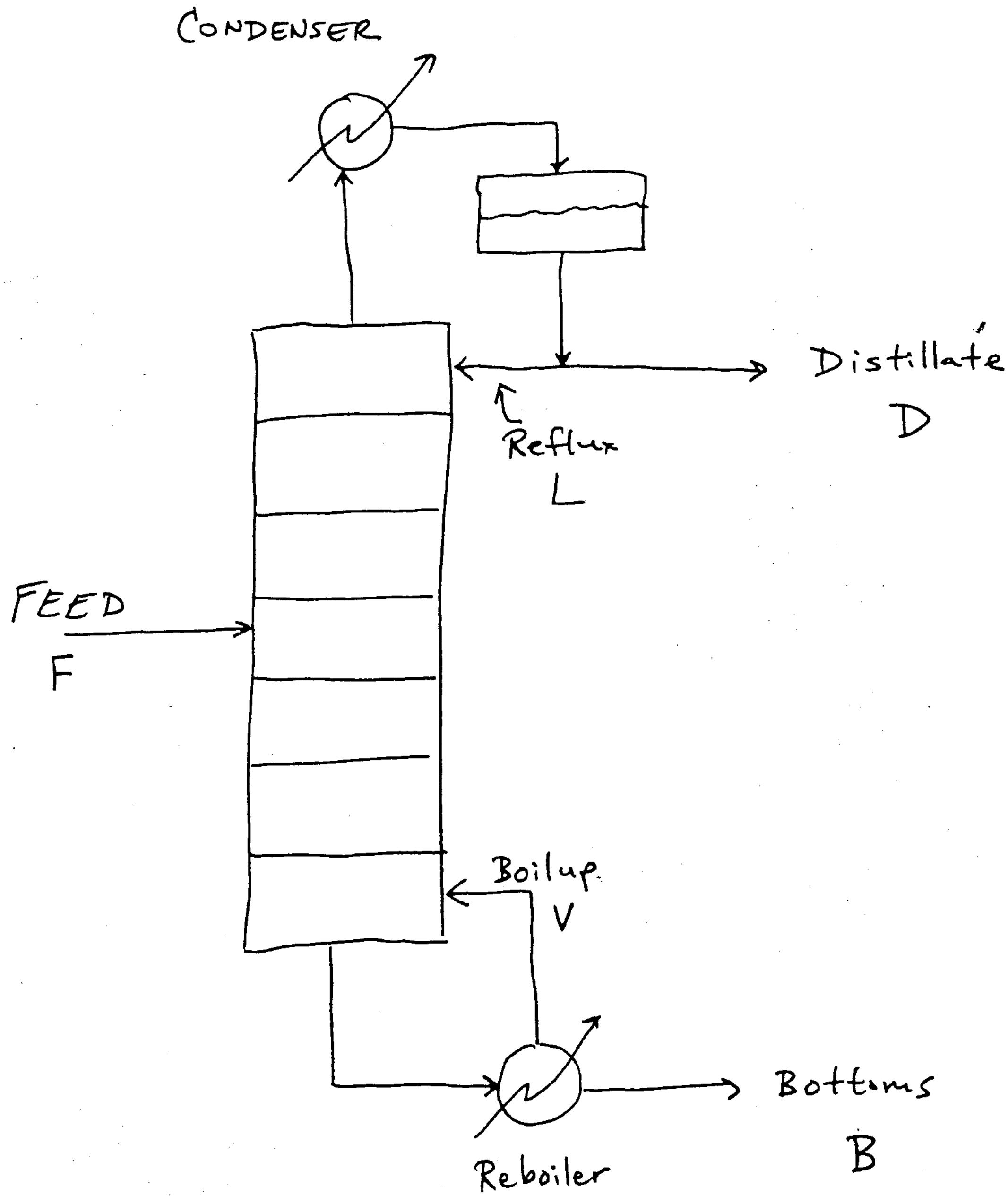
CHAPTER 7: DISTILLATION OF <u>BINARY</u> MIXTURES



WAYS TO RELATE FLOW RATES: (RATIOS)

REFLUX RATIO = $\frac{L}{D}$ ← L: Liquid, D: Distillate

BOILUP RATIO = $\frac{V}{B}$ ← V: Vapor, B: Bottoms

} FLOW RATES

ANY ASSUMPTIONS HERE?

→ STEADY STATE

→ CONSTANT FLOWS

DO THE ASSUMPTIONS MAKE SENSE?

→ BESIDES WHAT HAPPENS ON THE STAGES...

BIGGEST EVENT TO ALTER L & V?

FEED

FEED CONDITION –

RECALL SINGLE STAGE FLASH

$$\psi = \frac{V}{F} \quad \& \quad 0 \leq \psi \leq 1$$

WHY?

⇒ NEEDED 2 PHASES FOR SEPARATION.

NOW, ALREADY HAVE 2 PHASES IN COLUMN.

⇒ FEED CONDITION BECOMES A FACTOR.

[redacted]

POSSIBILITIES:

	REFLUX RATIO	BOILUP RATIO
(1)		
(2)		
(3)		
(4)		
(5)		

PURE MATERIAL OUT THE TOP ⇒

FOCUS ON REFLUX RATIO

BALANCING ACT

\# of stages

reflux ratio

(1) Minimize reflux ratio

→ Liquid only from condensation in each stage.

→ for high purity, # of stages large.

\# of stages → ∞

(2) Minimize # of stages

→ NEED LOTS OF LIQUID AT EACH STAGE FOR GOOD MASS TRANSFER

$$\text{Reflux Ratio} = \frac{L}{D}$$

$$L \uparrow \Rightarrow D \downarrow$$

$$\Rightarrow \text{Reflux Ratio} \rightarrow \infty$$

MORE ON DISTILLATION...

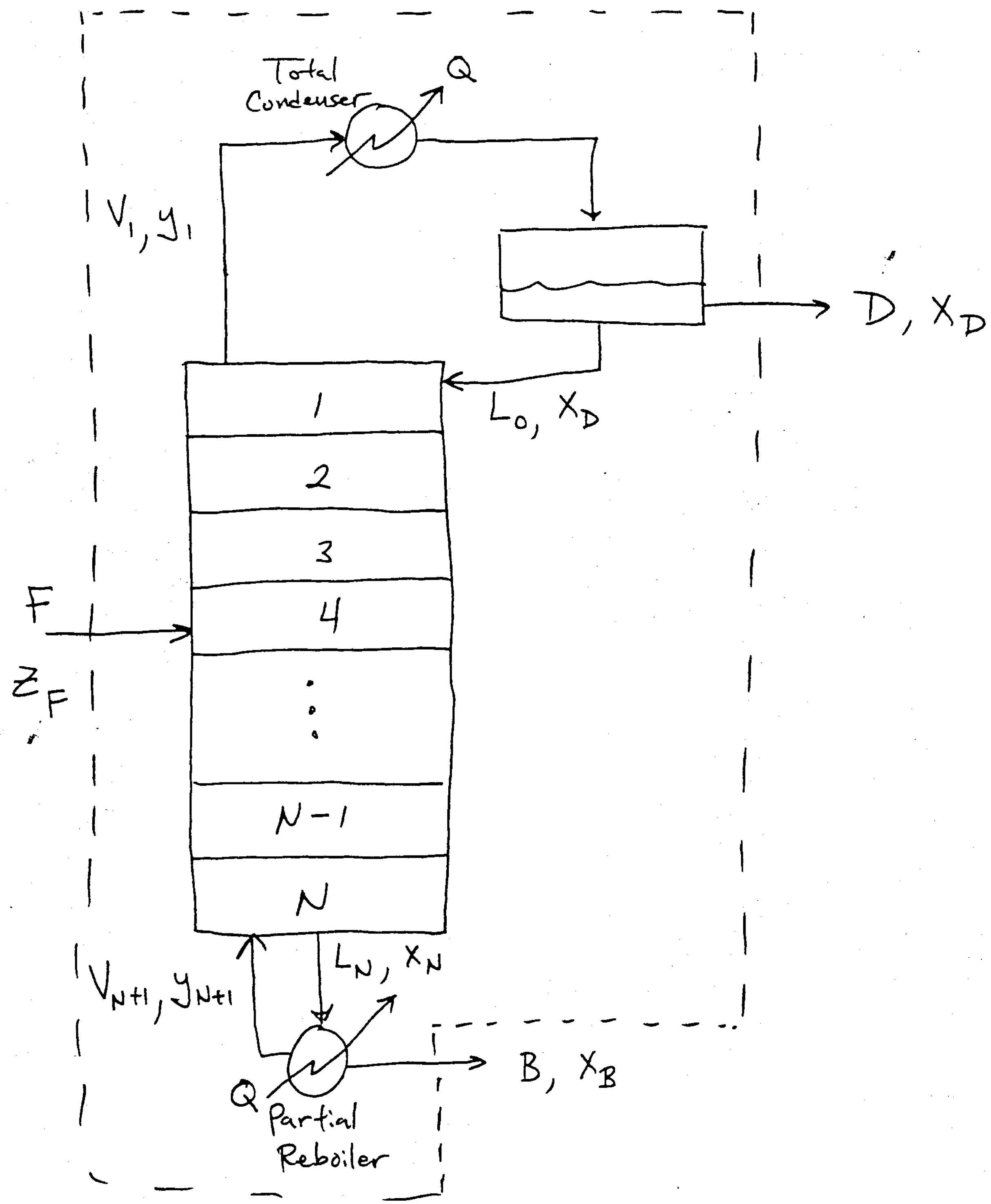
WOULD LIKE A SYSTEMATIC APPROACH

⇒ McCABE – THIELE GRAPHICAL TECHNIQUE

1. Equilibrium (EQ) Line
2. Operating (OP) Line
3. Binary feed mixture
4. Defined column pressure.
5. Allows estimates for:
   a) # of EQ Stages
   b) amount of reflux for desired separation

⇒ WHAT ARE OPERATING LINES?

BEFORE WE LOOK AT INDIVIDUAL OPERATING LINES, LET'S LOOK AT THE ENTIRE PROCESS



NOTE: MOLEFRACTIONS FOR LIGHT KEY.

⇒ OVERALL MOLE BALANCE

$$\underbrace{F}_{IN} = \underbrace{D + B}_{OUT} \qquad (1)$$

⇒ COMPONENT MOLE BALANCE (LIGHT KEY)

$$\underbrace{F z_F}_{IN} = \underbrace{D x_D + B x_B}_{OUT} \qquad (2)$$

COMBINE EQNS (1) + (2) AND SOLVE FOR D...

$$F z_F = D x_D + (F-D) x_B$$

$$F z_F = D x_D + F x_B - D x_B$$

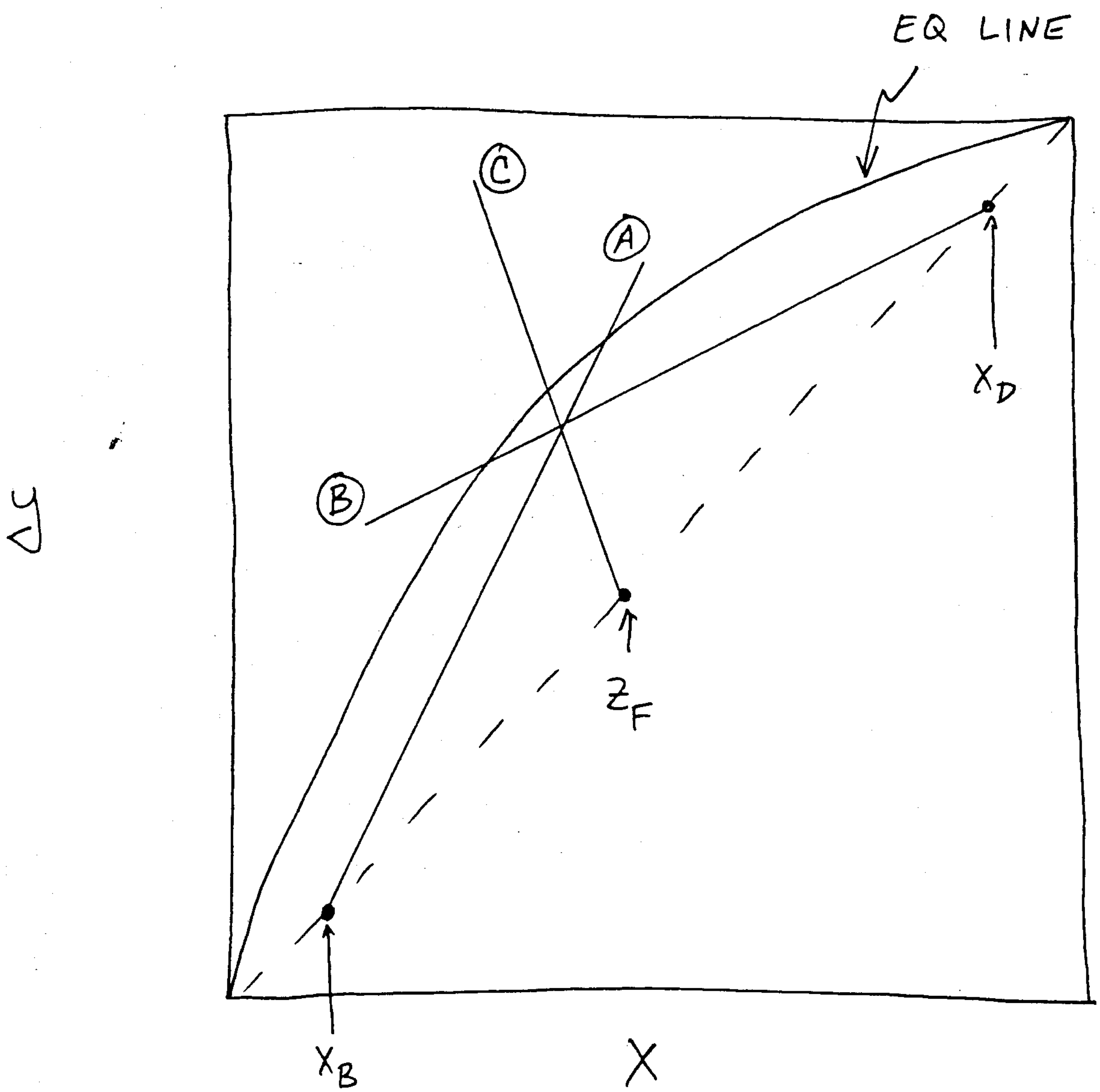
$$D = \frac{F z_F - F x_B}{x_D - x_B} = F\left(\frac{z_F - x_B}{x_D - x_B}\right)$$

WHAT DOES THIS MEAN?

$$X_D > Z_F > X_B$$

⇒ MAKES SENSE. REMEMBER HOW COMPOSITION OF LIGHT KEY CHANGES IN COLUMN.

WELL, WHERE ARE WE HEADED WITH THIS?



(A) STRIPPING SECTION OPERATING LINE

$$\text{Slope} = \frac{\bar{L}}{\bar{V}}$$

(B) RECTIFYING SECTION OPERATING LINE

$$\text{Slope} = \frac{L}{V}$$

(C) q-line

$$\text{Slope} = \frac{\psi - 1}{\psi}$$

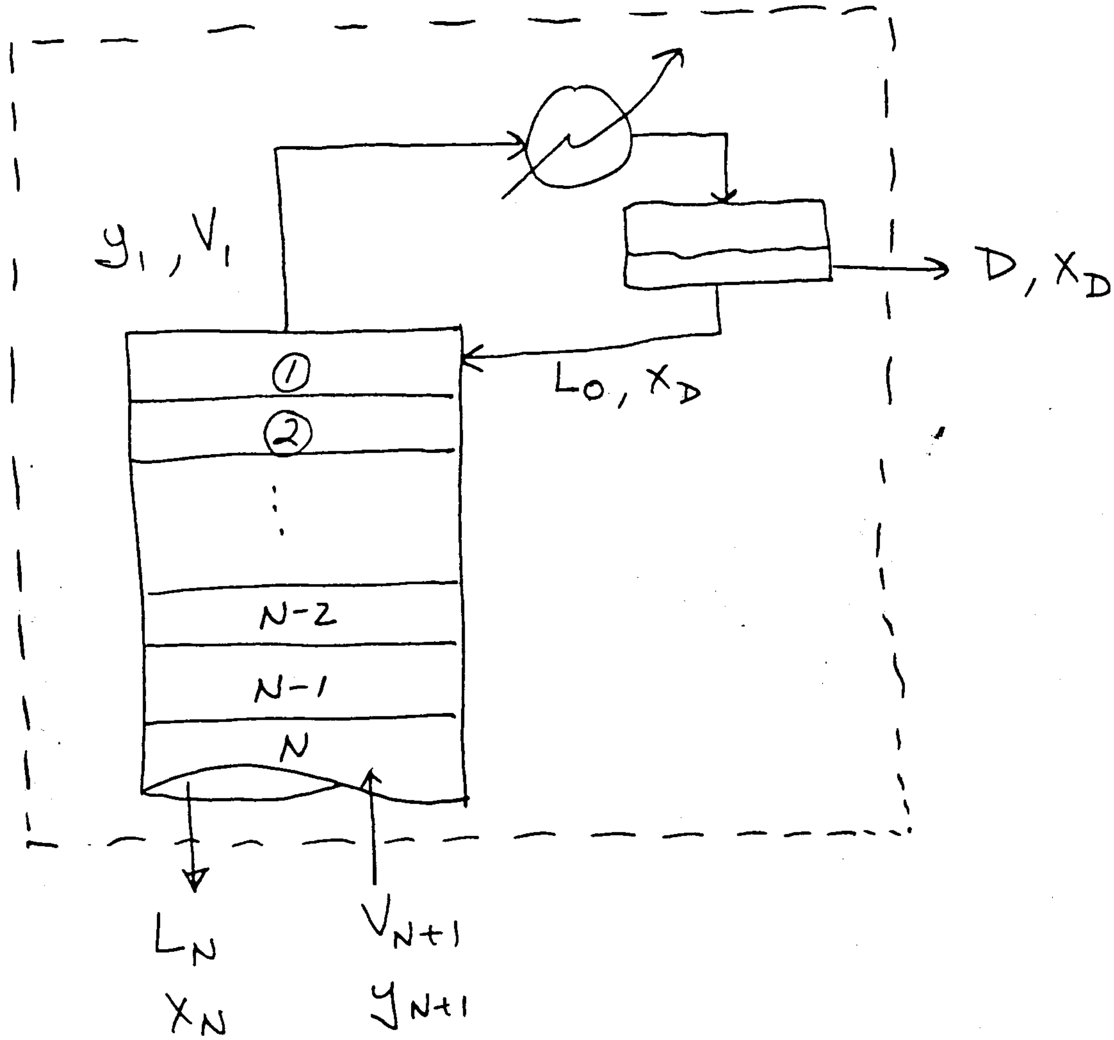
Gives location of feed tray

⇒ WHERE DO THESE COME FROM?

⇒ OPERATING LINES...

[redacted]

RECTIFIER OPERATING LINE



COMPONENT MOLE BALANCE (LIGHT KEY)

$$\underbrace{(V_{N+1})(y_{N+1})}_{\text{IN}} = \underbrace{(L_N)(x_N) + (D)(x_D)}_{\text{OUT}}$$

SOLVE FOR y_{N+1} . . .

$$y_{N+1} = \left(\frac{L_N}{V_{N+1}}\right) x_N + \left(\frac{D}{V_{N+1}}\right) x_D$$

⇒ LOOKS LIKE DIFFERENT OPERATING LINE FOR EACH STAGE ⇒ SIMPLIFYING ASSUMPTIONS.

ASSUMPTIONS

1) L + V CONSTANT IN RECTIFYING SECTION

⇒ a) No pressure drop

b) $(\Delta H^{Vap})_A = (\Delta H^{Vap})_B$

c) $(C_p \Delta T)_A + (C_p \Delta T)_B \ll \Delta H^{Vap}$

d) column well insulated

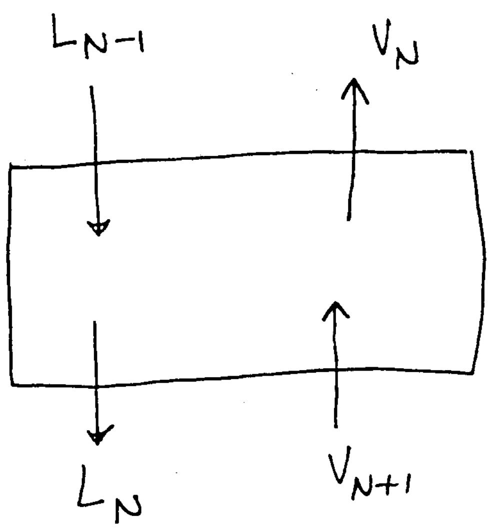
2) Total Condenser ⇒ liquid mole fraction for D.

$$\Rightarrow \boxed{y_{N+1} = \left(\frac{L}{V}\right) x_N + \left(\frac{D}{V}\right) x_D}$$

RECTIFIER OPERATING LINE

$\Rightarrow$ RELATES y_{N+1} and x_N

THESE ARE PASSING STREAMS:



STAGE N

EQUILIBRIUM LINE RELATES COMPOSITIONS IN L_N + V_N

OPERATING LINE RELATES COMPOSITIONS IN

a) L_{N-1} and V_N

b) L_N and V_{N+1}

FROM OPERATING LINE, SLOPE = $\frac{L}{V}$

NEED A POINT TO START AT ...

⇒ 45° Line, $y_{N+1} = X_N$

⇒ Substitute & solve for X_N

$$X_N = \frac{L}{V} X_N + \frac{D}{V} X_D$$

$$X_N \left(1 - \frac{L}{V}\right) = \frac{D}{V} X_D$$

$$X_N = \frac{D}{V} X_D \left(\frac{V}{V-L}\right)$$

But $V = L + D$ (overall mole balance)

⇒ $D = V - L$

$$X_N = \frac{\not{D}}{\not{V}} X_D \left(\frac{\not{V}}{\not{D}}\right)$$

$$\boxed{X_N = X_D}$$ ⇐ Starting point on 45° line.

CLOSER LOOK @ SLOPE

FOR RECTIFIER, SLOPE < 1

$\Rightarrow$ $L < V$ in Rectifier

$$\frac{L}{V} = \frac{L}{L+D} \quad \text{(overall mole balance)}$$

RECALL REFLUX RATIO

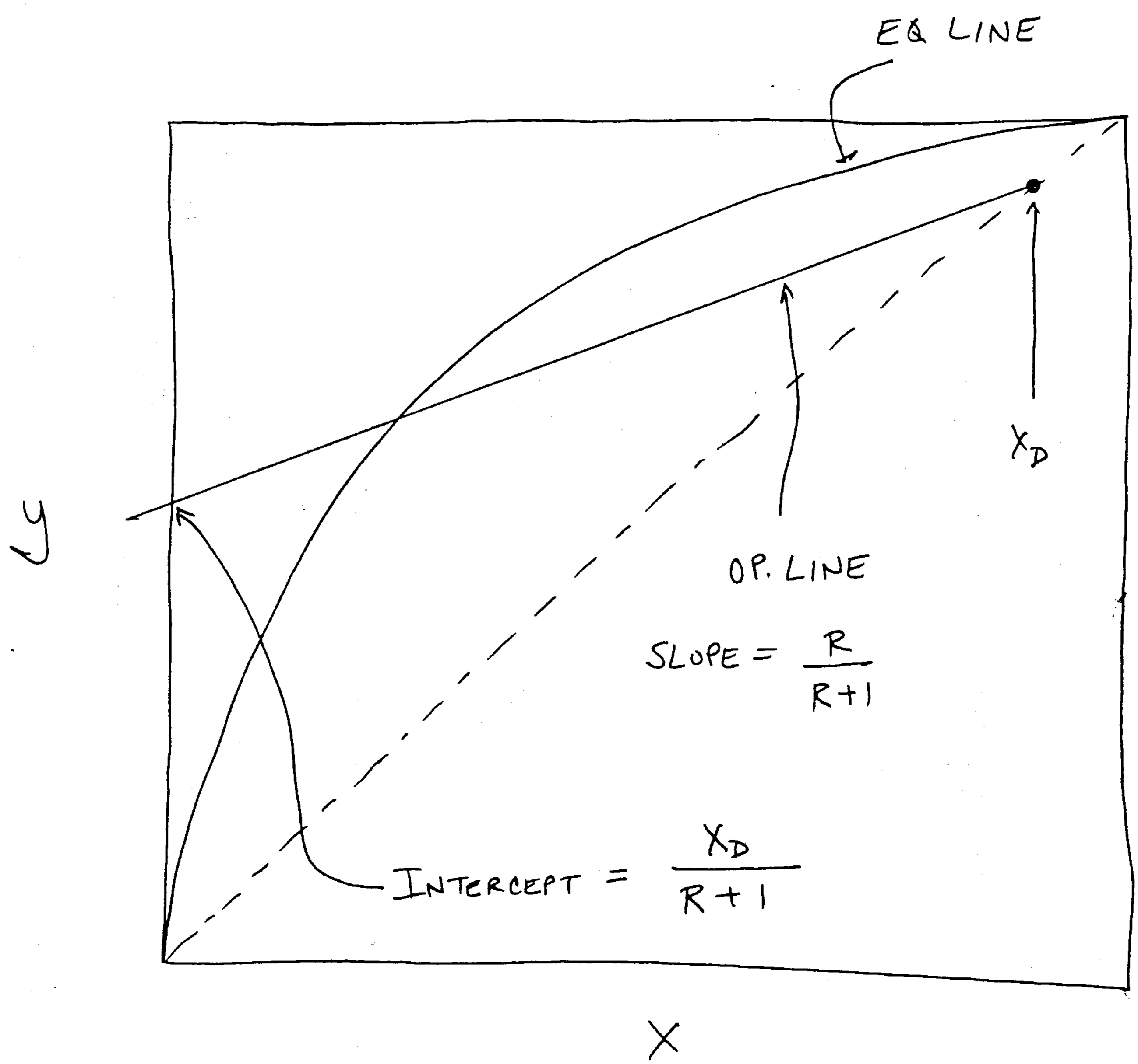
$$\frac{L}{D} = R$$

$$\frac{L}{L+D} = \frac{\frac{1}{D}(L)}{\frac{1}{D}(L+D)} = \frac{\frac{L}{D}}{\frac{L}{D}+1}$$

$$\Rightarrow \boxed{\text{Slope} = \frac{L}{V} = \frac{R}{R+1}} \quad \text{Rectifier}$$

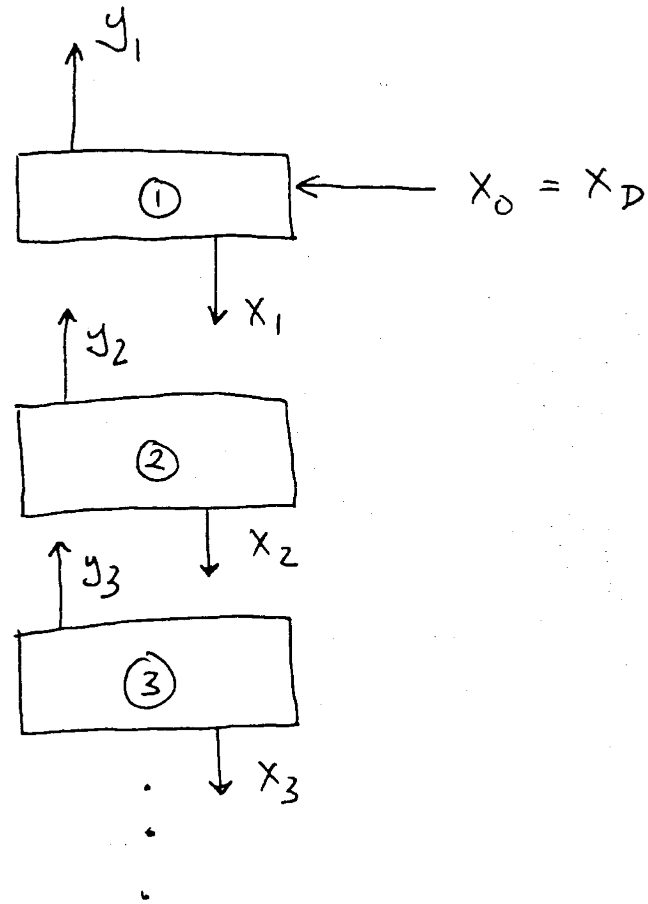
$$\frac{D}{V} = \frac{D}{L+D} = \frac{1}{\frac{L}{D}+1} = \boxed{\frac{1}{R+1}} \quad \text{INTERCEPT}$$

$$\boxed{y_{N+1} = \frac{R}{R+1} x_N + \frac{1}{R+1} x_D} \quad \text{OPERATING LINE RECTIFIER}$$



⇒ NOW THAT WE HAVE THE OPERATING LINE, HOW DO WE USE THIS FOR DESIGN?

⇒ STEPPING OFF STAGES



PROCEDURE:

1) KNOW SPEC. ($x_D = x_0$)

2) Total Condenser $\Rightarrow$ $x_D = y_1$

AND y_1 on EQ LINE

3) y_1 in EQ w/ x_1 (EQ Line)

4) x_1 passing y_2 (OP Line)

5) y_2 in EQ w/ x_2 (EQ Line)

etc. (until EQ Line + OP Line touch)

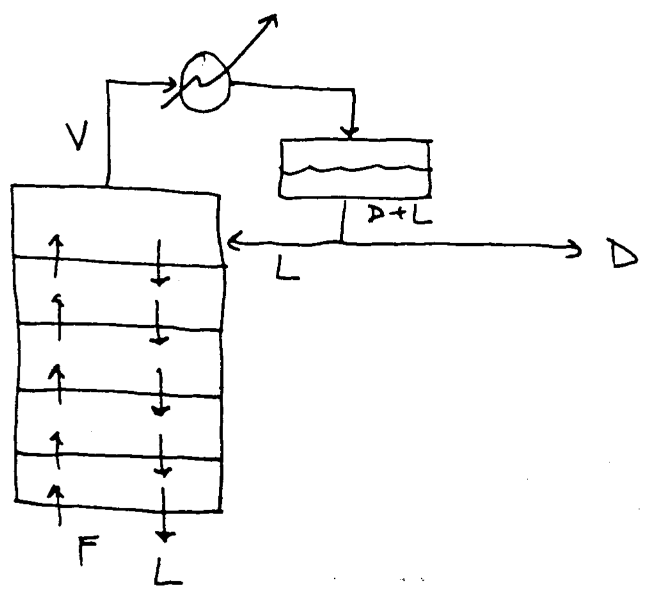
EXAMPLE: Hexane (1) / Octane (2)

- Spec is 95% hexane
- Total condenser
- Reflux ratio = 2
- Uniform pressure of 1 bar
- XY phase diagram given
- Feed = 100 moles/hour (all vapor)
- Rectifier

⇒ HOW GOOD CAN WE DO?

SOLUTION:

Step 1 Picture



STEP 2 WHAT DO WE KNOW?

- → $X_D = 0.95$
- → Total condenser ⇒ Not a stage
- → $R = \frac{L}{D} = 2$
- → $F = 100$ mol/hr
- → Pressure = 1 bar

STEP 3 BULK FLOWS

$\frac{L}{D} = 2$ (Reflux Ratio)

$F = L + D$ (Overall mole balance)

$F = 100$ (given)

⇒ $L = 2D$

$100 = 2D + D$ ⇒

$D = 33.3$ mol/hr
$L = 66.7$ mol/hr

STEP 4 BALANCE AROUND DRUM

$V = D + L = F$

⇒ $V = 100$ mol/hr

STEP 5 OPERATING LINE

$X_D = 0.95$ (Starting point on 45° line)

$$\text{Slope} = \frac{R}{R+1} = \frac{2}{2+1} = \frac{2}{3}$$

(Note: Double check slope < 1)

STEP 6 ONTO XY DIAGRAM.

(see next page)

STEP 7 STEP OFF STAGES

① $X_D = 0.95$ (spec)

② $y_1 = X_D = 0.95$ (total condenser)

③ $X_1 = 0.75$ (EQ Line)

④ y_2 + X_1 passing streams (OP Line)

$y_2 = 0.825$

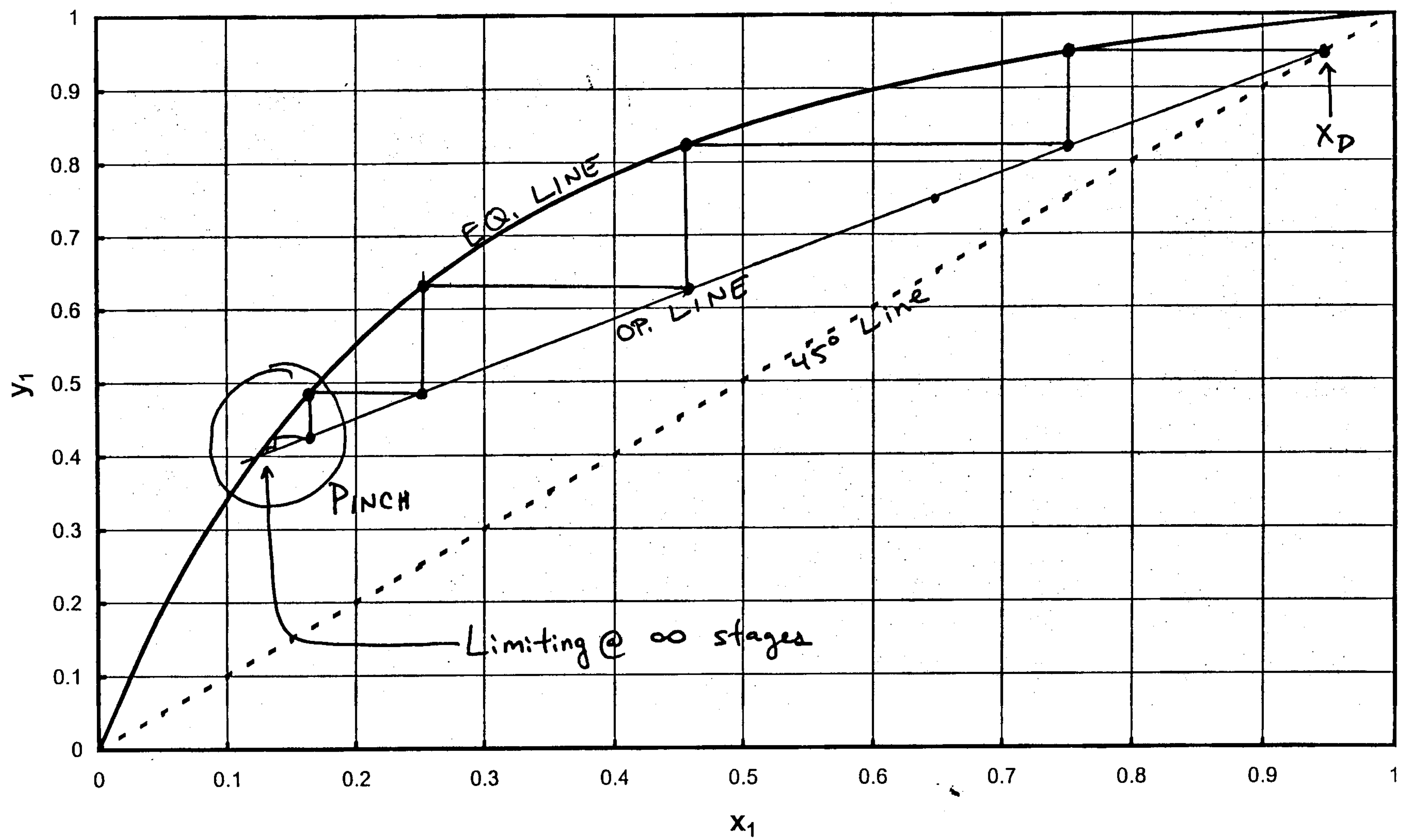
⑤ X_2 + y_2 in EQ (EQ Line)

$X_2 = 0.45$

and onward . . .

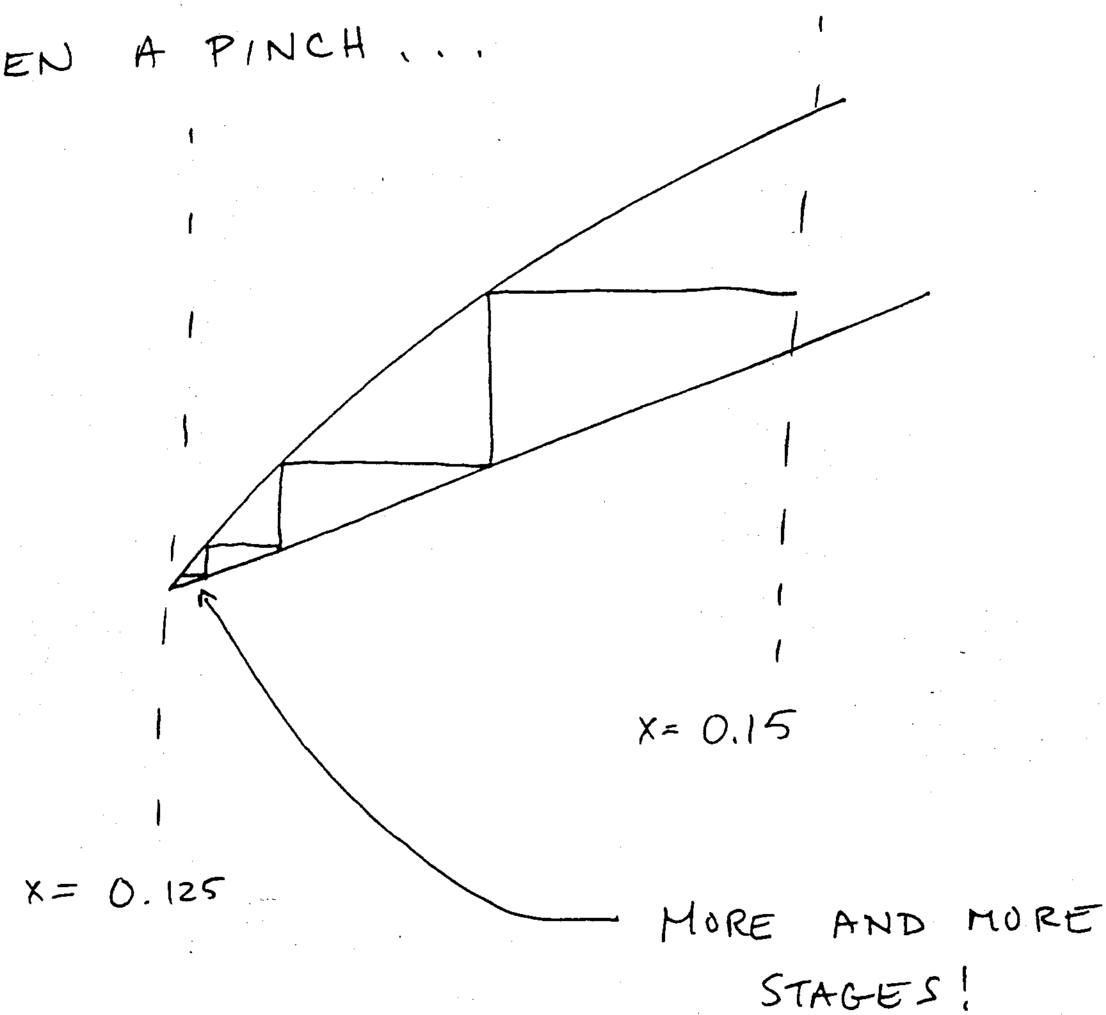
RECTIFIER ONLY

XY Phase Diagram for a System of Hexane (1) in Octane (2) at 1 bar



FOUR STAGES GOT TO $x_4 = 0.16$

THEN A PINCH . . .



$\Rightarrow$ DESIGN CHANGE

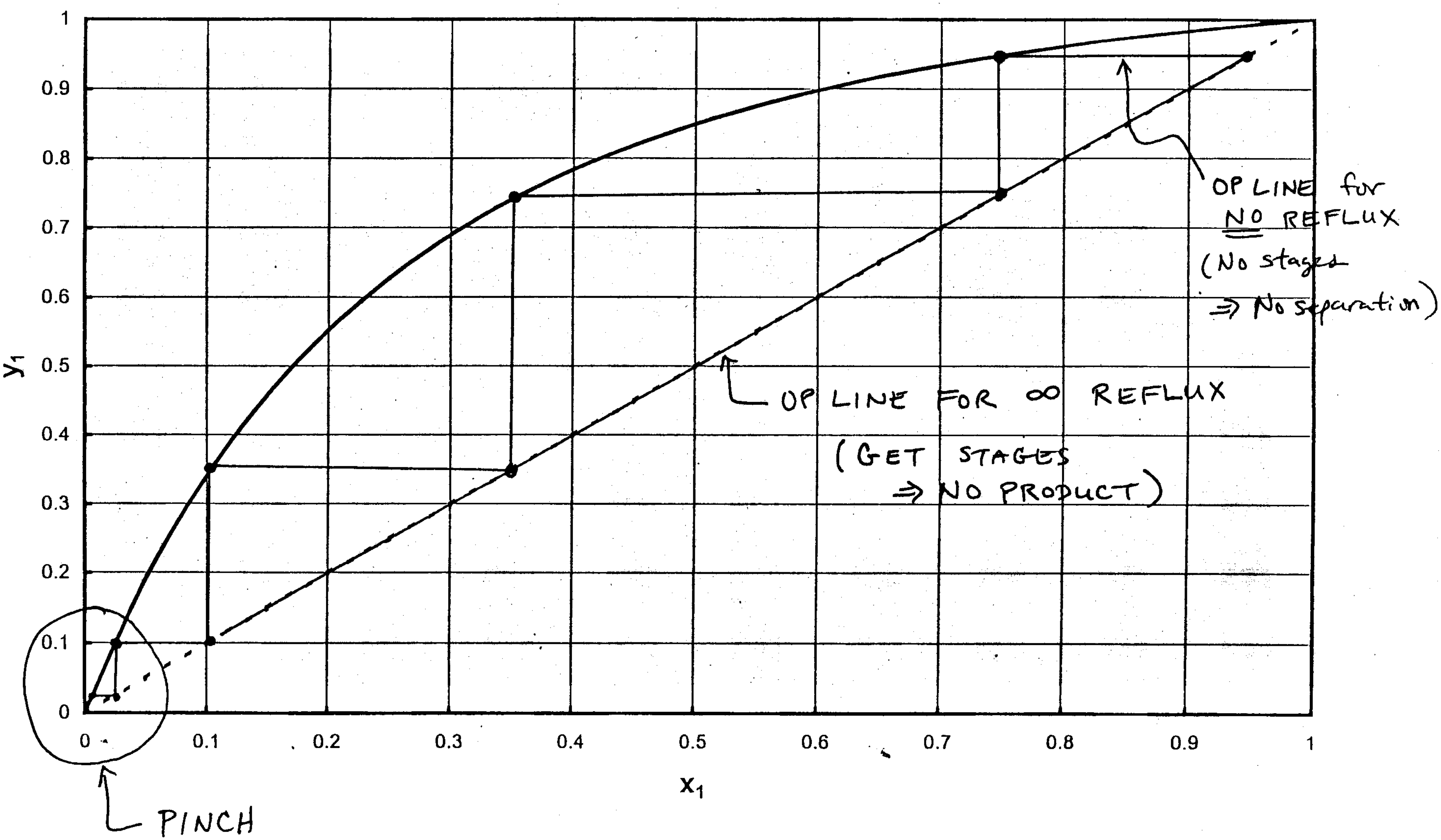
REFLUX RATIO

a) R smaller $\Rightarrow \frac{R}{R+1} \to 0$

b) R larger $\Rightarrow \frac{R}{R+1} \to 1$

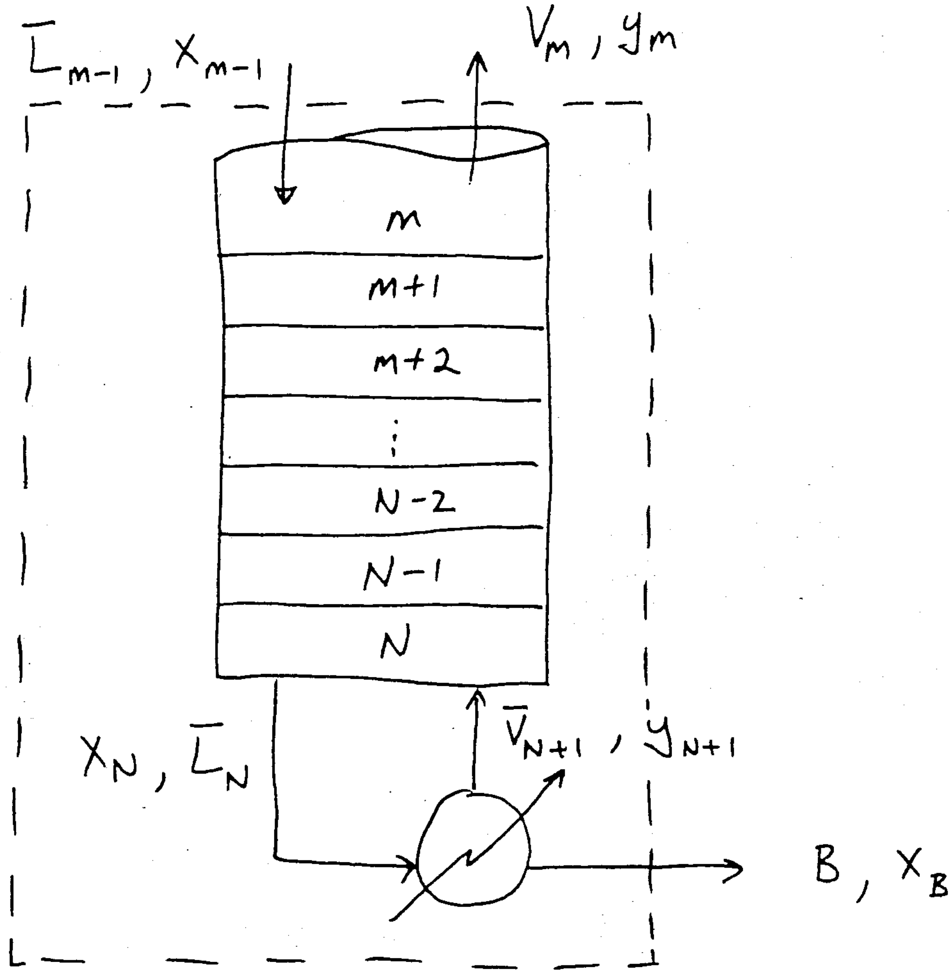
RECTIFIER ONLY

XY Phase Diagram for a System of Hexane (1) in Octane (2) at 1 bar



⇒ NEED BALANCE

STRIPPING SECTION OPERATING LINE



OVERALL MOLE BALANCE:

$$\underbrace{\bar{L}_{m-1}}_{\text{IN}} = \underbrace{\bar{V}_m + B}_{\text{OUT}}$$

COMPONENT MOLE BALANCE (LIGHT KEY):

$$\underbrace{(\bar{L}_{m-1})(x_{m-1})}_{\text{IN}} = \underbrace{(\bar{V}_m)(y_m) + (B)(x_B)}_{\text{OUT}}$$

JUST LIKE FOR RECTIFIER, SOLVE FOR y_m

$$\boxed{y_m = \frac{\bar{L}_{m-1}}{\bar{V}_m}(x_{m-1}) - \frac{B}{\bar{V}_m}(x_B)}$$

⇒ AGAIN, DIFFERENT OPERATING LINE FOR EACH STAGE ⇒ SIMPLIFYING ASSUMPTIONS

ASSUMPTIONS:

1) $\bar{L}$ + $\bar{V}$ constant.

$$\Rightarrow \frac{\bar{L}_{m-1}}{\bar{V}_m} = \frac{\bar{L}}{\bar{V}}$$

2) Bottoms liquid product $\Rightarrow X_B$
(liquid mole fraction)

3) No pressure drop.

4) $(\Delta H^{vap})_A = (\Delta H^{vap})_B$

5) $(C_p \Delta T)_A + (C_p \Delta T)_B << \Delta H^{vap}$

6) Column well insulated.

Slope of Stripping Section Op. Line $= \dfrac{\bar{L}}{\bar{V}}$

NOTE: SLOPE > 1

$\Rightarrow \bar{L} > \bar{V}$ in STRIPPING SECTION

$$\Rightarrow \boxed{y_m = \frac{\bar{L}}{\bar{V}}(X_{m-1}) - \frac{B}{\bar{V}} X_B}$$

STRIPPER OPERATING LINE

CLOSER LOOK @ SLOPE:

$$\frac{\bar{L}}{\bar{V}} = \frac{\bar{V} + B}{\bar{V}} \quad \text{(overall mole balance)}$$

RECALL BOILUP RATIO

$$V_B = \frac{\bar{V}}{B}$$

$$\Rightarrow \frac{\frac{1}{B}(\bar{V}+B)}{\frac{1}{B}\bar{V}} = \frac{\frac{\bar{V}}{B} + 1}{\frac{\bar{V}}{B}}$$

$$\Rightarrow \boxed{\frac{\bar{L}}{\bar{V}} = \frac{V_B + 1}{V_B}} \quad \text{SLOPE}$$

$$\boxed{\frac{B}{\bar{V}} = \frac{1}{V_B}} \quad \text{INTERCEPT.}$$

$$\boxed{y_m = \left(\frac{V_B + 1}{V_B}\right)(x_{m-1}) - \frac{1}{V_B} x_B} \quad \text{STRIPPER OP. LINE.}$$