.

In figure 4.64b for a given block height *h*, both ΔS_w values, above zero line for capillary forces and below zero line for gravitational forces, will result. The values ΔS_{wG} and ΔS_{wC} represent total recoveries of oil obtainable from the matrix in a very long time if the block height is known and if the matrix block was completely invaded by water.



•In a conventional reservoir the capillary pressure curve controls fluid distribution through the reservoir; therefore, the transition zone will come between the water-oil contact and the oil zone which, in the case of important capillary forces (tight formation), may be very thick. In a fractured reservoir this situation is completely different.

•The discontinuity of the matrix caused by the fracture network cutting the *continuum* of the matrix bulk into small individual matrix blocks, explains why the water table is only related to the fracture network.

•In addition, since the fractures are large channels with negligible capillary forces, the transition zone disappears in a fractured reservoir, and water-oil contact becomes a horizontal plane. On the other hand, capillary and gravitational forces (through the capillary pressure curve and gravitational curve) control the static and dynamic equilibrium of each matrix block.

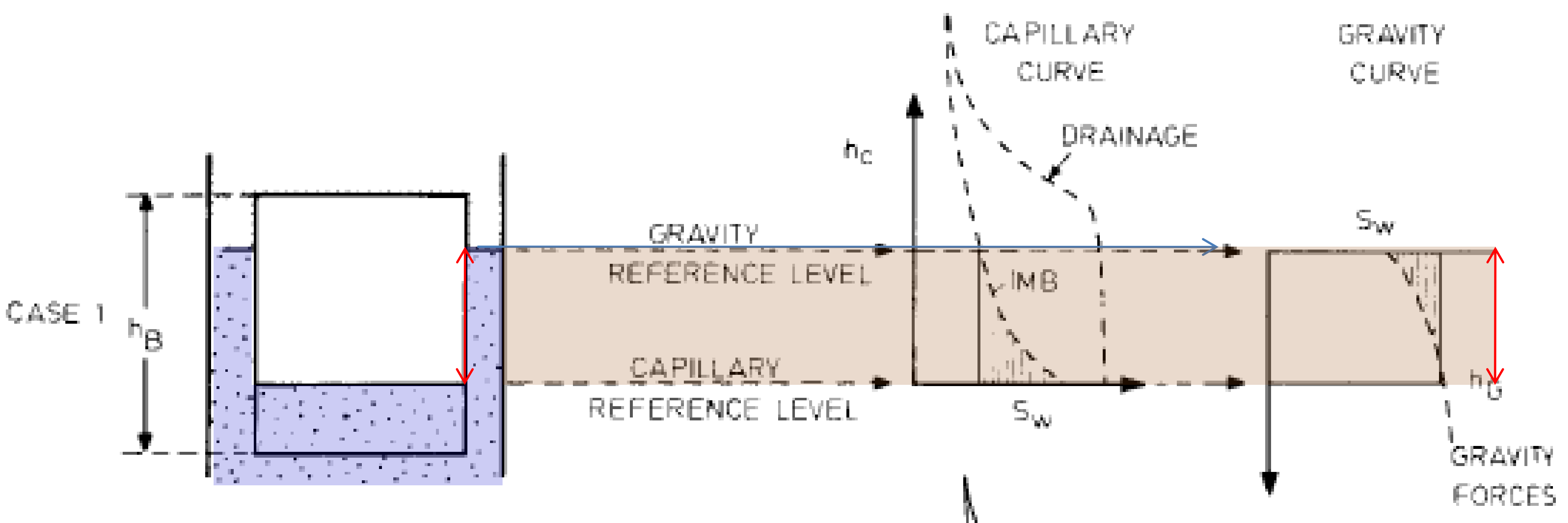
•The basic element which relates individual block behavior to reservoir behaviour is the water-oil contact in fractures and is called *water table level. These water-oil contacts* in fractures, together with the *oil-water contacts inside the matrix*, the last corresponding to *displacement front level, are essential reference* planes for the evaluation of the driving mechanism of capillary and gravity forces.

•An analogical situation will take place in the case of a gas-cap for both gas-oil contacts in fractures and matrix blocks, where the first is called *gas-cap table and the second gas displacement front.*

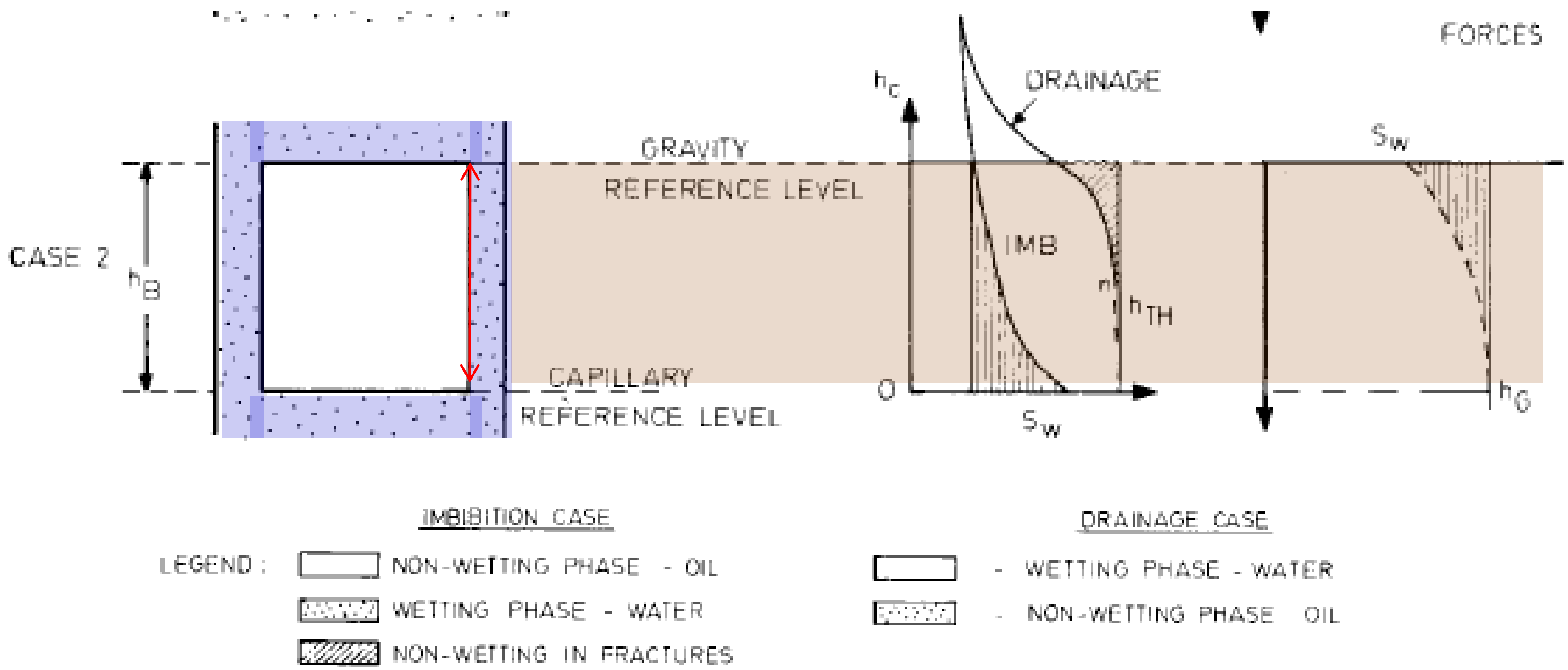
EXAMPLE: Considering a block height h_B, as is graphically described in the below figure, a procedure through which (at any stage) a correlation between the driving forces and fluid equilibrium may be established can be developed.

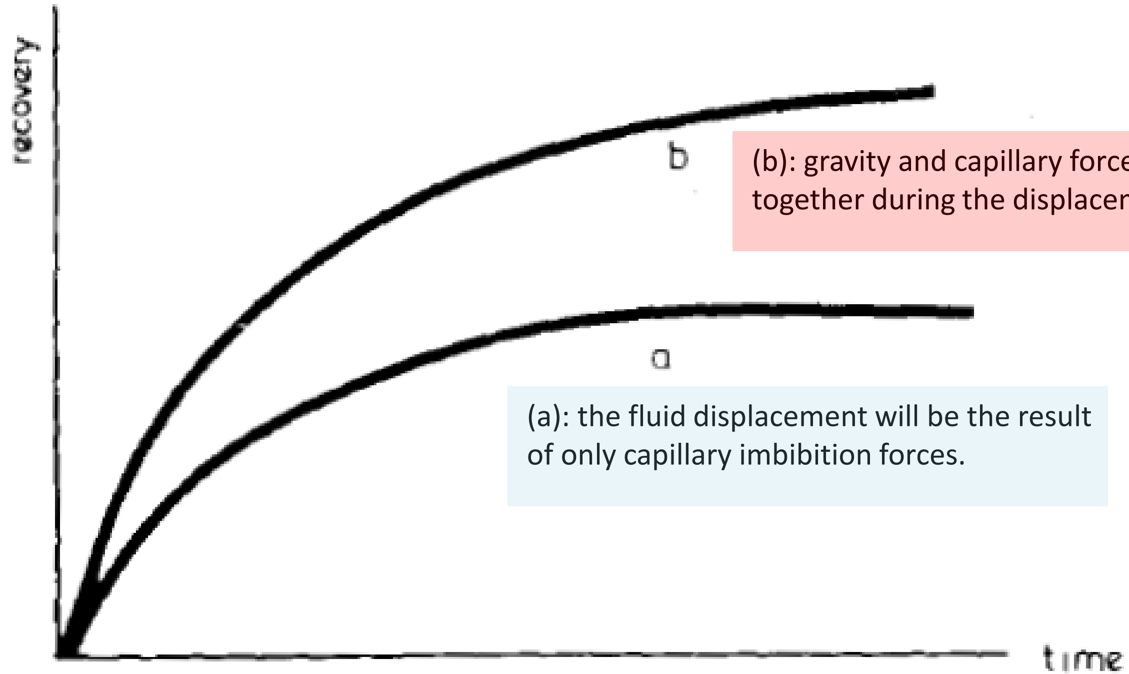
•**Case 1**; As observed, the water-oil contact advanced during displacement in matrix and fractures, so that the water-oil level in fractures is above the bottom level in matrix. In this case the reference level of capillary forces should be related to the water-oil level of the matrix. A dotted line represents capillary forces in the imbibition capillary curve. The gravity forces, in this case, refer to the fracture water-oil contact, and therefore, the height of the gravity forces will be limited to the water-oil contact in the matrix.

•In the same **case 1**, when a wetting phase is in the matrix and non-wetting phase in fractures, the same procedure will be followed on the drainage capillary pressure curve. As observed, capillary forces are higher on the drainage curve than gravity forces, which explains why it is impossible to displace water with oil in fractures under existing conditions of equilibrium. Capillary forces, which are larger than gravity forces, oppose the entrance of oil into the block.



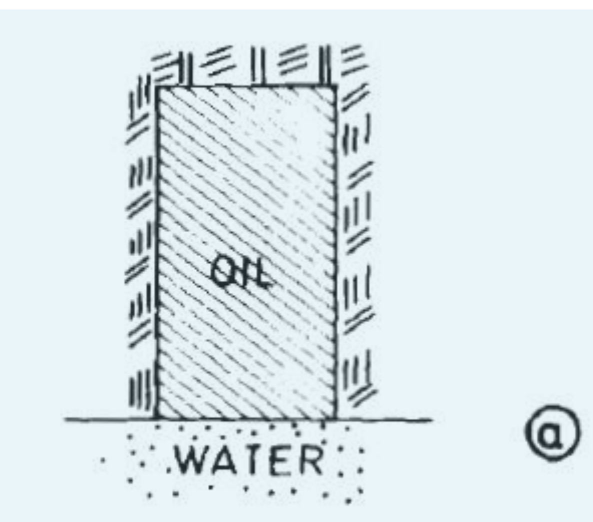
Case 2; The oil-saturated block is immersed in water so that the reference for capillary forces is at water-oil contact in the matrix (bottom face of block), and the reference for gravity forces is at the higher level of the block (top face). Capillary and gravity efficiencies are represented by dotted zones which indicate the magnitude of total recovery expected from gravity and capillary forces. In the case that water saturates the matrix a drainage process will take place. By using the drainage curve (the oil-non-wetting phase displaces water-wetting phase), the threshold height h_{th} being somewhat lower than block height, a partial imbibition of oil becomes possible in the block (hatched area).

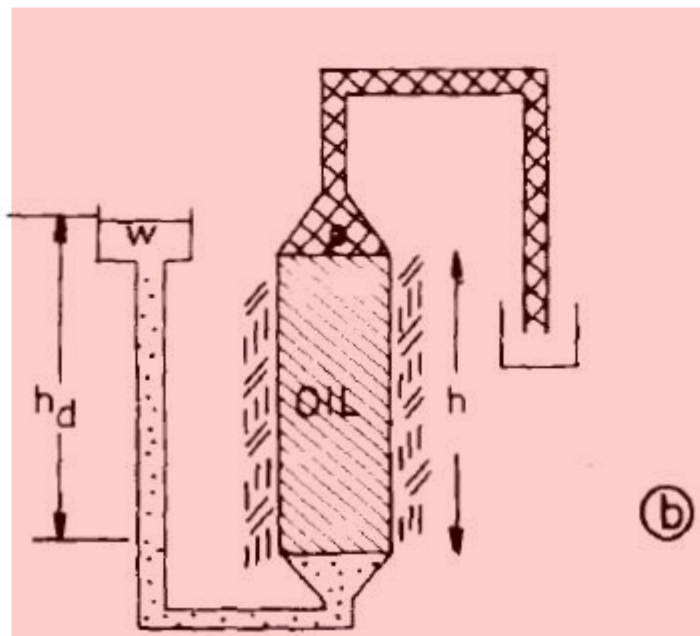


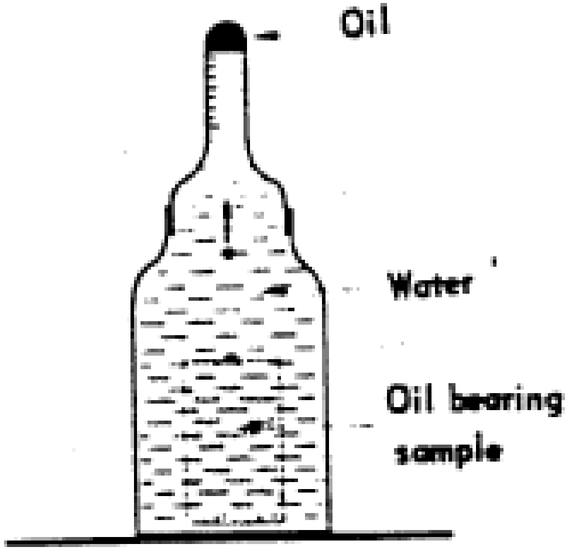


(b): gravity and capillary forces are working together during the displacement process

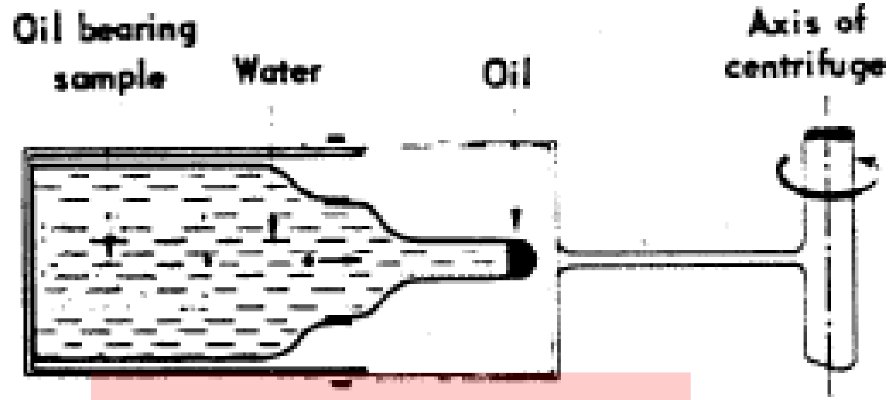
(a): the fluid displacement will be the result of only capillary imbibition forces.







(a) Simple immersion
(only capillary forces)

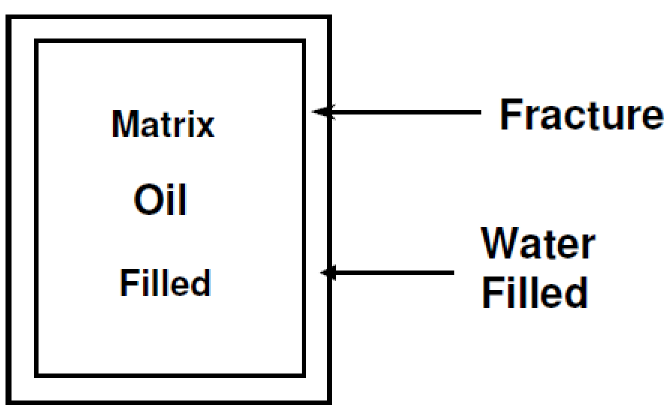


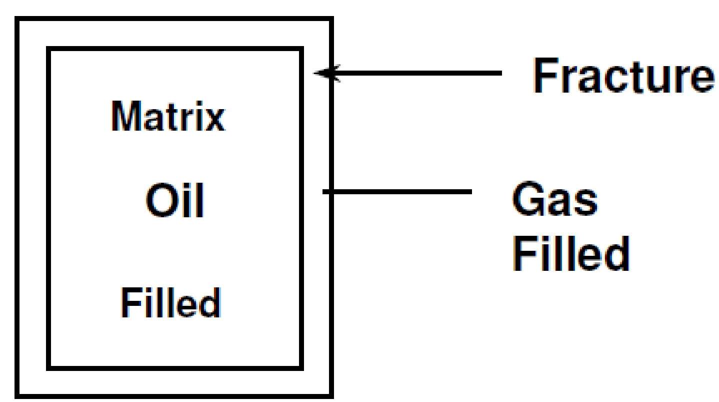
(b) Immersion in a centrifuge
(capillarity and gravity)

FLUID DISPLACEMENT PROCESS IN A SINGLE MATRIX BLOCK

❑A single block is a volumetric, matrix unit completely surrounded by a network of fractures without any communication with other blocks. Consequently, the continuity of flow from one matrix block to another virtually does not exist, thus the problem of fluid displacement only affects the interaction between fluids which saturate the matrix and fluids which saturate the surrounding network of fractures.

❑The change in saturation as a result of the displacement process may take place under imbibition or drainage conditions, where capillary pressure and gravity forces could work for or against the displacement.





SIMPLIFIED DYNAMIC APPROACH TO MATRIX FLUID DISPLACEMENT

The displacement process in a fractured reservoir occurs when the matrix block saturated with oil is partially or entirely surrounded by another fluid, gas and/or water.