Site: SANGAMO
Break: 1.1.1
Other: v.4

DNAPL IN POROUS AND FRACTURED MEDIA

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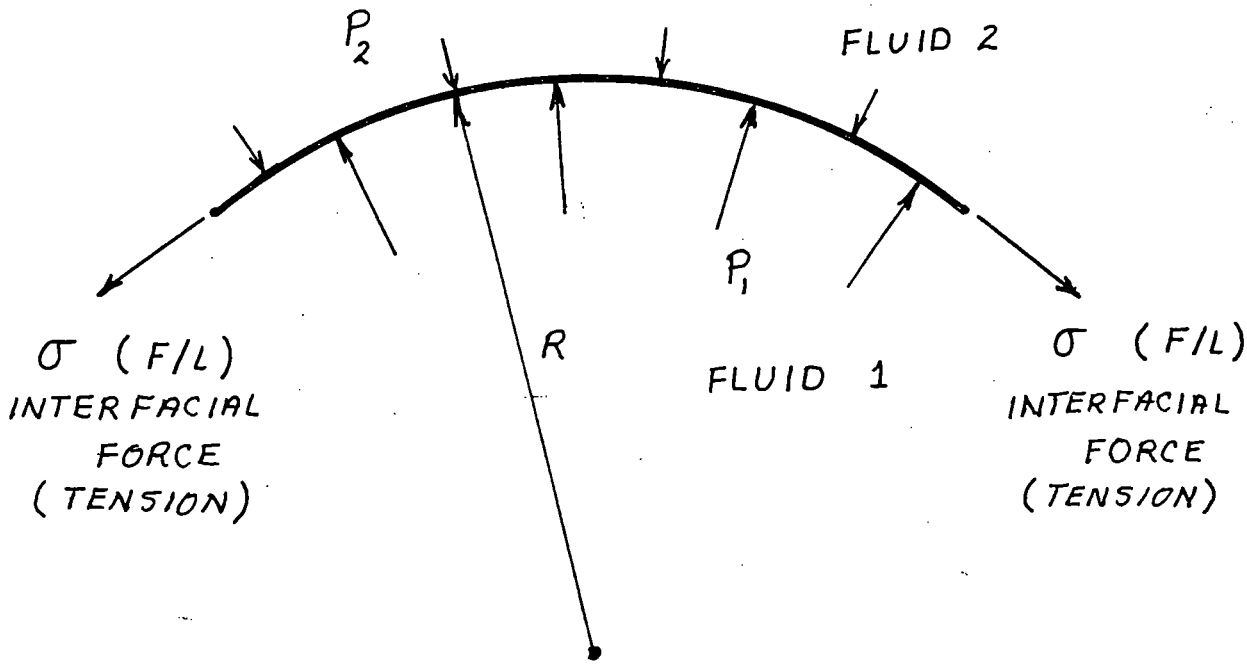
INTERFACIAL TENSION AND FORCE BALANCE ON A CURVED INTERFACE



FOR INTERFACES THAT ARE SUBSECTIONS OF A SPHERE

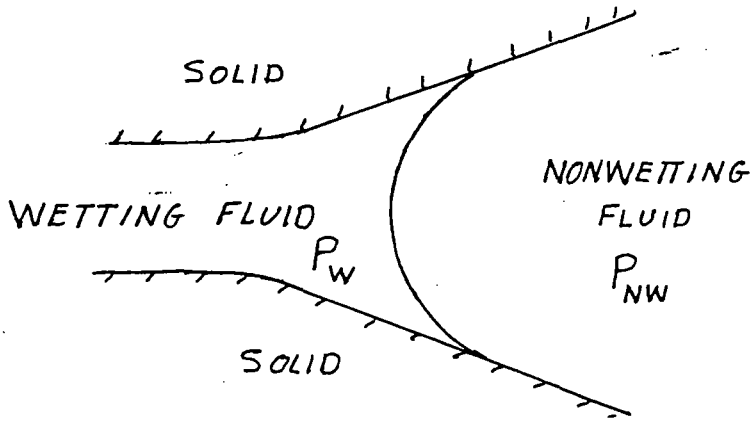
$$P_1 - P_2 = \frac{2\sigma}{R}$$

CAPILLARY PRESSURE $= P_c = P_1 - P_2$

WETTABILITY

- FLUID WITH GREATER AFFINITY FOR THE SOLID IS THE WETTING FLUID

- NONWETTING FLUID IS ON CONCAVE SIDE OF INTERFACE AND IS AT THE HIGHER PRESSURE



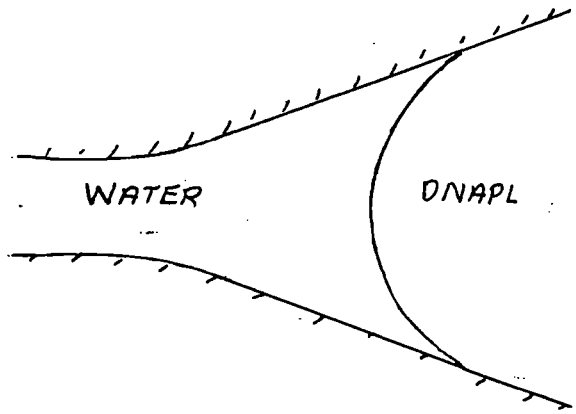
CAPILLARY PRESSURE $= P_c = P_{NW} - P_W$

WATER $\Rightarrow$ WETTING FLUID

DNAPL $\Rightarrow$ NONWETTING FLUID

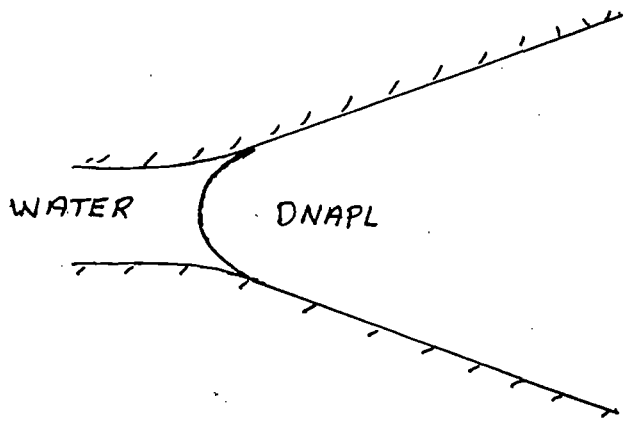
CAPILLARY PRESSURE AND FLUID CONTENTS

- LOW WATER CONTENTS ARE ASSOCIATED WITH HIGH CAPILLARY PRESSURES



LARGE R
SMALL P_c

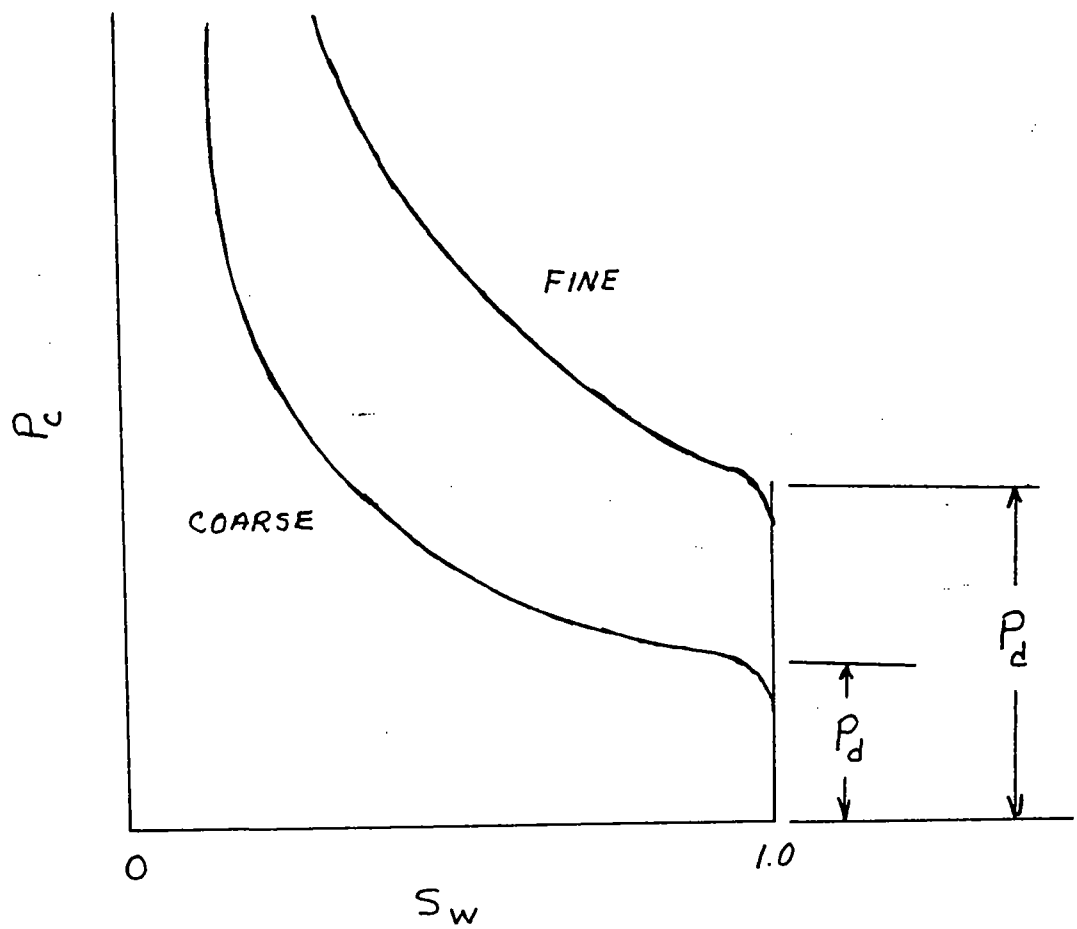
LARGE WATER CONTENT



SMALL R
LARGE P_c

SMALL WATER CONTENT

TYPICAL CAPILLARY PRESSURE - WATER CONTENT RELATIONSHIPS

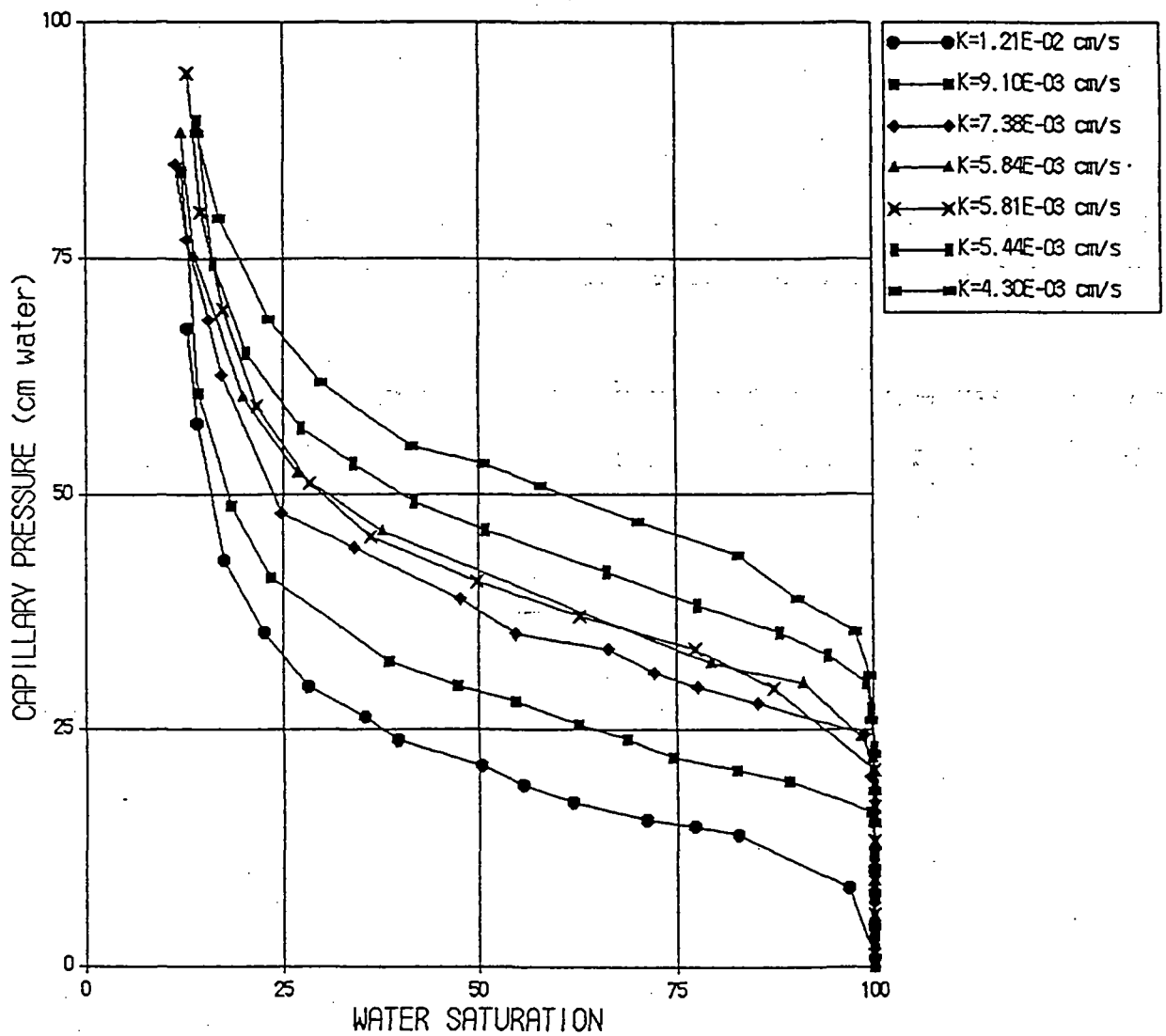


S_w = WATER SATURATION = VOL WATER / PORE VOLUME

P_d = DISPLACEMENT CAPILLARY PRESSURE

$$P_d \propto k^{-0.5}$$

k = INTRINSIC PERMEABILITY



Drainage tetrachloroethylene - water capillary pressure curves after Kueper (1989). Interfacial tension = 0.045 N/m determined with platinum ring tensiometer.

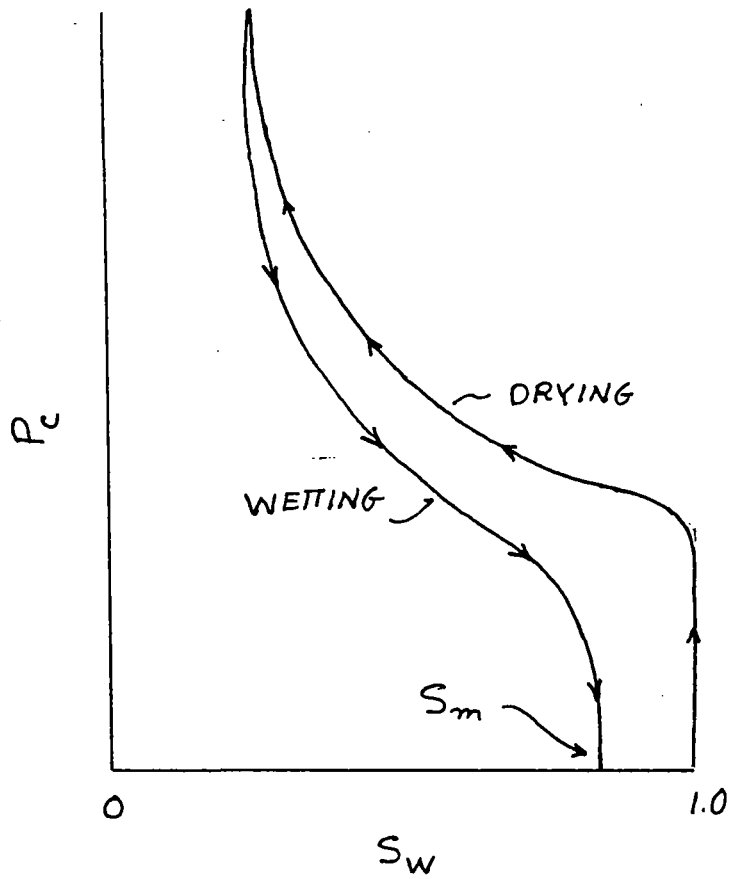
CAPILLARY PRESSURE CURVE

- lower interfacial tension results in a vertical downwards shift of the curves

- lower permeability sands and smaller aperture fractures exhibit a vertical upwards shift of the curve

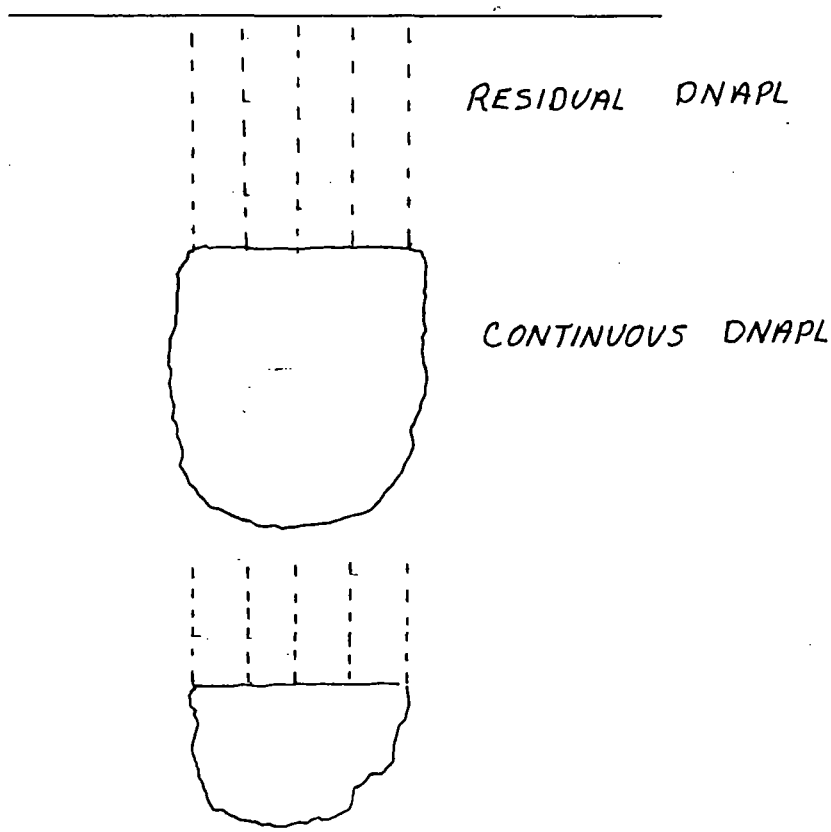
- well sorted sands and "well sorted " aperture distributions exhibit flat curves

HYSTERESIS

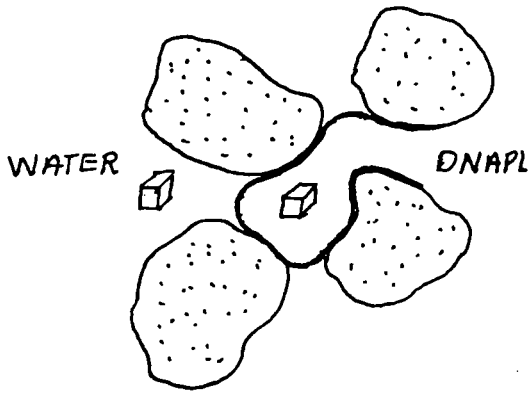


RESIDUAL DNAPL = $1 - S_m$

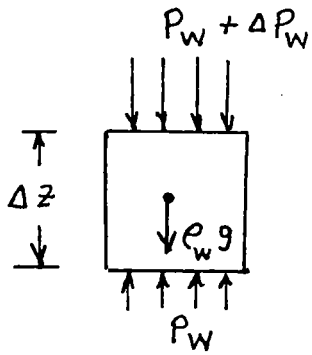
DEPLETION OF A SINKING BODY OF DNAPL



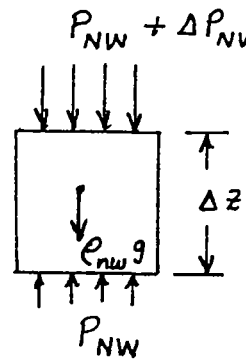
DRIVING FORCES ON FLUIDS
(VERTICAL DIRECTION)



WATER "PARTICLE"



DNAPL "PARTICLE"



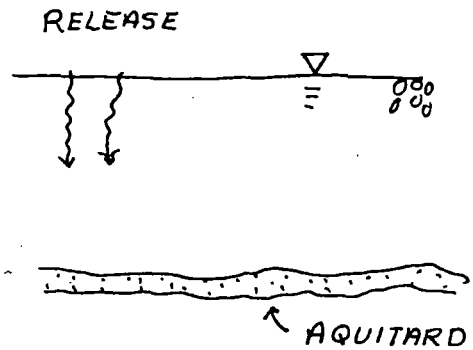
FORCE PER UNIT VOL. DUE TO GRAVITY $= \rho_w g \longrightarrow \rho_{NW} g$

FORCE PER UNIT VOL DUE TO PRESS. GRAD $= \dfrac{\Delta P_W}{\Delta z} \longrightarrow \dfrac{\Delta P_{NW}}{\Delta z}$

TOTAL DRIVING FORCE PER UNIT VOL $= \dfrac{\Delta P_W}{\Delta z} + \rho_w g \longrightarrow \dfrac{\Delta P_{NW}}{\Delta z} + \rho_{NW} g$

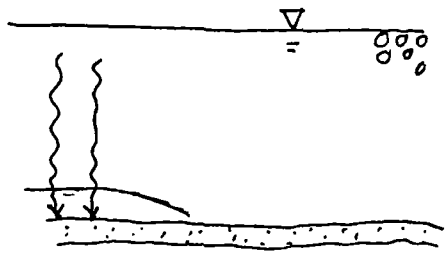
EXAMPLE I

DNAPL PERCHED ON AN AQUITARD



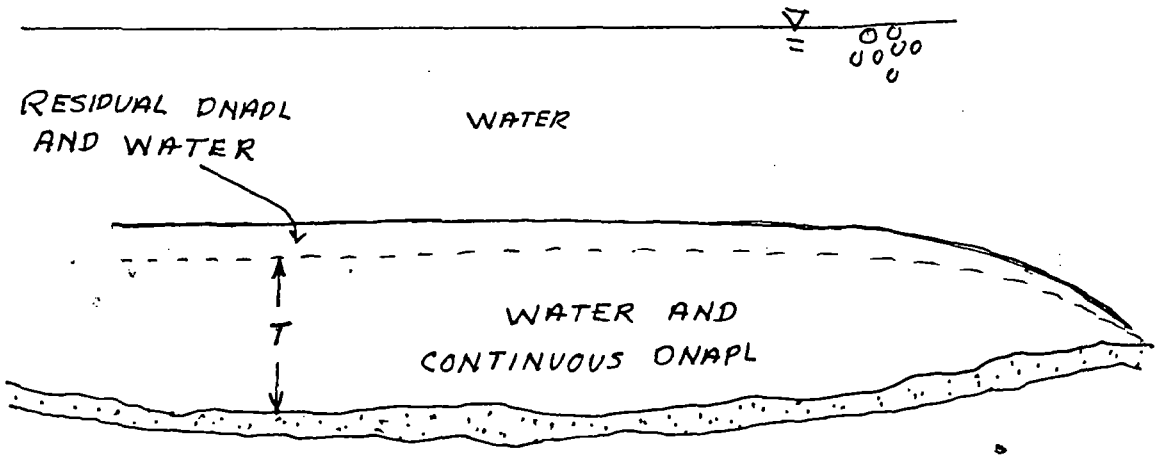
DNAPL SINKING THROUGH AQUIFER

CAPILLARY PRESSURE AT THE FRONT IS P_d FOR AQUIFER



DNAPL ENCOUNTERS AQUITARD. DISPLACEMENT PRESSURE FOR AQUITARD IS GREATER THAN P_d FOR AQUIFER. DNAPL IS UNABLE TO PENETRATE AQUITARD. POOLING OF DNAPL BEGINS.

DNAPL SOURCE IS DEPLETED. LATERAL SPREADING OF DNAPL HAS FORMED POOL OVER AQUITARD.



EXAMPLE I

(CONTINUED)

- DNAPL POOL THICKNESS IS T.
- CAPILLARY PRESSURE ON TOP OF POOL IS ZERO AS DICTATED BY THE WETTING LOOP OF THE CAPILLARY PRESSURE CURVE.
- ALL FLUID MOTION HAS CEASED.

NET DRIVING FORCE ON FLUIDS IS ZERO:

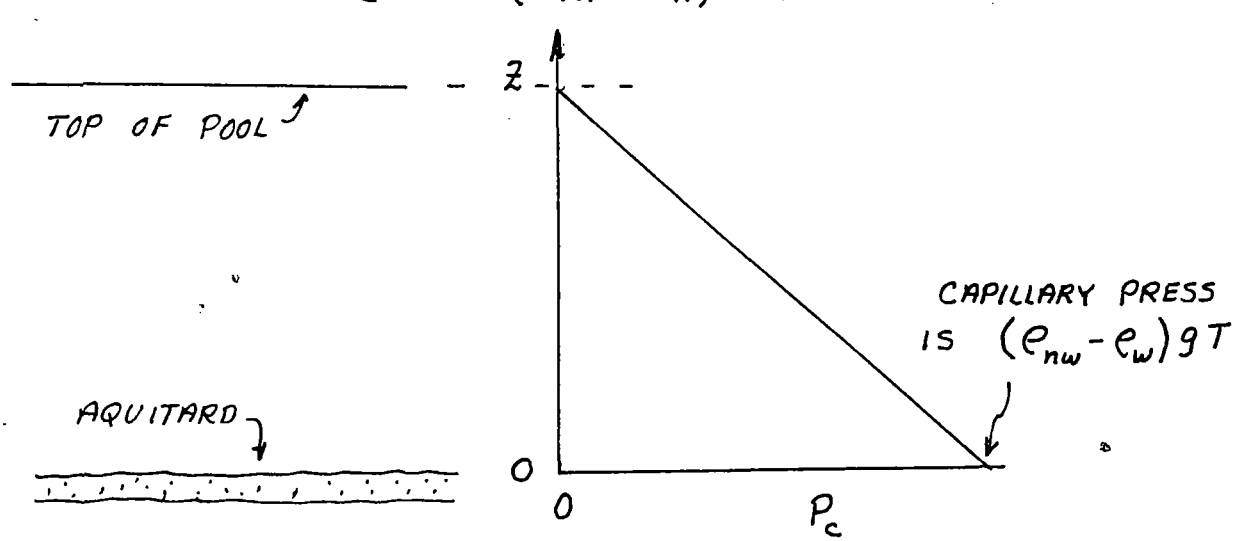
$$P_W + \rho_W g z = \text{CONSTANT}$$

$$P_{NW} + \rho_{NW} g z = \text{CONSTANT}$$

$$\boxed{\therefore \quad P_{NW} - P_W = P_c = -(\rho_{NW} - \rho_W) g z + \text{CONSTANT}}$$

BUT $P_c = 0$ AT $z = T$

$$\therefore \quad P_c = (\rho_{NW} - \rho_W) g (T - z)$$



EXAMPLE I

(CONTINUED)

- CAPILLARY PRESSURE AT TOP OF AQUITARD IS

$$P_c = (\rho_{NW} - \rho_W) g T$$

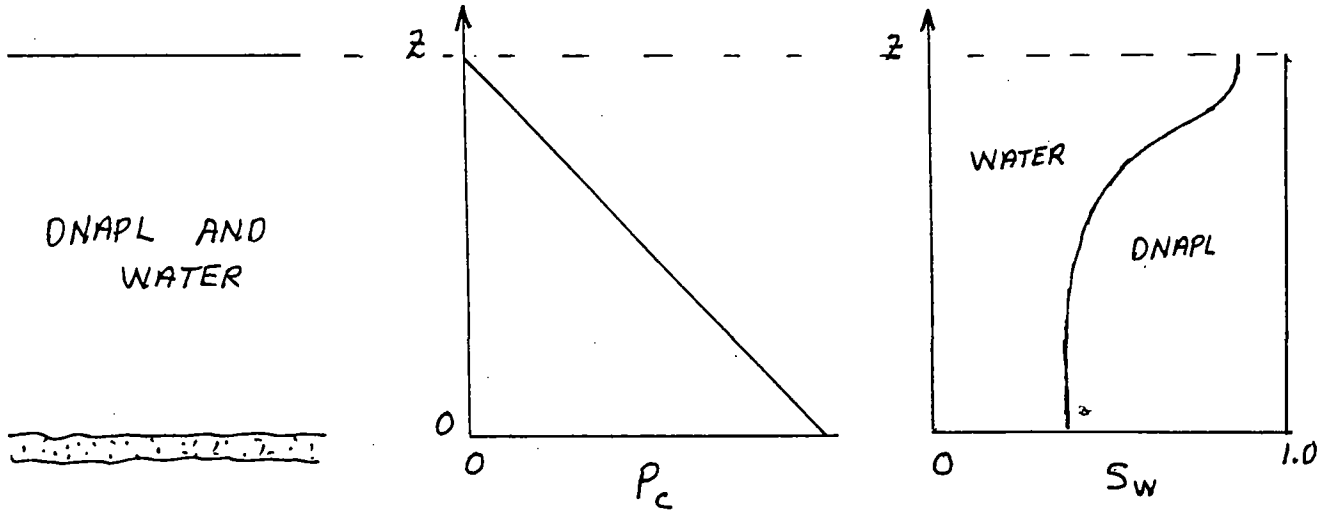
- THIS IS INDEPENDENT OF HOW FAR BELOW THE WATER TABLE THE DNAPL POOL IS LOCATED

- INCIPIENT PENETRATION OF THE AQUITARD IS GIVEN BY

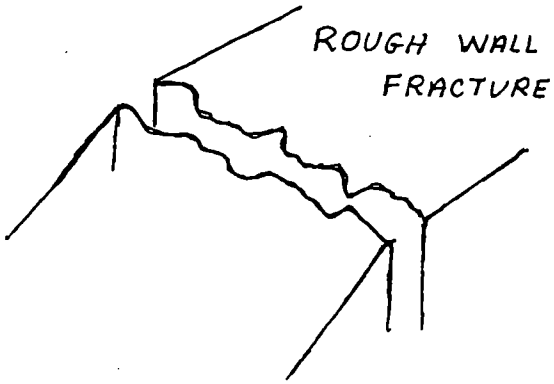
$$T = \frac{P_d}{(\rho_{NW} - \rho_W) g}$$

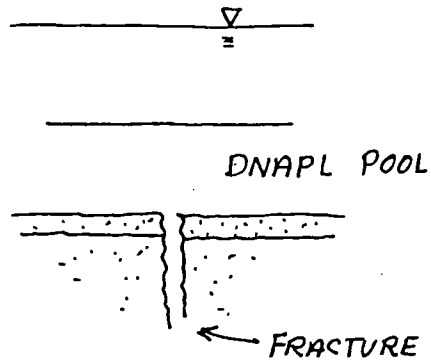
WHERE P_d IS THE DISPLACEMENT PRESSURE OF THE AQUITARD.

- WITH $P_c = (\rho_{NW} - \rho_W) g (T - z)$ AND $P_c = P_c(S_W)$ FROM THE CAPILLARY PRESSURE CURVE, THE FLUID CONTENT IS READILY DETERMINED.



DNAPL POOLED ON A FRACTURED AQUITARD





DISPLACEMENT PRESS FOR A CIRCULAR OPENING

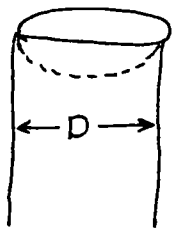
DISPLACEMENT PRESS FOR A SLIT

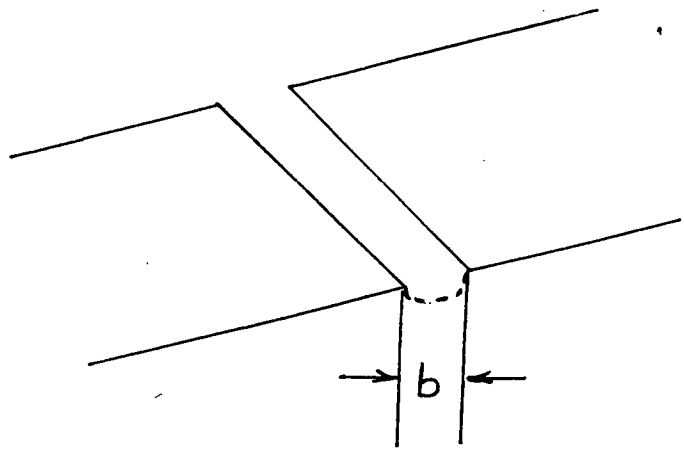
$$P_d = \frac{4\sigma \cos\alpha}{D}$$

$$P_d = \frac{2\sigma \cos\alpha}{b}$$

α = CONTACT ANGLE
σ = INTERFACIAL TENSION
D = DIAMETER OF OPENING

b = APERTURE

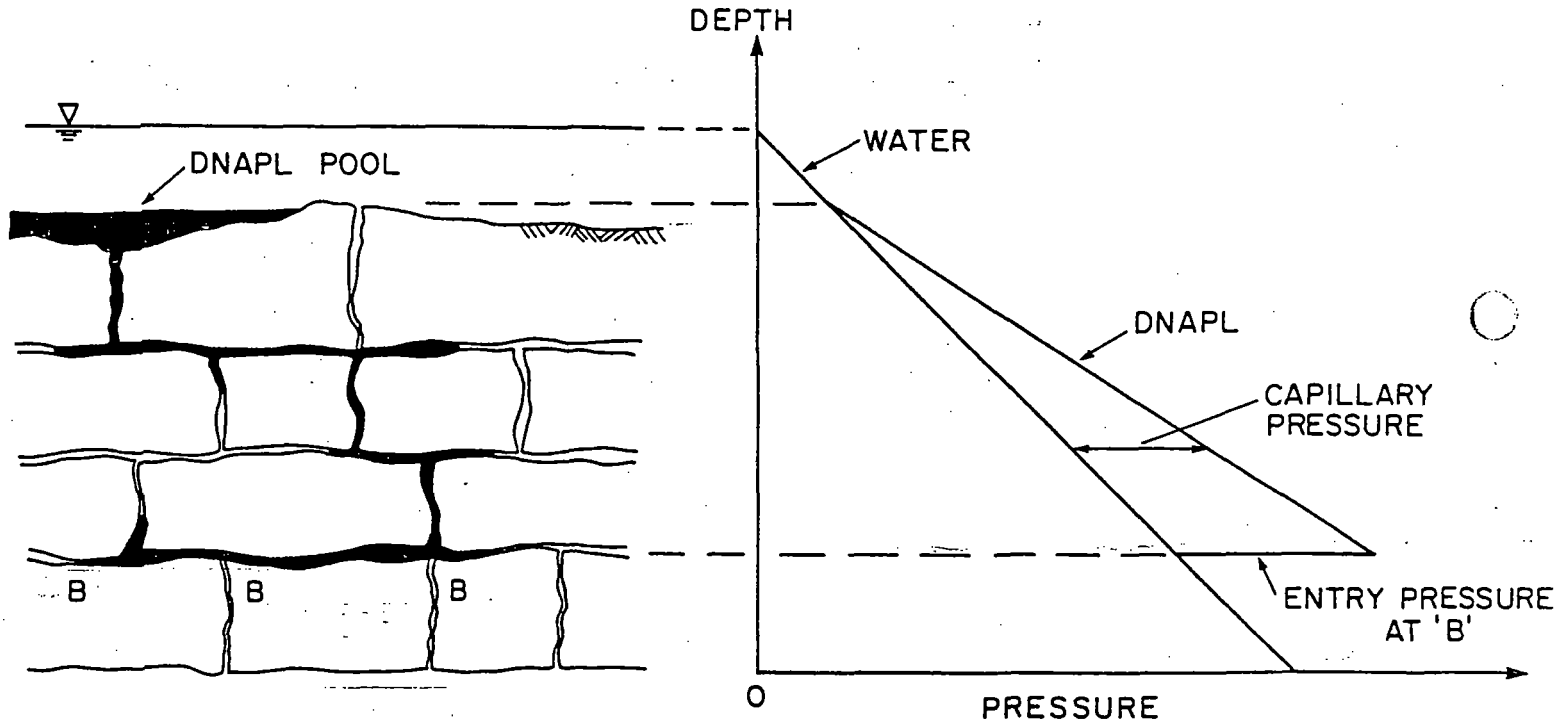


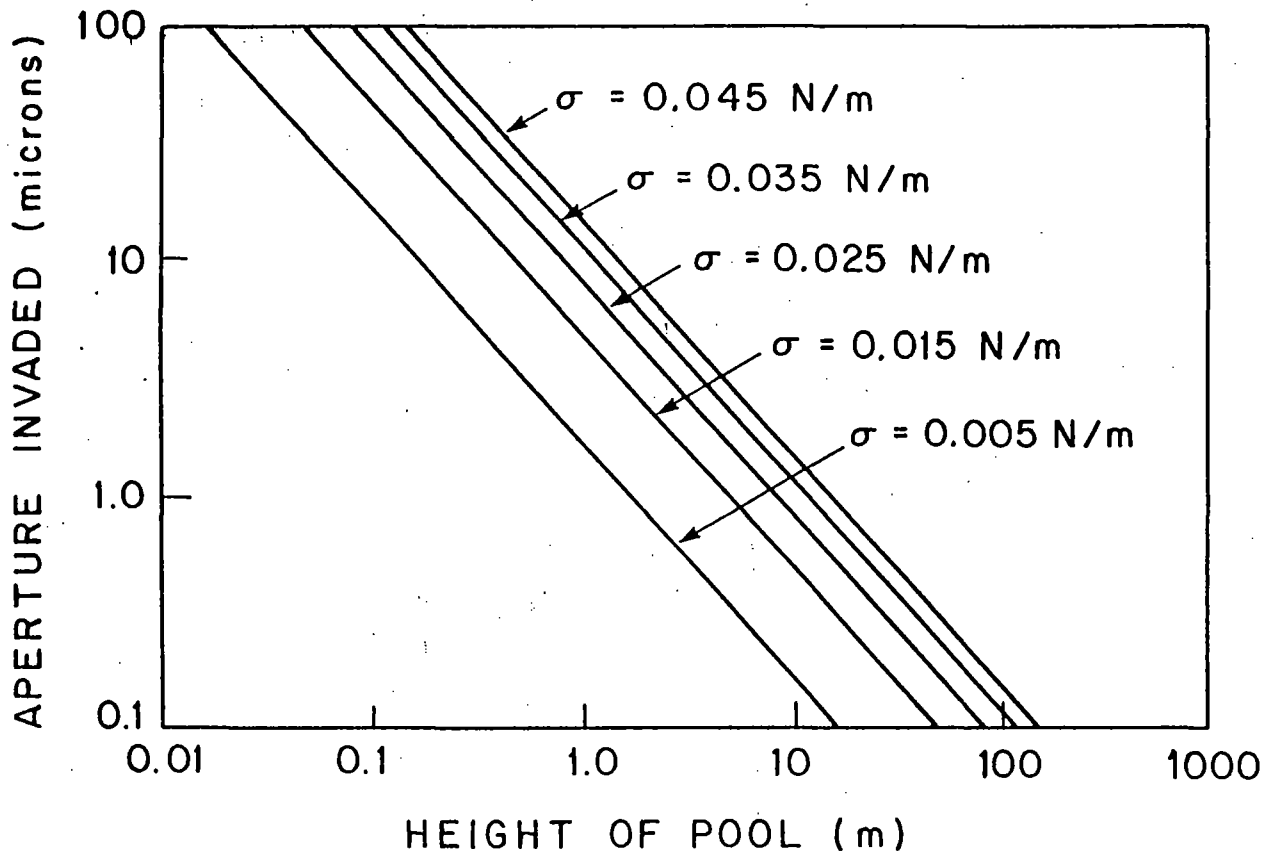


CRITICAL POOL THICKNESS:

$$T = \frac{P_d}{(\rho_{NW} - \rho_W)g}$$

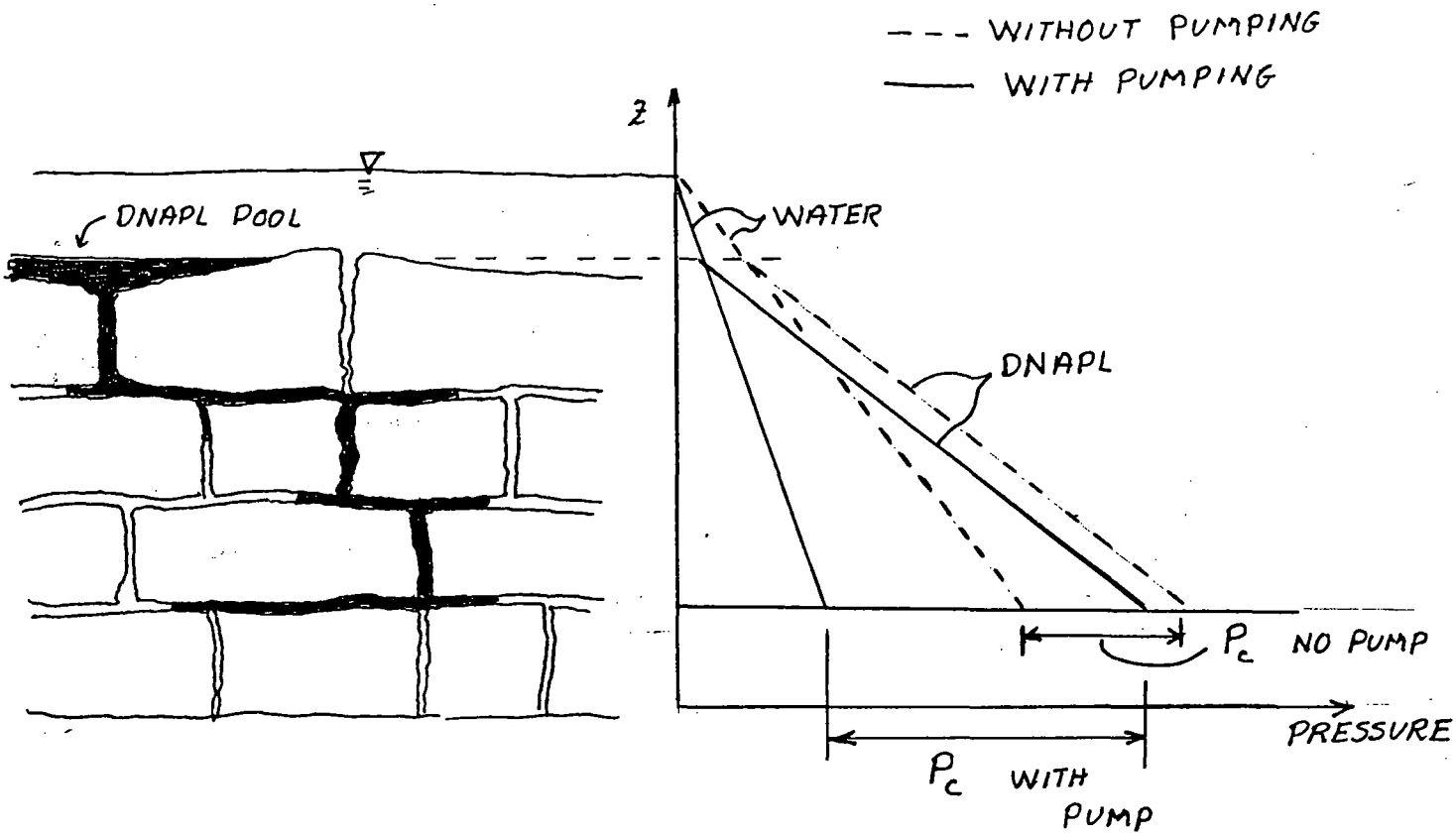
, P_d = DISPLACEMENT PRESSUR FOR FRACTURE


DEPTH
WATER
DNAPL POOL
DNAPL
CAPILLARY PRESSURE
B
B
B
ENTRY PRESSURE AT 'B'
0
PRESSURE



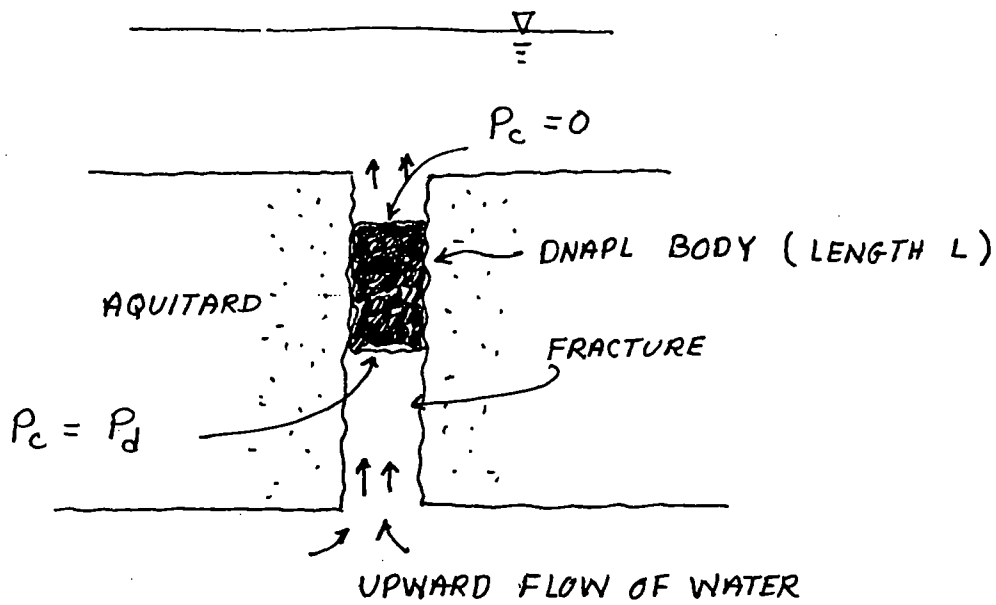
- calculations assume a DNAPL density of 1600 kg/m³ and a fracture entry pressure given by $2\sigma/e$

EFFECT OF DOWNWARD GW FLOW



- PUMPING CREATES VERTICAL GRADIENT OF HYDRAULIC HEAD AND STEEPENS THE WATER PRESSURE LINE
- DNAPL PRESSURE LINE REMAINS AT SAME SLOPE
- DNAPL & WATER PRESSURE GRAPHS DIVERGE MORE RAPIDLY WITH PUMPING
- CREATION OF DOWNWARD GRADIENTS IN WATER INCREASES CAPILLARY PRESSURE IN DNAPL POOL AND PROMOTES FURTHER DOWNWARD FLOW

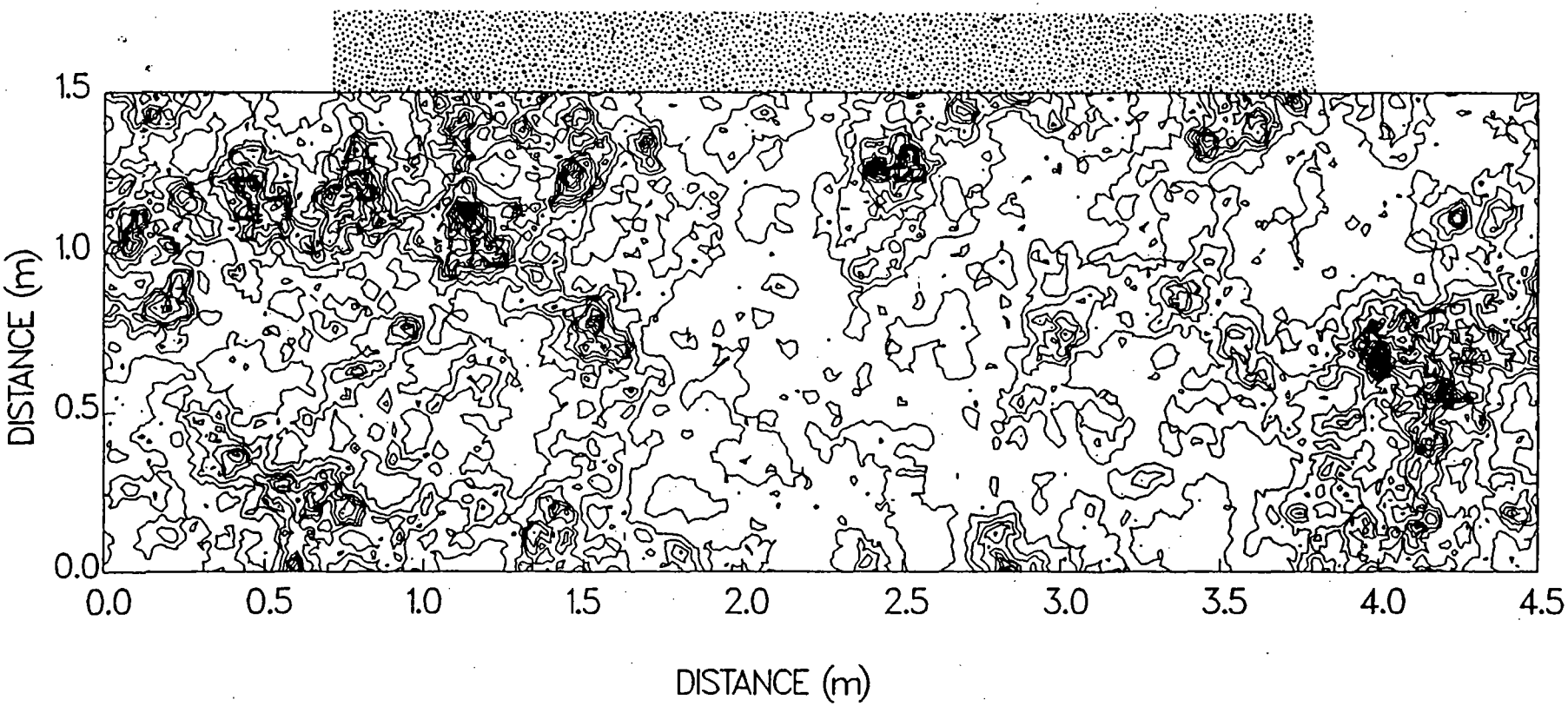
EFFECT OF UPWARD GW FLOW ON TENDENCY FOR DNAPL TO SINK



FORCE BALANCE:

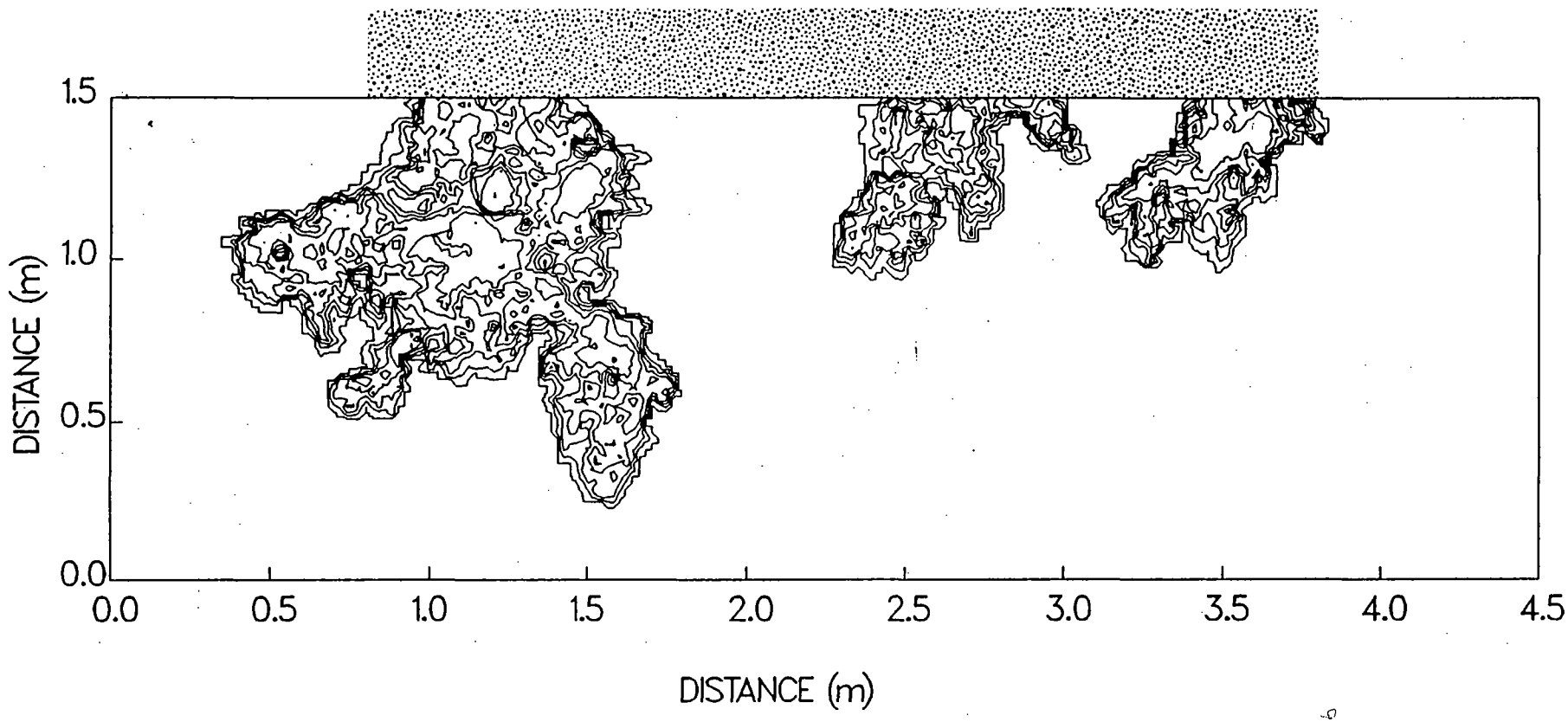
$$\frac{\Delta H}{L} \geq \frac{\Delta \rho}{\rho_w} - \frac{P_d}{\rho_w g L}$$

- DNAPL WILL NOT SINK WHEN THIS CONDITION IS SATISFIED.
- LARGER GRADIENTS ARE REQUIRED FOR LONG BLOBS THAN FOR SHORT ONES



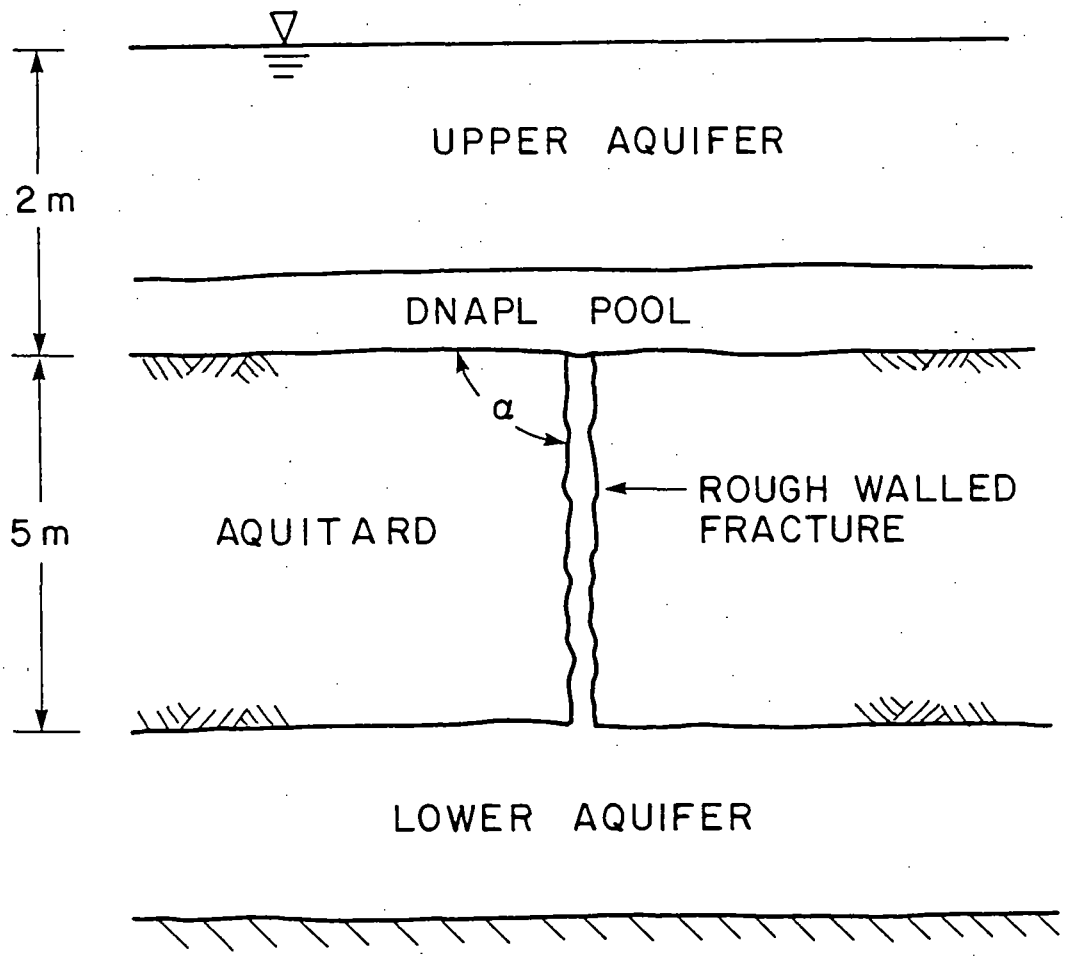
CONTOURS OF RANDOMLY GENERATED APERTURES IN A FRACTURE PLANE. SHADED AREA AT TOP REPRESENTS POOLED DNAPL.

T1
c

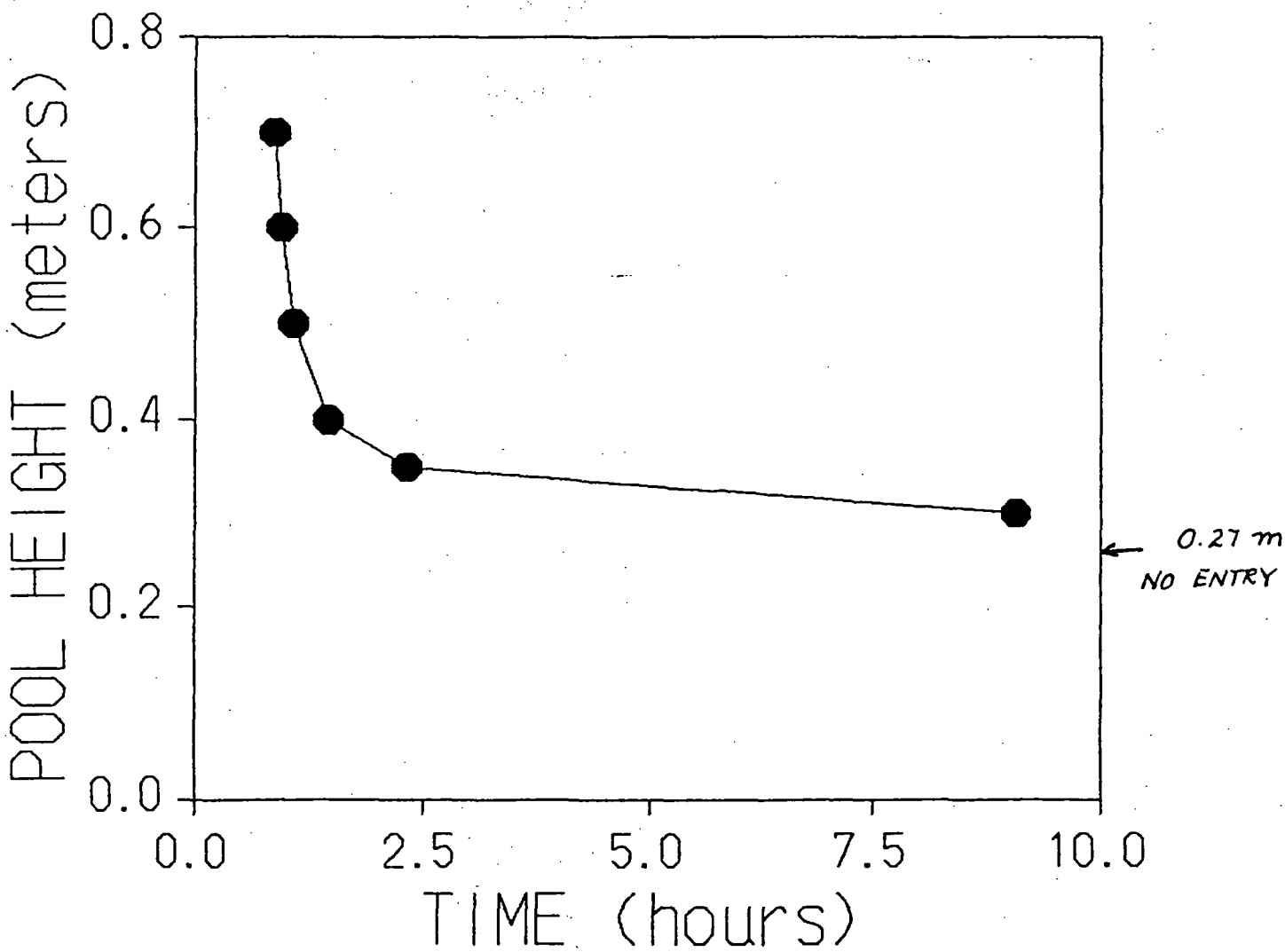


DISTRIBUTION OF DNAPL IN FRACTURE PLANE

F12



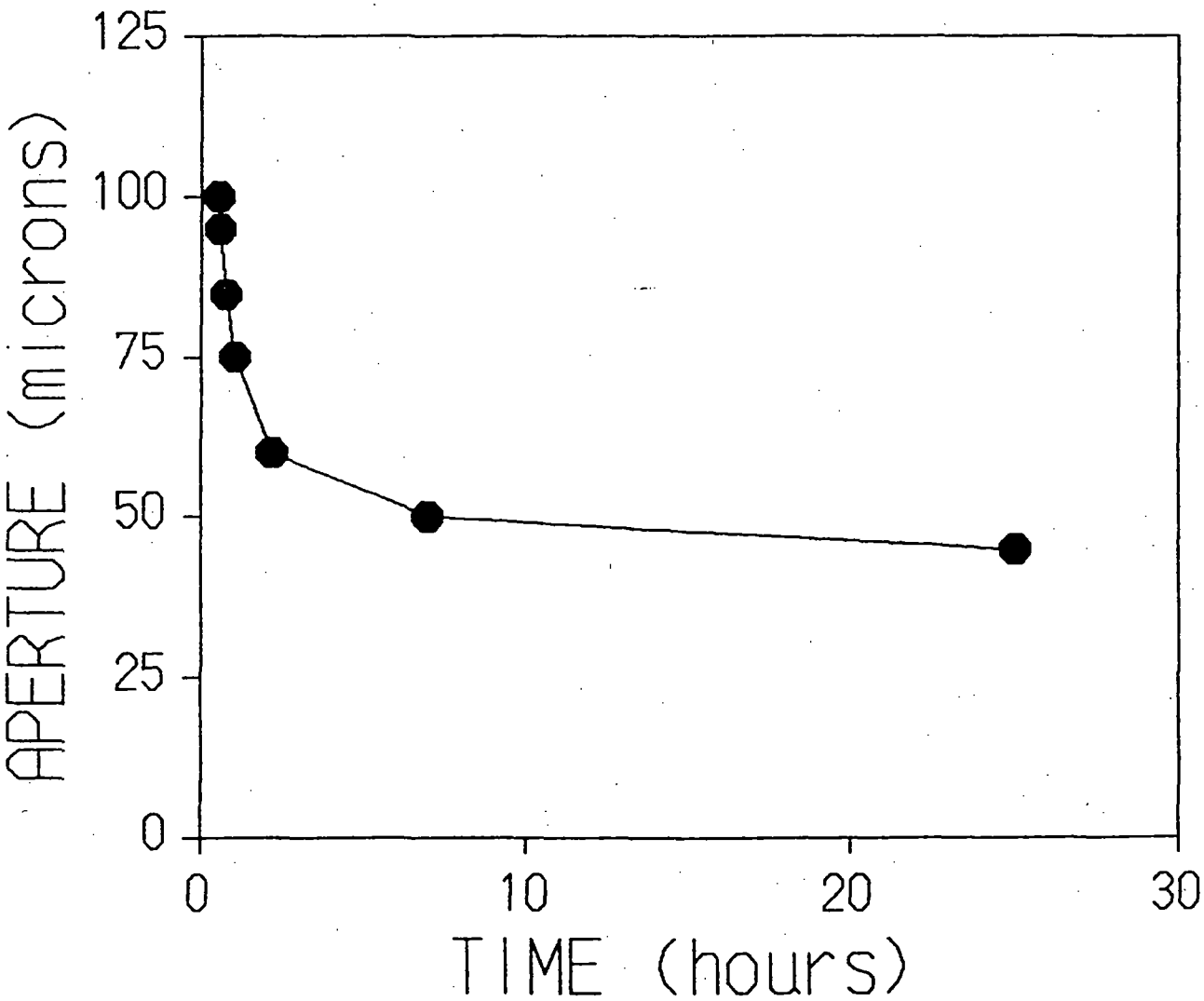
FLOW IN A SINGLE FRACTURE - SIMULATION



TIME TO TRAVERSE FRACTURE AS A FUNCTION OF POOL THICKNESS

APERTURE = 75 MICRONS

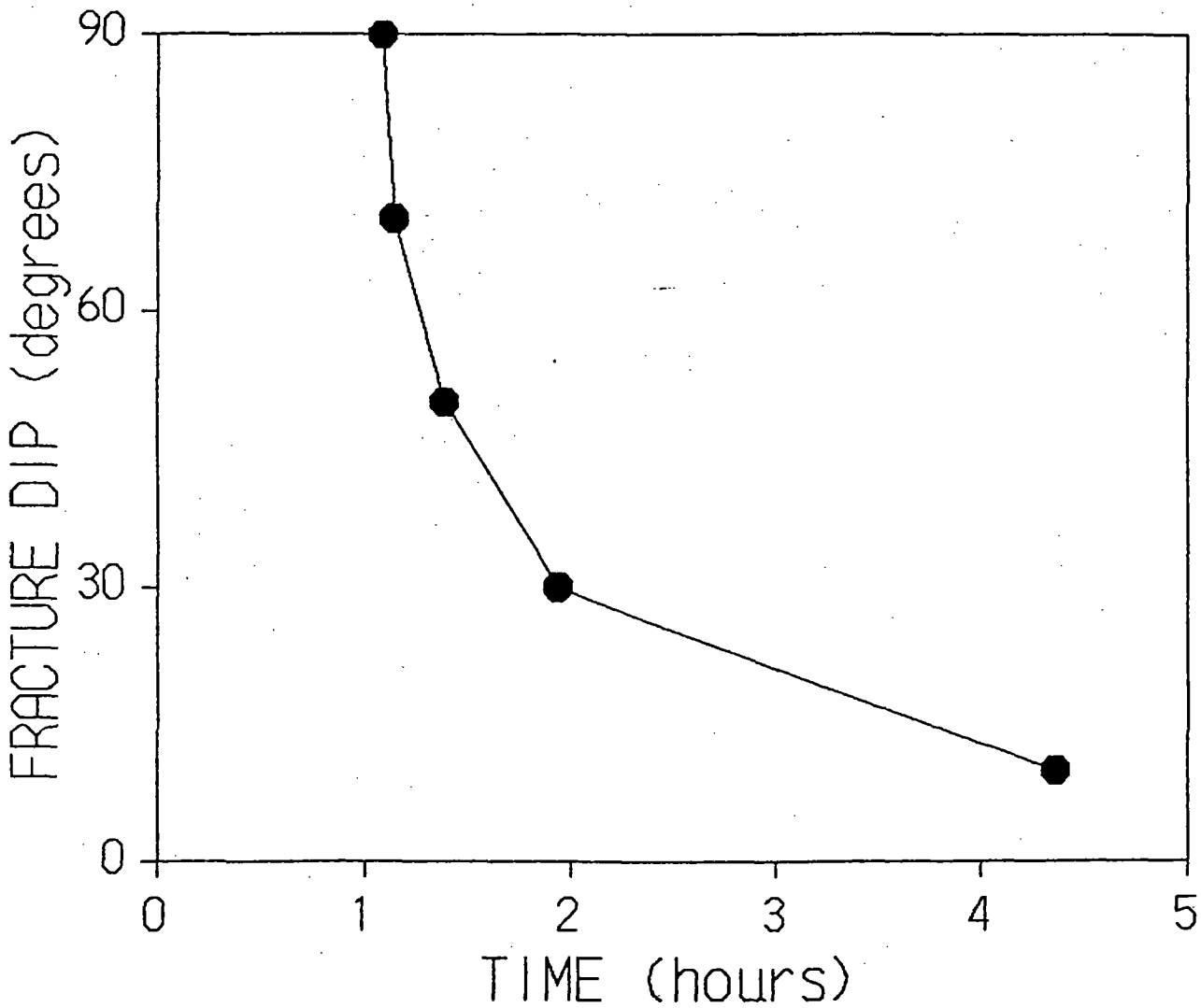
F15



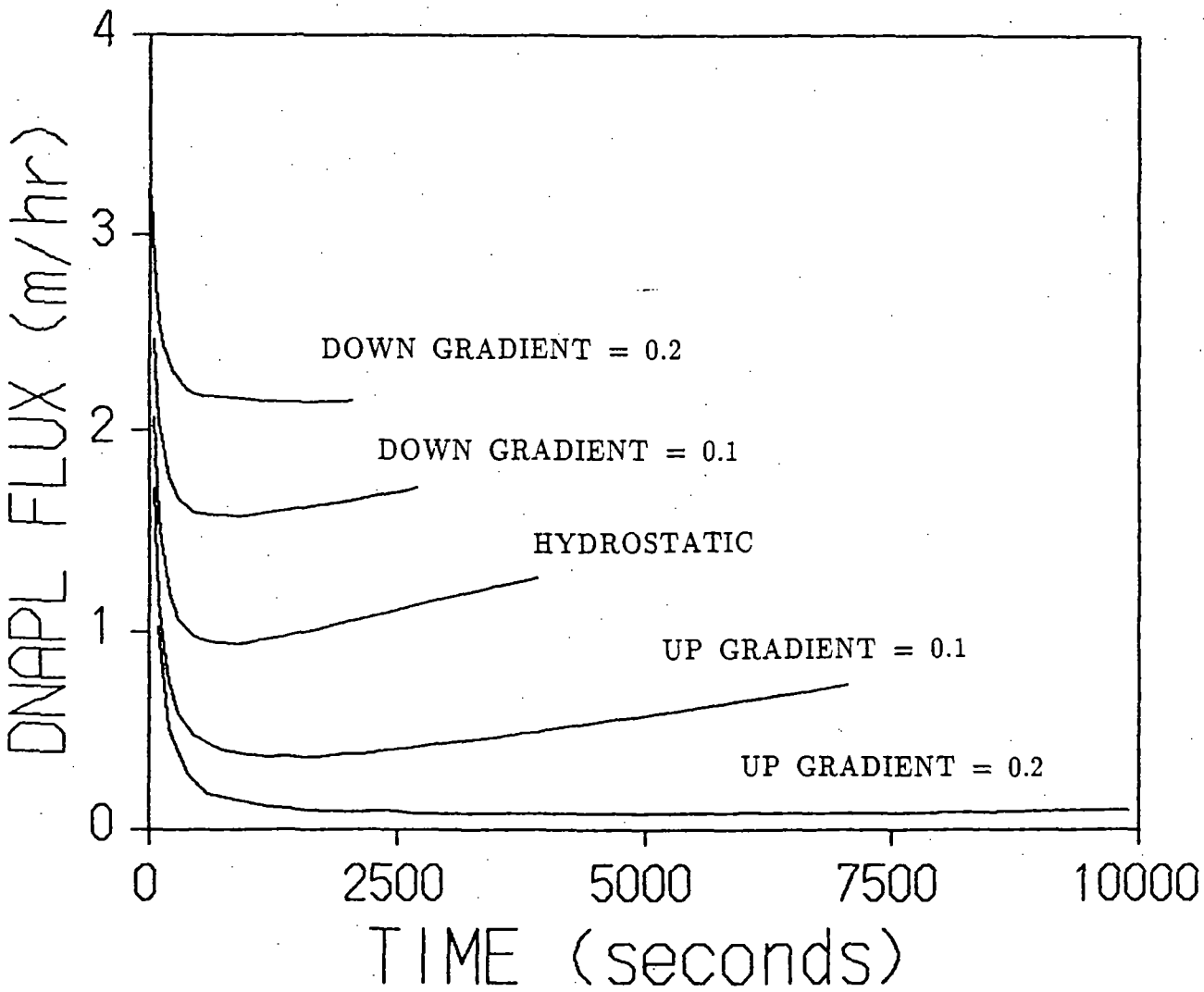
TIME TO TRAVERSE FRACTURE AS A FUNCTION OF APERTURE

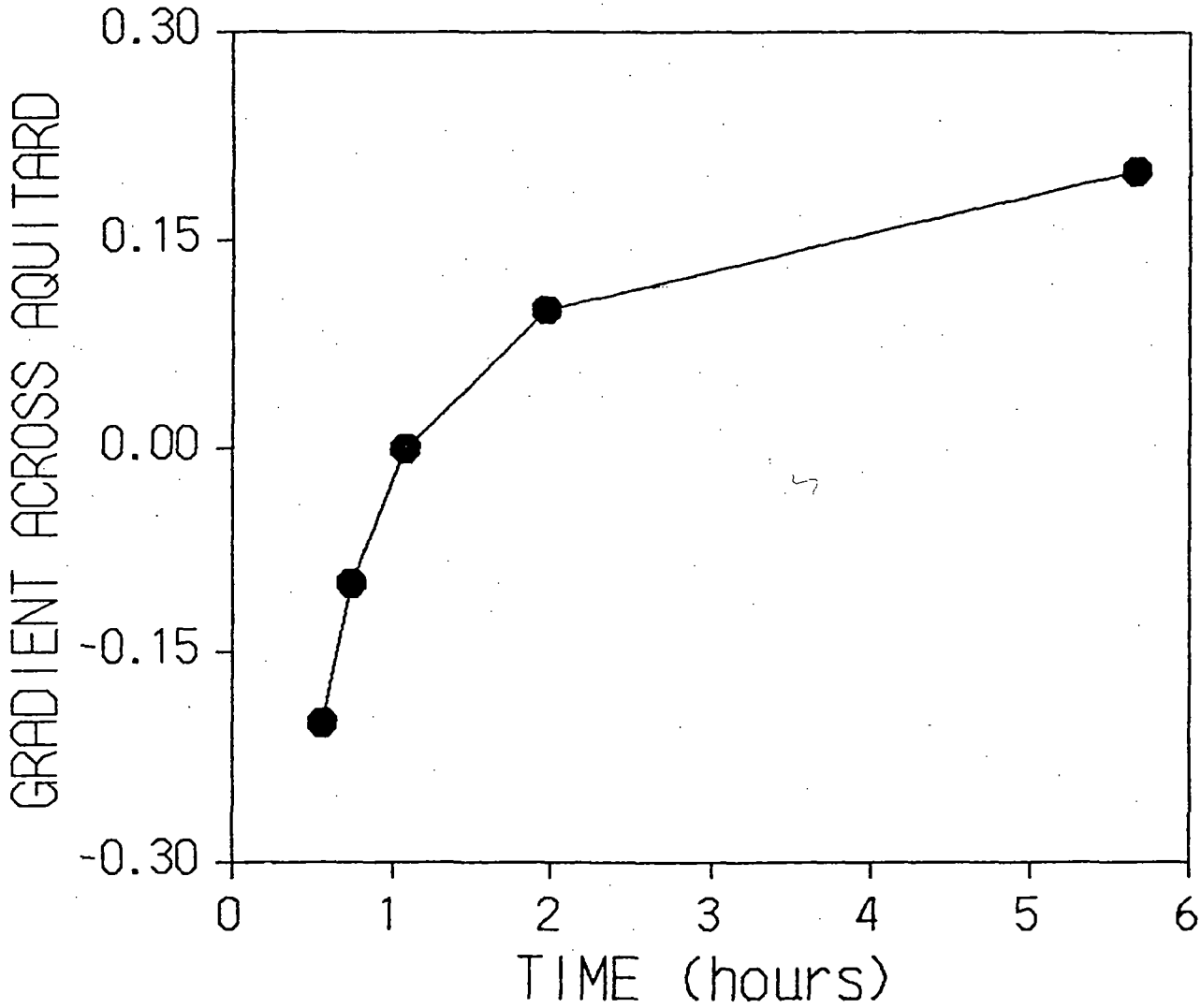
POOL THICKNESS = 0.5 m

F16



F17


DNAPL FLUX (m/hr)
4
3
2
1
0
DOWN GRADIENT = 0.2
DOWN GRADIENT = 0.1
HYDROSTATIC
UP GRADIENT = 0.1
UP GRADIENT = 0.2
0
2500
5000
7500
10000
TIME (seconds)



TIME TO TRAVERSE FRACTURE AS A FUNCTION OF GRADIENT ACROSS AQUITARD

POOL THICKNESS = 0.5 m
APERTURE = 75 MICRONS