Part I. Write your answer in the space provided. Use equations and sketches in addition to words (as needed).

1. a. Give a qualitative definition of adhesion tension.

The difference between two solid-fluid interfacial tensions.

b. Give a quantitative definition of adhesion tension (A_T) in an oil-water system. Define all terms.

$$A_T = \sigma_{os} - \sigma_{ws} = -|\sigma_{ow}| \cos\theta$$

where:

σ – interfacial tension

σ_{os} – between oil & solid

σ_{ws} – between water & solid

σ_{ow} – between oil & water

θ – contact angle

c. List two factors affecting adhesion tension.

- composition of the solids
- composition of the fluids

2. a. Explain and give an example of an "imbibition process".

Fluid flow process in which saturation of wetting phase decreases (non wetting phase increases)

Ex. Hydrocarbon accumulations in a water-wet rock (others – see Slide 4, Lec 15)

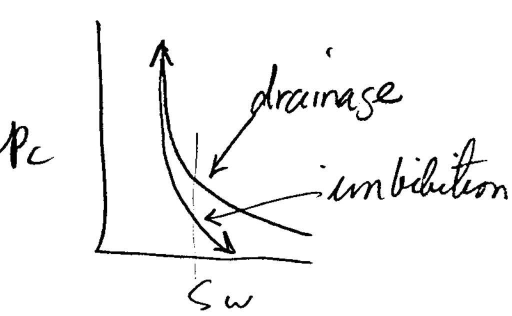
b. Explain and give an example of a "drainage process".

Fluid flow process in which saturation of wetting phase increases (nonwetting phase decreases)

Ex. Water flooding a water-wet oil reservoir (others – see Slide 5, Lec 15)

c. Explain the term, "hysteresis" in capillary pressure.

- The lagging of an effect behind its cause
- explains difference in Pc at same saturation due to path dependence
- different pores are occupied by wetting phase



3. a. Explain the porous ~~plate~~ diaphragm method for determining capillary pressure in the laboratory.

A core is saturated with the wetting fluid and placed on a porous diaphragm in capillary contact with wetting fluid below the diaphragm (selected to permit flow of wetting fluid only). Non wetting fluid is introduced. After equilibrium, pressure and displaced wetting fluid are meas.

b. Give three more methods for determining capillary pressure in the laboratory.

- centrifuge method
- mercury injection method
- dynamic method

c. Show that the dimension of the equation (see Problem 5 below) used to calculate capillary pressure from centrifuge data is $[FL^{-2}]$.

$$p_c = N^2 \Delta\rho \left(r_e - \tfrac{1}{2}\right) L$$

$$[p] = \left[\frac{F}{L^2}\right] = \left[\frac{1}{t}\right]^2 \left[\frac{M}{L^3}\right] \left[\frac{L^2}{1}\right] = \left[\frac{ML}{t^2} \cdot \frac{\cancel{1}}{L} \cdot \frac{1}{L^2}\right] = \left[\frac{F}{L^2}\right]$$

4. a. Give a qualitative definition of capillary pressure at a point in a reservoir.

The pressure difference existing across the interface separating two immiscible fluids -- the difference between the non-wetting and wetting phase pressures.

b. Give a quantitative definition of capillary pressure (p_c) at a point in a reservoir. Define all terms.

$$p_c = p_{nw} - p_w = (\rho_w - \rho_{nw}) g h$$

nw = non wetting
w = wetting

where: p = pressure, g = acceleration due to gravity
ρ = density, h = height above ($p_{nw} = p_w$) level

c. List four factors affecting the capillary pressure saturation relationship.

- permeability
- size and distribution of pores
- fluids and solids involved
- saturation history

Part II. Work out the answer in the space provided. Show details of your work and clearly identify your answer. Grading will be on the basis of approach and answers.

5. The equation shown below is used to calculate capillary pressure from centrifuge data.

$$p_{ci} = 4\pi^2 N^2 \Delta\rho (r_e - L/2) L$$

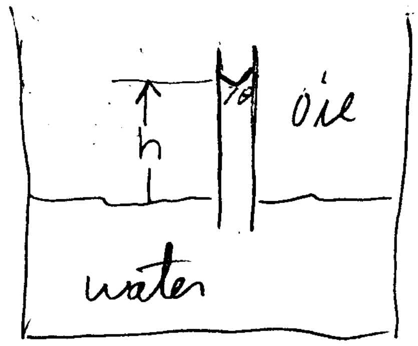
Determine the constant, and its units to calculate p_c in psi, when N is revolutions per minute, the density, ρ, is in lb_m/ft^3, and the lengths, r_e and L, are in inches.

$4\pi^2$ has units $\dfrac{dynes/cm^2 \cdot s^2}{g/cm^3 \cdot cm^2}$ or $\dfrac{Pa \cdot s^2}{Kg/m^3 \cdot m^2}$

$$\frac{4\pi^2\, Pa \cdot s^2}{Kg/m^3 \cdot m^2} \left| \frac{min^2}{(60)^2 s^2} \right| \frac{14.696\ psi}{101325\ Pa} \left| \frac{0.45359\ Kg}{lbm} \right| \frac{ft^3}{(0.3048)^3 m^3} \left| \frac{(0.3048)^2 m^2}{ft^2} \right| \frac{ft^2}{144\ in^2} =$$

$$1.6437 \times 10^{-8} \ \frac{psi \cdot min^2}{lbm/ft^3 \cdot in^2}$$

6. Consider the balance of forces at the interface between oil and water in a small capillary tube of radius, r, inserted vertically across the oil-water contact in a container. Derive the equation for the height of water rise, h, in the tube. Include a sketch for this case where water, the denser phase, is the wetting phase.



Forces up = Forces down

Adhesion tension acting on circumference of tube = Pressure due gravitational forces acting on area of tube

$$(A_T)(2\pi r) = (\Delta\rho g h)(\pi r^2)$$

$$(\text{dynes/cm})(\text{cm}) = (\text{dynes/cm}^2)(\text{cm}^2)$$

From above,

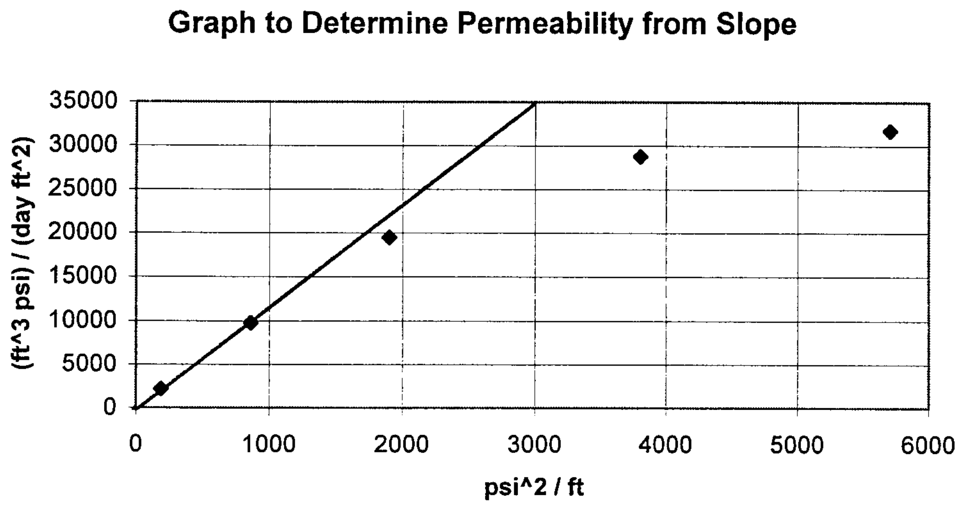
$$(\sigma_{ow}\cos\theta)(2\pi r) = (\Delta\rho g h)(\pi r^2)$$

$$h = \frac{2\sigma_{ow}\cos\theta}{\Delta\rho g r} \quad \square.$$

7. Horizontal, isothermal, linear flow of a gas at moderate pressure, is given by the pressure-squared form of Darcy's Law (for Darcy units),

$$q_{sc} = \frac{T_{sc}}{Tp_{sc}} \frac{kA}{\mu zL} \left(\frac{p_1^2 - p_2^2}{2} \right).$$

If flow is measured at $T = T_{sc}$ and a relatively low pressure, so that $z \cong 1$, then plotting $\frac{q_{sc} \cdot p_{sc}}{A}$ versus $\frac{p_1^2 - p_2^2}{2L}$ as shown below allows permeability of the porous media to be determined from the slope of the graph, if viscosity is known.



Determine the permeability of the porous media from the above graph if the gas is has a viscosity of 0.011 cp, T_{sc} = 60 °F, and p_{sc} = 14.73 psia.

$$\text{Slope} = \frac{35000}{3000} = \frac{35}{3} \frac{ft^2}{psi\text{-}day}$$

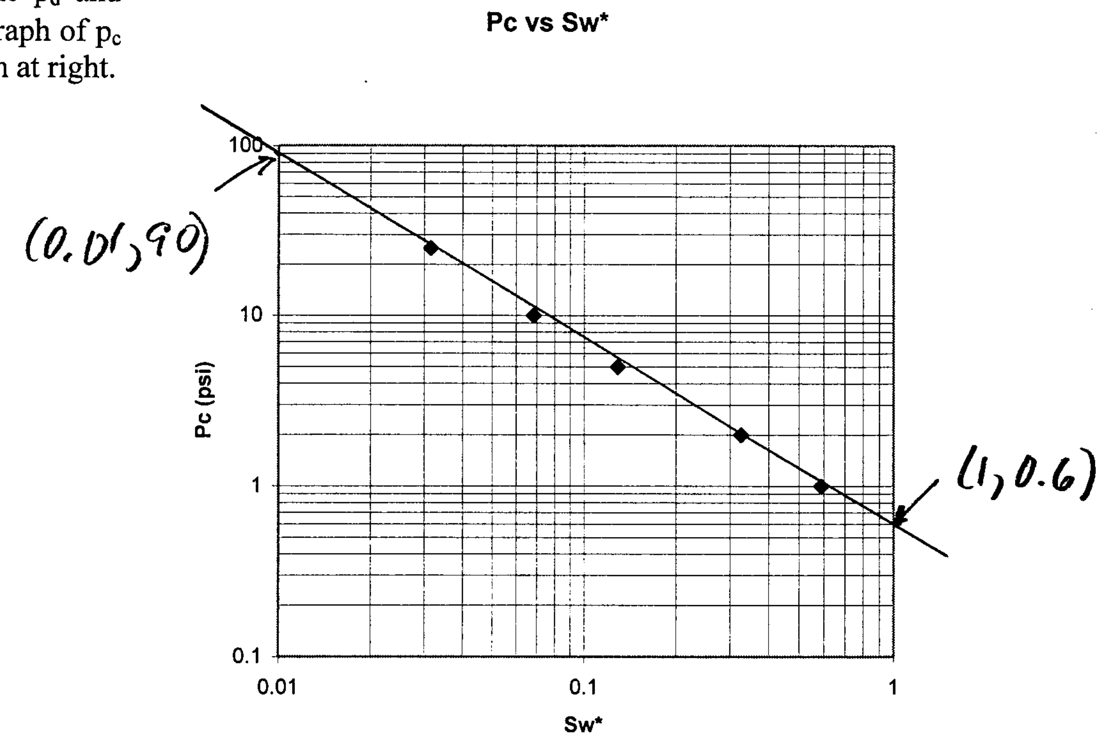
From eqn. page

$$\underbrace{\frac{q_{sc}\, p_{sc}}{A}}_{Y} = (3.1641 \times 10^{-3})(2) \frac{T_{sc}}{T} \frac{k}{\mu z} \underbrace{\left(\frac{p_1^2 - p_2^2}{2L} \right)}_{X}$$

$$\Rightarrow \frac{k}{\mu} = \frac{1}{6.3282 \times 10^{-3}} \text{ Slope}$$

$$\Rightarrow k = \frac{\left(\frac{35}{3} \frac{ft^2}{psi\text{-}day}\right)(0.011\ cp)}{6.3282 \times 10^{-3} \frac{cp \cdot ft^2}{md \cdot psi\text{-}day}} = \underline{\underline{20.3\ md}}$$

8. Determine p_d and λ from the graph of p_c vs S_w* shown at right.



$$Slope = \frac{\log(0.6/90)}{\log(1/0.01)} = \frac{-2.176}{2} = -1.088$$

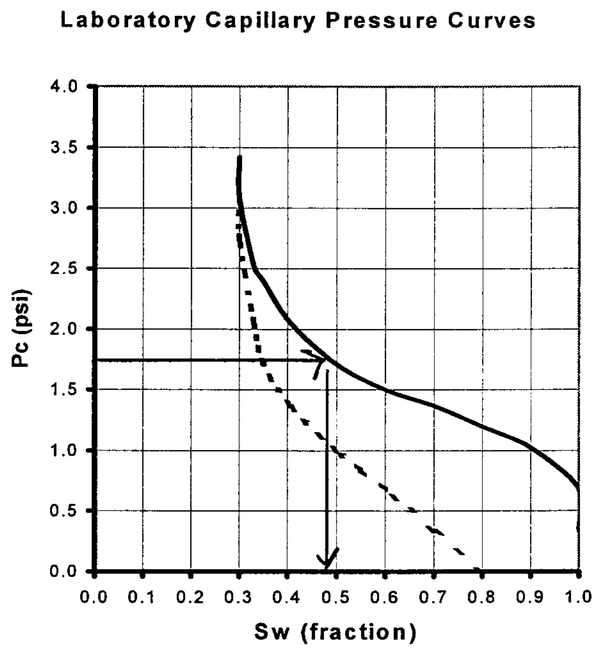
$\lambda = 0.919$, $p_d = 0.6$ psi

$$p_c = 0.6\left(S_w^*\right)^{-\frac{1}{0.919}}$$

9. The laboratory capillary pressure curves shown at right were measured using air/ water displacement tests (interfacial tension of 72 dynes/cm and contact angle of zero degrees) for a core plug having porosity of 0.22 and permeability of 135 md.

Estimate the initial water saturation at a point 10 feet above the Free Water Level in the reservoir, for the reservoir data shown below. Assume the reservoir is water wet.

porosity	0.17
permeability	110 md
interfacial tension	30 dynes/cm
contact angle	8 degrees
oil density	53.0 lb_m/ft^3
water density	63.0 lb_m/ft^3



$$P_c\ res = \Delta\rho g h = \left(10 \frac{lbm}{ft^3}\right)\left(\frac{g}{g_c}\frac{lbf}{lbm}\right) 10\ ft = 100 \frac{lbf}{ft^2} = \frac{100}{144} psi$$

$$J_{Lab} = J_{res}$$

$$P_c\ lab = P_{c\,res} \frac{\sigma \cos\theta\ lab}{\sigma \cos\theta\ res} \sqrt{\frac{K/\phi\ res}{K/\phi\ lab}}$$

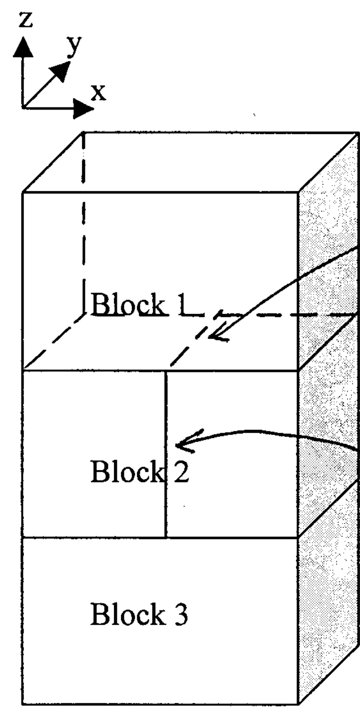
$$= \frac{100}{144} psi \ \frac{72 \cos 0^\circ}{30 \cos 8^\circ} \sqrt{\frac{110/0.17}{135/0.22}} = 1.73\ psi$$

From lab curve, $\underline{\underline{S_w \simeq 0.48}}$

$k_f = 5.4476 \times 10^{10} w^2$
$= 54476 \text{ md}$

Assume linear flow!

10. Consider a layered rock formation. Assume the permeability of the three blocks shown at right is representative of permeability of the formation. Each block is 1.75 ft wide, 1.0 ft deep, and 1.25 ft high—measurements in the x,y,z directions, respectively. Block 2 has a 0.001 inch vertical fracture normal to the x-y and x-z planes.



$A_{f_v} = \left(\frac{0.001 \text{ in}}{12 \text{ in/ft}}\right)(1 \text{ ft})$
$= 8.33 \times 10^{-5} \text{ ft}^2$
$A_{T_v} = 1.75 \text{ ft}^2$

$A_{f_y} = \left(\frac{0.001 \text{ in}}{12 \text{ in/ft}}\right)(1.25 \text{ ft})$
$= 1.042 \times 10^{-4} \text{ ft}^2$
$A_{T_y} = 2.1875 \text{ ft}^2$

The directional permeability of the rock matrix in the blocks is shown in the table below.

Layer	k_x (md)	k_y (md)	k_z(md)
1	25.5	25.5	12.2
2	13.4	13.4	6.7
3	26.5	26.5	13.3

Determine the average horizontal permeability normal to the x-z plane (k_y) and the average vertical permeability (k_z).

horizontal

$$\bar{k}_{2y} = \frac{\Sigma kA}{A_T} = \frac{(13.4)(2.1875 - 1.042\times10^{-4}) + (54476)(1.042\times10^{-4})}{2.1875} = 15.99 \text{ md}$$

$$\bar{k}_y = \frac{\Sigma kh}{\Sigma h} = \frac{(25.5 + 15.99 + 26.5)(1.25)}{3.75} = \underline{22.7 \text{ md}}$$

vertical

$$\bar{k}_{2z} = \frac{\Sigma kA}{A_T} = \frac{(6.7)(1.75 - 8.33\times10^{-5}) + (54476)(8.33\times10^{-5})}{1.75} = 9.29 \text{ md}$$

$$\bar{k}_z = \frac{L_T}{\Sigma \frac{L}{K}} = \frac{3.75}{\frac{1.25}{12.2} + \frac{1.25}{9.29} + \frac{1.25}{13.3}} = \underline{\underline{11.3 \text{ md}}}$$