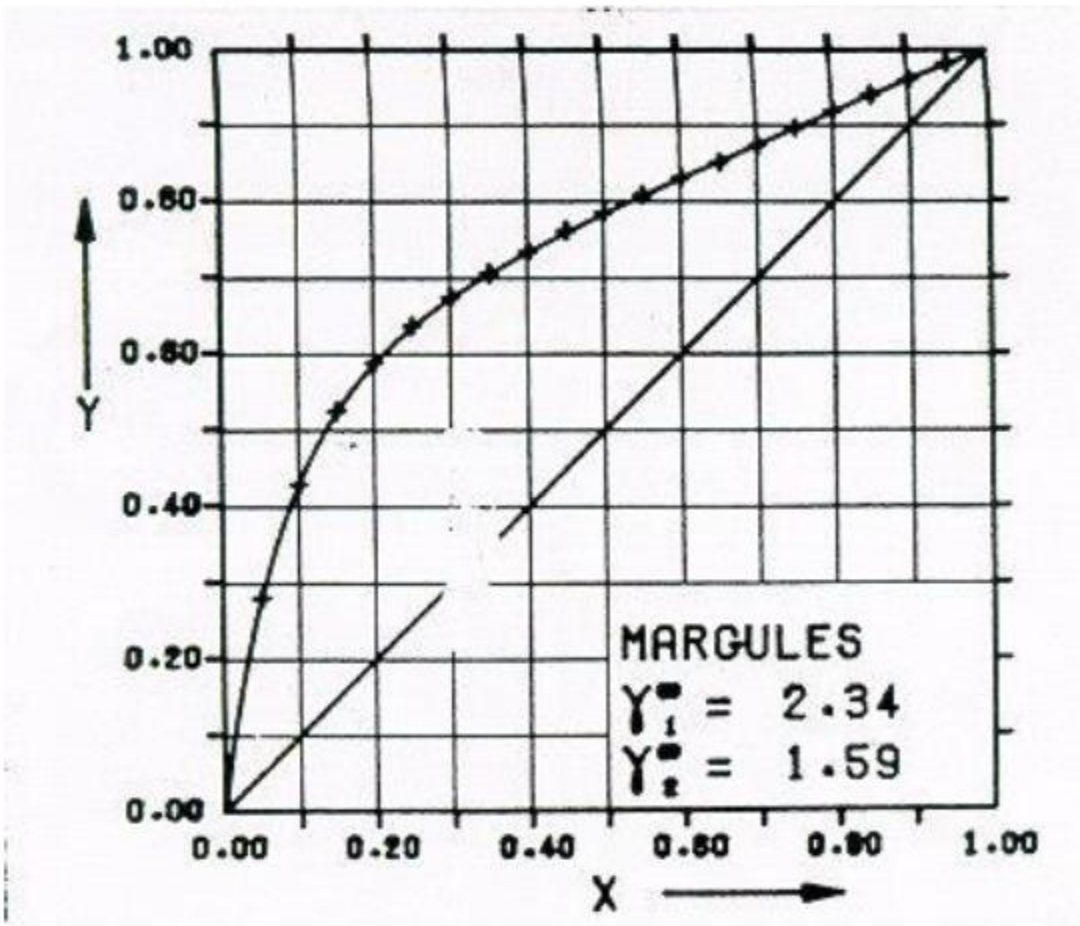
CE 407 Notes
Binary distillation McCabe-Thiele examples

## Example 1

An 80 mol/h feed stream with composition 45 mole % methanol ("light"), 55 mole % water ("heavy") is to be separated by continuous distillation in a sieve plate column fitted with a total condenser. The distillate should have methanol mole fraction equal to 0.95 and the bottom product should have water mole fraction equal to 0.98. Feed enters as saturated liquid. All plates behave as ideal stages. If the reflux ratio is 1.5 times the minimum, how many plates will be required?



$x_F = 0.45$ , $x_D = 0.95$, $x_B = 1 - 0.98 = 0.02$
Sat. liquid feed ⇒ $q = 1$. $R = (1.5) R_{min}$. Ideal stages.

(i) <u>$R_{min}$</u>

Op. line for rectifying section passes through point $(x_D, x_D) = (0.95, 0.95)$. Feed line passes through point $(x_F, x_F) = (0.45, 0.45)$ and is vertical because $q = 1$. From graph,

$$\text{intercept} = \frac{x_D}{R_{min}+1} = 0.58$$

⇒

$$R_{min} = \frac{x_D}{0.58} - 1 = \frac{0.95}{0.58} - 1 = 0.638$$

(ii) <u>Actual column operation</u>

$R = 1.5 R_{min} = (1.5)(0.638) = 0.957$

<u>1. Op. line for rectifying section:</u>

Passes through $(x_D, x_D) = (0.95, 0.95)$ and has intercept $x_D/(R+1) = 0.485$. Draw on graph.

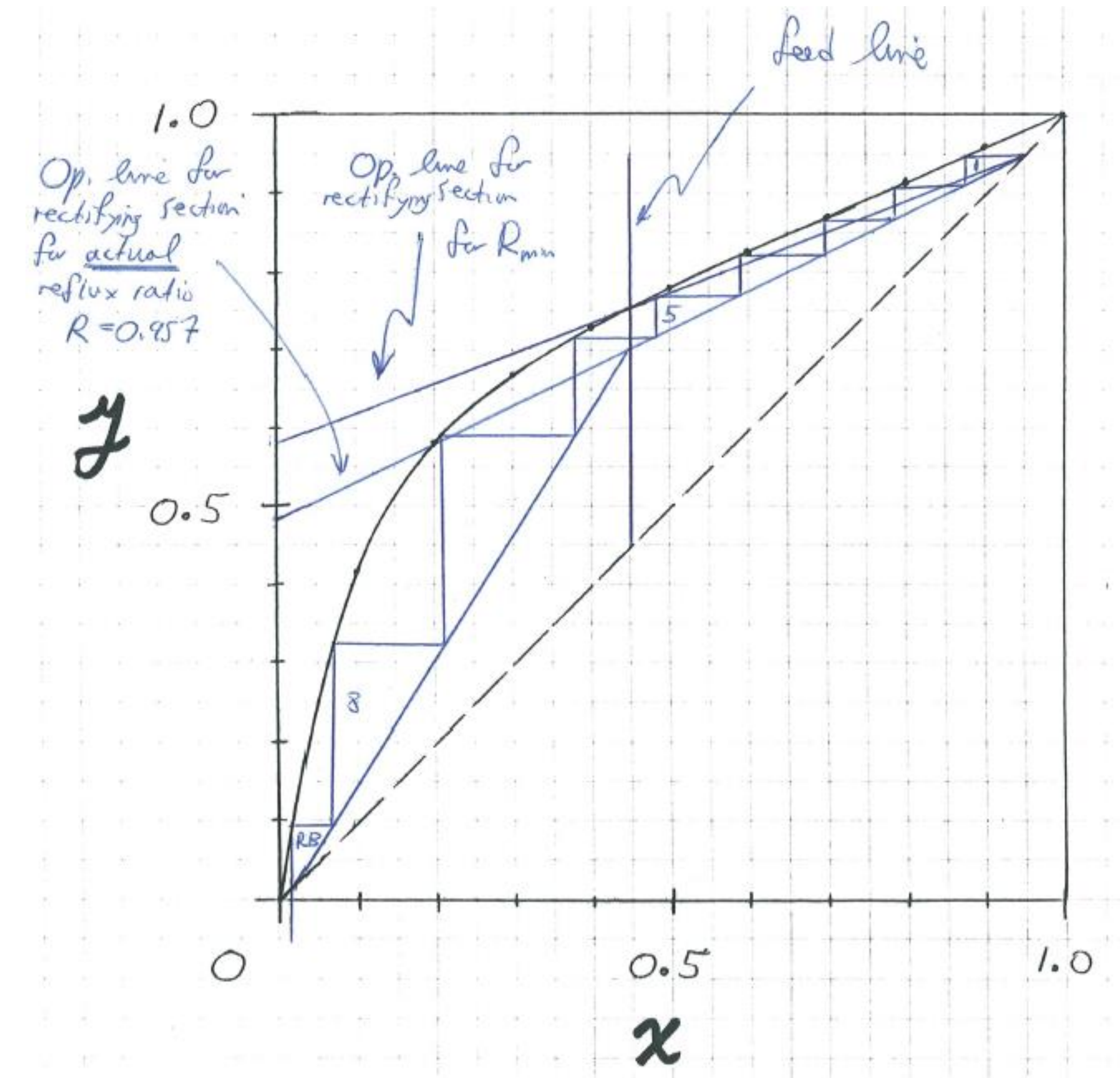
(0.957)

<u>2. Feed line</u>: already drawn

<u>3. Op. line for stripping section:</u>

Passes through $(x_B, x_B) = (0.02, 0.02)$ and the intersection of feed line and op. line for rectifying section. Draw on graph.

4. Count steps. First step is stage 1 in column because total condenser is used. Transfer from op. line for rectifying section to op. line for stripping section at first available opportunity. Last step corresponds to reboiler. Need **8 plates** in the column itself.



## Example 2

**Example.** In the development of a new process it will be necessary to fractionate 910 kg/h of an ethanol-water solution containing 0.3 mole fraction ethanol, supplied as cold liquid 88.9 °C below its bubble point. It is desired to produce exactly 535 kg/h of distillate containing 0.70 mole fraction ethanol. The distillation column is to be constructed partly out of existing pieces of hardware. In particular, the rectifying section is a one-piece unit with six sieve trays. This is not subject to any changes, so feed will have to be introduced on the seventh tray. accidentally dropped the rectifying section off a bridge, and the top three sieve trays were so badly damaged that they now have Murphree efficiencies equal to 0.50. *All other trays behave as ideal stages.* The column will be fitted with a *partial* condenser (for which exiting liquid and vapor streams are at equilibrium). The reflux ratio should be 1.875 times the minimum. VLE data for ethanol + water measured by Elroy's pet mushroom are as follows (mole fractions refer to the more volatile component, ethanol):

| $x$ | $y$ |
|---|---|
| 0.01 | 0.10 |
| 0.02 | 0.20 |
| 0.04 | 0.30 |
| 0.10 | 0.44 |
| 0.20 | 0.53 |
| 0.30 | 0.58 |
| 0.40 | 0.62 |
| 0.50 | 0.66 |
| 0.60 | 0.70 |
| 0.70 | 0.76 |

Not counting the reboiler, how many trays will be required in the stripping section to achieve the desired separation? (Note: according to normal convention, the feed tray is regarded as belonging to the stripping section.) **Draw** a simple sketch of the column indicating stages, condenser, reboiler, and locations of feed, distillate and bottoms streams.
Other data you may need: The feed solution has $C_{P_{\text{liq}}}$ = liquid heat capacity = 90 J/(mol °C) and $\lambda$ = heat of vaporization = 40 kJ/mol.

(i) Preliminaries and material balance.

Feed: 1 mol contains

$$0.3 \text{ mol } C_2H_5OH \times \frac{46.069\text{ g}}{1\text{ mol}} = 13.82\text{ g } C_2H_5OH$$

plus

$$0.7 \text{ mol } H_2O \times \frac{18.015\text{ g}}{1\text{ mol}} = 12.61\text{ g } H_2O$$

$$26.43\text{ g total}$$

Basis = 1h. Then

$$F = 910\text{ kg} \times \frac{1000\text{ g}}{1\text{ kg}} \times \frac{1\text{ mol}}{26.43\text{ g}} = 3.443\times10^4\text{ mol}.$$

Distillate: 1 mol contains

$$0.7 \text{ mol } C_2H_5OH \times \frac{46.069\text{ g}}{1\text{ mol}} = 32.25\text{ g } C_2H_5OH$$

plus

$$0.3 \text{ mol } H_2O \times \frac{18.015\text{ g}}{1\text{ mol}} = 5.40\text{ g } H_2O$$

$$37.65\text{ g total}$$

Then

$$D = 535\text{ kg} \times \frac{1000\text{ g}}{1\text{ kg}} \times \frac{1\text{ mol}}{37.65\text{ g}} = 1.421\times10^4\text{ mol}$$

Material balances (over whole column): (eqs. (18-3) and (18-4) on p. 479)

$$F = D + B, \text{ so } B = F - D = 2.022\times10^4\text{ mol}$$

$$Fx_F = Dx_D + Bx_B, \text{ so } x_B = \frac{Fx_F - Dx_D}{B} = 0.019$$

(ii) Minimum reflux.

Feed line: Passes through point $(x_F, x_F) = (0.30, 0.30)$.

Eq. (18-22), p. 488:
$$q = 1 + \frac{C_{pL}(T_b - T_F)}{\lambda}$$

From problem statement, $T_F = T_b - 88.9\,°C$ (feed is "supplied as cold liquid 88.9 °C below its bubble point."). Thus $T_b - T_F = +88.9\,°C$ and

$$q = 1 + \frac{\left(90 \frac{J}{mol\,°C}\right)(88.9°C)}{\left(40 \frac{kJ}{mol}\right) \times \frac{1000\,J}{1\,kJ}} = 1.20$$

Slope of feed line $= -q/(1-q) = 6.0$.

Op. line for rectifying section: Passes through point $(x_D, x_D) = (0.70, 0.70)$. As slope is decreased, contact with equil. curve first occurs where equil. curve crosses feed line (see graph page [13]). From graph, y-intercept $= x_D/(R+1) = 0.500$ so $R = \frac{x_D}{0.500} - 1 = \frac{0.7}{0.5} - 1 = 0.4$.

So: $R_{min} = 0.4$.

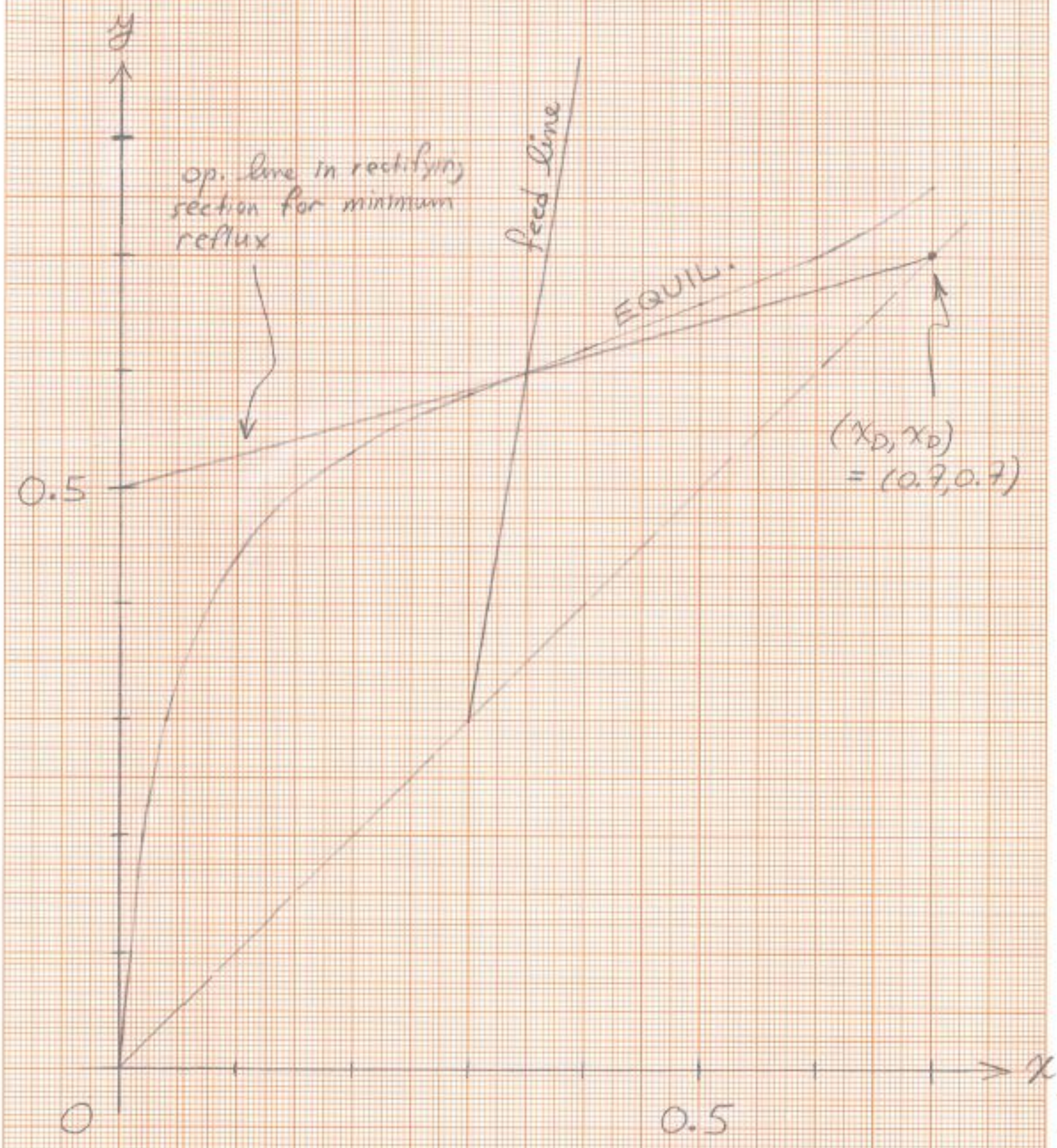
(iii) Operating reflux. $R = (1.875)R_{min} = (1.875)(0.4) = 0.75$.

Op. line for rectifying section: Passes through $(x_D, x_D) = (0.7, 0.7)$ and has y-intercept $x_D/(R+1) = (0.7)/(0.75+1) = 0.40$.

Feed line: already discussed.

Op. line for stripping section: Passes through $(x_B, x_B) = (0.019, 0.019)$ and the point where feed line intersects rectifying line.

Effective equil. curve: After drawing rectifying line, draw dashed curve half-way to

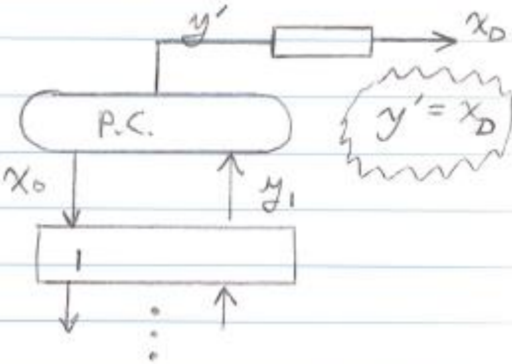


y
x
op. line in rectifying section for minimum reflux
feed line
EQUIL.
(x_D, x_D) = (0.7,0.7)
0.5
0
0.5

equil. curve (measured vertically) because $\eta_M = 0.50$.

<u>Counting stages</u>: Exiting streams at equil. for partial condenser.

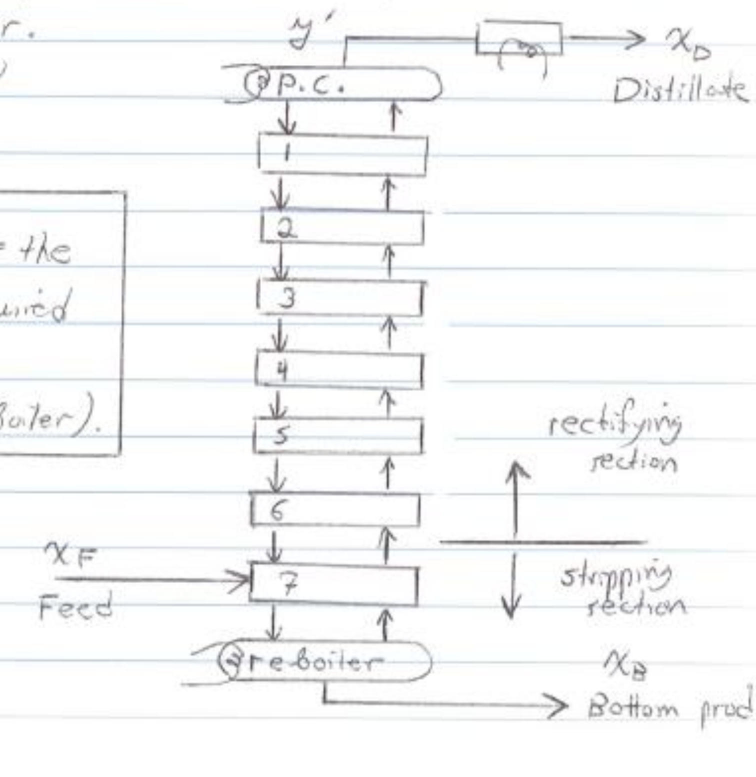
$\therefore (x_0, y') = (x_0, x_D)$ lies on equil. curve (and we know $x_D = 0.7$). Then $(x_0, y_1)$ is on op. line. <u>Remember</u>: do NOT use Murphree efficiency for partial condenser.

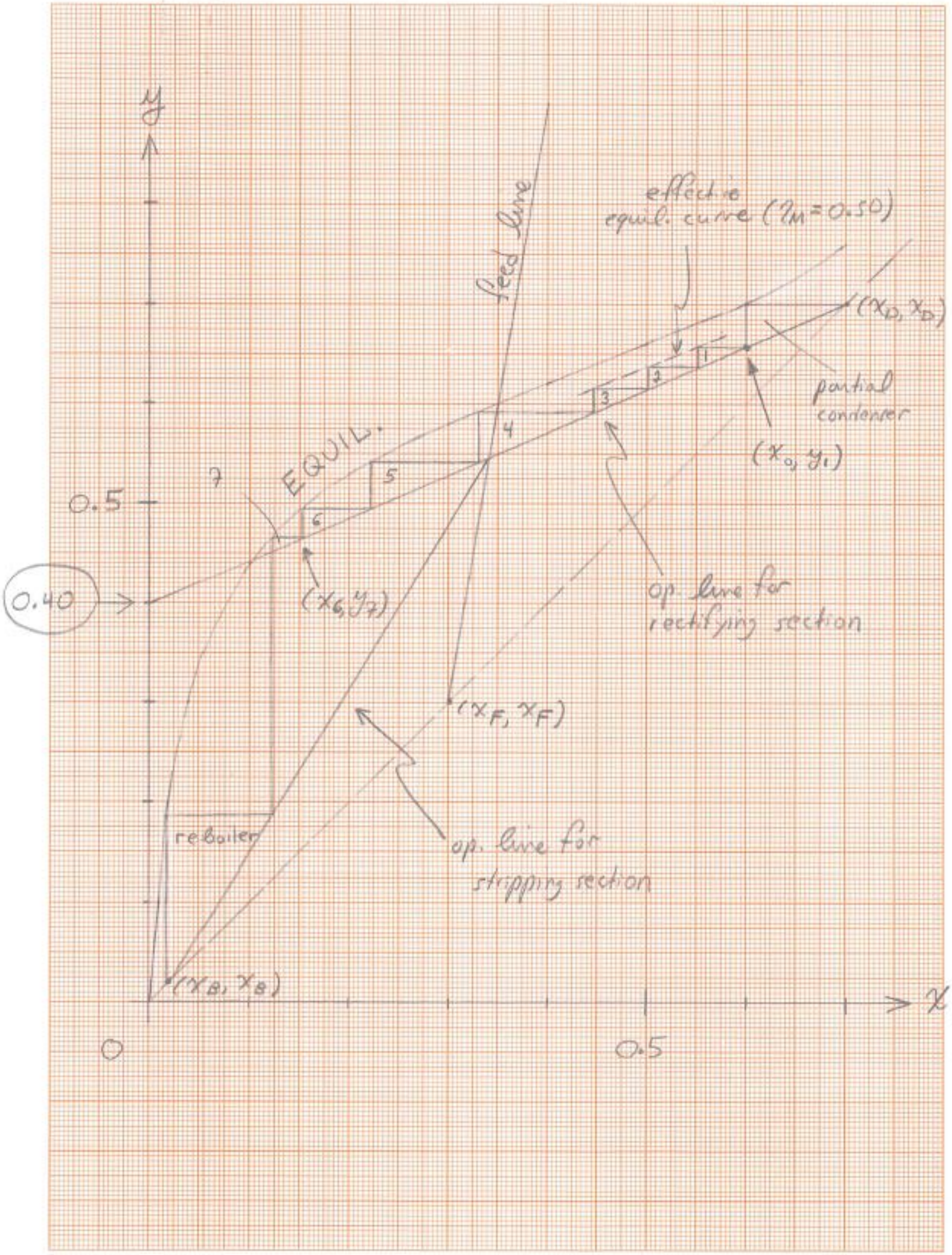



Use effective equil. curve for first three steps. Thereafter use equil. curve. Make 6 steps using rectifying line, <u>then</u> transfer to stripping line at $7^{th}$ step.

From graph, need 8 stages. Last stage is reboiler. Column looks as follows:

One tray (= the feed tray) is required in stripping section (not counting reboiler).





y
x
0
0.5
0.5
0.40
feed line
effective
equil. curve ($\eta_M$ = 0.50)
$(x_D, x_D)$
partial
condenser
$(x_0, y_1)$
EQUIL.
$(x_6, y_7)$
op. line for
rectifying section
$(x_F, x_F)$
reboiler
op. line for
stripping section
$(x_B, x_B)$
1
2
3
4
5
6
7