1. (25p) Rectification column

1. ① Mass conservation, Derive F and B

3 p

$F = B + D$ $\qquad$ $x_F F = x_B B + x_D D$

$\rightarrow F = B + 70$ $\qquad$ $\rightarrow 0.5F = 0.05(F - 70) + 0.95(70)$

or $B = F - 70$

$\rightarrow 0.45F = 0.90(70)$

$\rightarrow F = 140$ mole/s

$B = 70$ mole/s

② Energy Conservation, Derive $\dot{Q}_D$

5 p

$\dot{Q}_B = \dot{Q}_D + h_D D + h_B B - h_F F$

$h = 779$ J/mol $= h_D = h_B = h_F$

$H = 7118$ J/mol

$\rightarrow 900 \times 10^3 = \dot{Q}_D + 779(70) + 779(70) - 779(140)$

$\rightarrow \dot{Q}_D = 900 \times 10^3$

③ Upper section Operating line

5 p

$$\frac{D}{V_n} = \frac{H - h}{\dot{Q}_D/D + h - h} = \frac{7118 - 779}{900 \times 10^3 / 70} = 0.493$$

$$\frac{L_{n+1}}{V_n} = 1 - 0.493 = 0.507$$

$$\Rightarrow y_n = \frac{L_{n+1}}{V_n} x_{n+1} + \frac{D}{V_n} \times 0.95 = 0.507 x_{n+1} + 0.493 \times 0.95$$

$$= 0.507 x_{n+1} + 0.468$$

1. (Cont.) ④ Lower section Operating line.

5 p

$$\frac{B}{V_m} = \frac{H - h}{Q_B/B + h - h} = \frac{7118 - 779}{900\times10^3/770} = 0.493$$

$$\frac{L_{m+1}}{V_m} = 1 + 0.493 = 1.493$$

$$\Rightarrow y_m = \frac{L_{m+1}}{V_m} x_{m+1} - \frac{B}{V_m} \times 0.05$$

$$= 1.493\, x_{m+1} - 0.493 \times 0.05$$

$$= 1.493\, x_{m+1} - 0.0247$$

⑤ Equilibrium line

5 p

$$y_1 = \frac{K_1(1-K_2)}{K_1 - K_2}, \quad x_1 = \frac{y_1}{K_1}$$

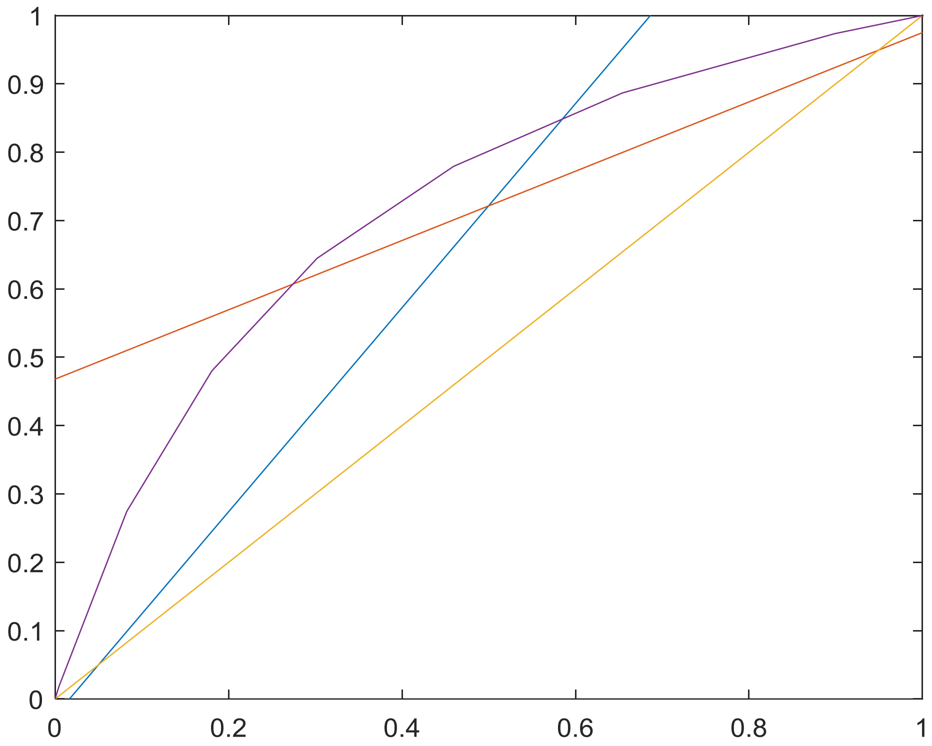
78K : $\ln(K_1 p/p_0) = 0.0798$ $\quad$ $\ln(K_2\, 8/p_0) = -1.3368$

$\rightarrow K_1 = e^{0.0798}$ $\quad$ $\rightarrow K_2 = e^{-1.3368}$

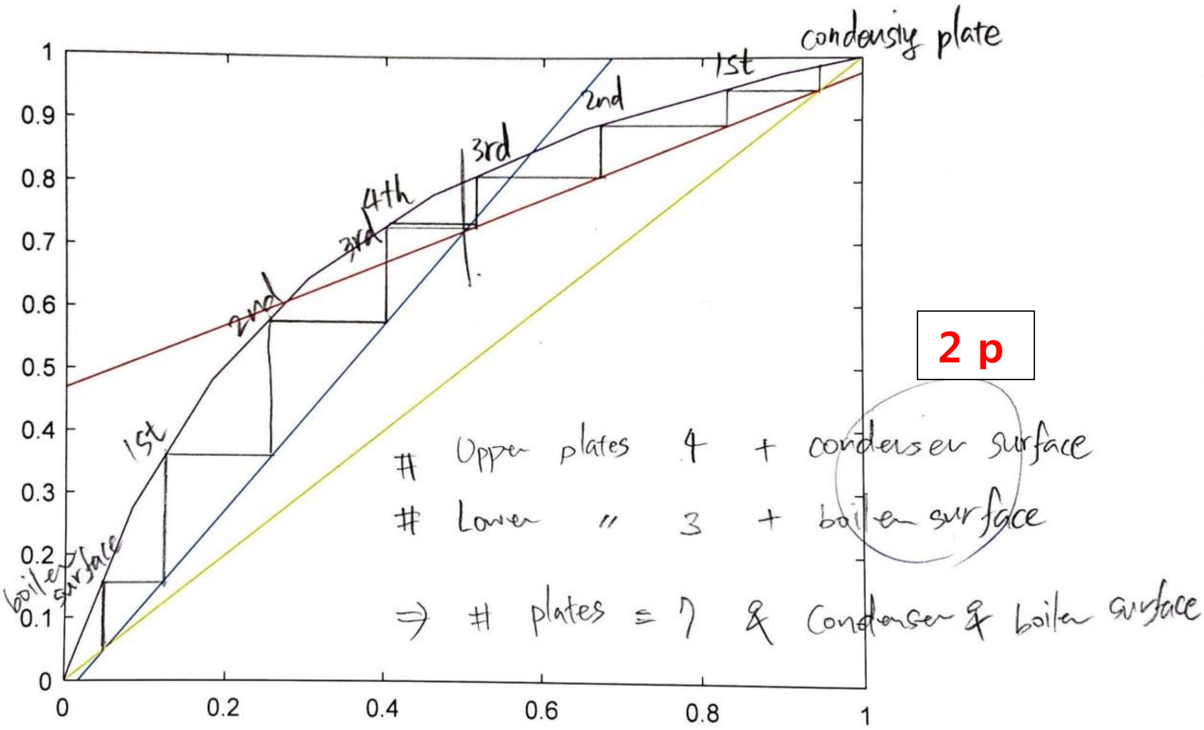
$= 1.08$ $\quad$ $= 0.263$

$$y_1 = \frac{1.08(1-0.263)}{1.08 - 0.263} = 0.974 \rightarrow x_1 = \frac{0.974}{1.08} = 0.902$$

80K ~ 90K as well



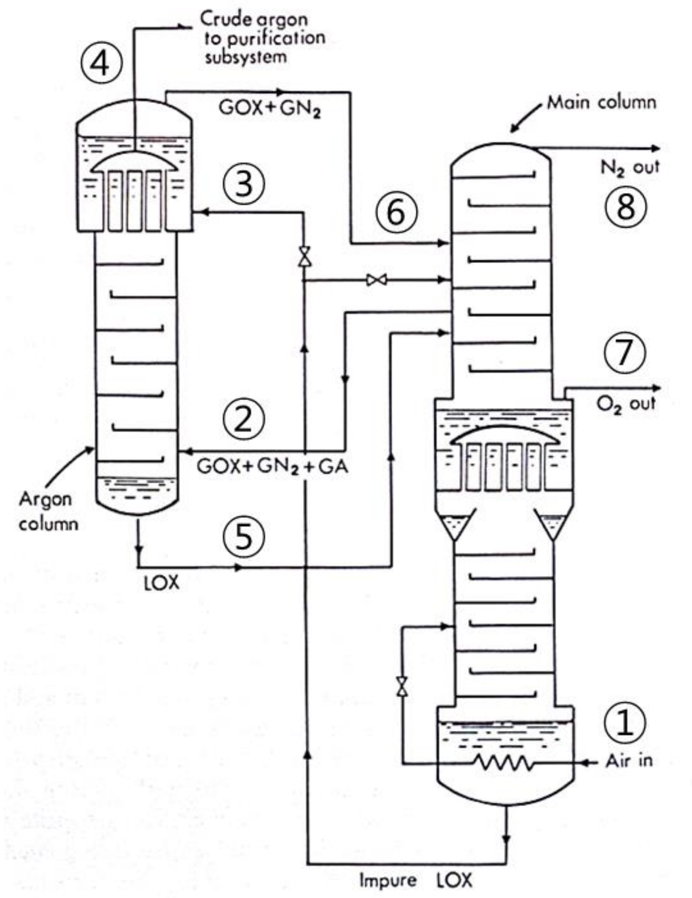

```
%% Lower & Upper operating line
x = [0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0];

y1 = 1.493 * x - 0.0247;
y2 = 0.507 * x + 0.468;

%% Diagonal line
y3 = x;

%% Equilibrium line
lnKpp0_N2 = [0.0798 0.3040 0.5282 0.7582 0.9766 1.2008 1.4249];
Kpp0_N2 = exp(lnKpp0_N2);

lnKpp0_O2 = [-1.3368 -1.1164 -0.8959 -0.6755 -0.4550 -0.2346 -0.0141];
Kpp0_O2 = exp(lnKpp0_O2);

p0 = 101.325;
p = 101.325;

K_N2 = Kpp0_N2 .*p0./p;
K_O2 = Kpp0_O2 .*p0./p;

y_N2 = K_N2 .* (1 - K_O2) ./ (K_N2 - K_O2);
x_N2 = y_N2./K_N2;

y_N2_expanded = [1, y_N2, 0];
x_N2_expanded = [1, x_N2, 0];

plot(x, y1, x, y2, x, y3, x_N2_expanded, y_N2_expanded)

hold on

axis([0 1 0 1])
```



condensing plate
1st
2nd
3rd
4th
3rd
2nd
1st
boiler surface
Upper plates 4 + condenser surface
Lower " 3 + boiler surface
⇒ # plates = 7 & Condenser & boiler surface
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1

2 p

2. **(10p) Argon-separation system**



Right: air-separation double-column system, Left: argon recovery subsystem

① **(1p)Feed air** comes into the lower column in the double-column system and is precooled by impure liquid oxygen in the bottom kettle.

② **(2p)Argon** tends to collect in that part of the upper column in the double-column system in which the fluid has a **high oxygen concentration and a relatively low nitrogen concentration.** **The argon-oxygen mixture is introduced** into the lower part of the argon-recovery column and is rectified there.

③ **(1p)**Some of the kettle liquid from the main column is **bypassed** through the condenser-reboiler of the argon column **to furnish the refrigeration** necessary to supply the reflux liquid there.

④ **(2p)**The **argon tends to collect in the top of the argon column** because the boiling point of argon is lower than that of oxygen and it is supplied to an argon purification subsystem.

⑤ **(1p)**The kettle liquid in the argon column is **practically all oxygen**; **therefore it is returned to the upper part of the main column.**

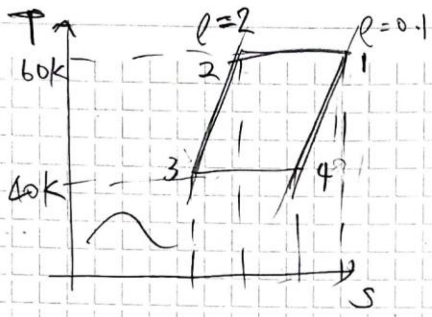
⑥ **(1p)**High nitrogen - **low oxygen concentration liquid** is also **passed to the far upper part of the main column**

⑦ **(1p)Pure oxygen** is **extracted** from the double-column system.

⑧ **(1p)Pure nitrogen** is also **extracted** from the double-column system.

3. (20p)Philips refrigerator

3. (1)



4 p

(2) $Q_a = mT_3(S_4 - S_3)$

or $Q_a = nT_3(S_4 - S_3)$

$\rightarrow \frac{Q_a}{n} = T_3(S_4 - S_3)$

4 p

$= 40K(93\,J/mol\cdot K - 67\,J/mol\cdot K)$

$= 1040\,J/mol$

$\frac{Q_r}{n} = T_1(S_2 - S_1)$

$= 60K(73\,J/mol\cdot K - 100\,J/mol\cdot K)$

$= 1620\,J/mol$

$\rightarrow \frac{W}{n} = \frac{Q_r}{n} - \frac{Q_a}{n}$

4 p

$= 1620\,J/mol - 1040\,J/mol$

$= 580\,J/mol$

$\rightarrow COP = \frac{1040\,J/mol}{580\,J/mol} = 1.79$

4 p

(1) Please refer to above.
(2) Please refer to above.
(3) **(4p)**If the regenerator were less than 100 percent effective, **the temperature of the gas leaving the regenerator at point 3 in Fig. 5.15 would be somewhat higher than the source temperature.** This means that some of the energy that could have been absorbed from the low-temperature region cannot be absorbed because energy is wasted to cool the refrigerator gas down to the source temperature.

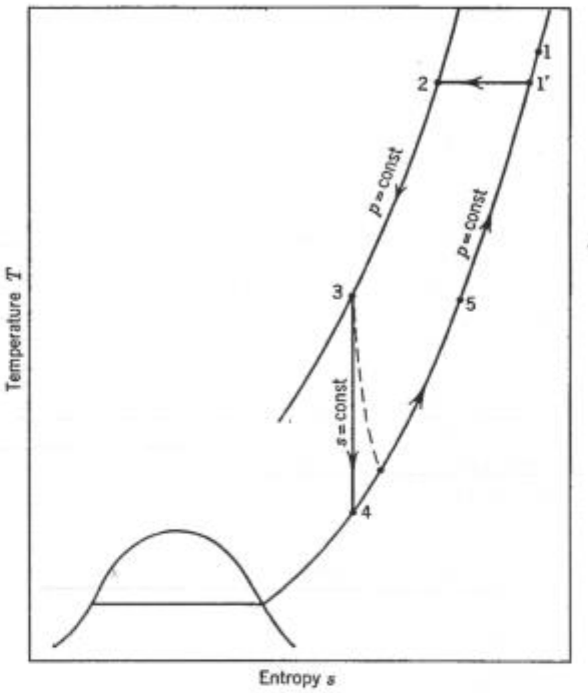
4. **(10p)Gifford-McMahon refrigerator**

(1) Reasons: GM system > Solvay system

A. **(2p)**Practically **no leakage past the displacer** in the GM system because of the small pressure difference across the displacer seals.

B. **(2p)Small force supportive displacer and crank arm** in the GM system; therefore simpler motion transmission system and fewer problems with vibration

(2) **(3p)**T-s diagram

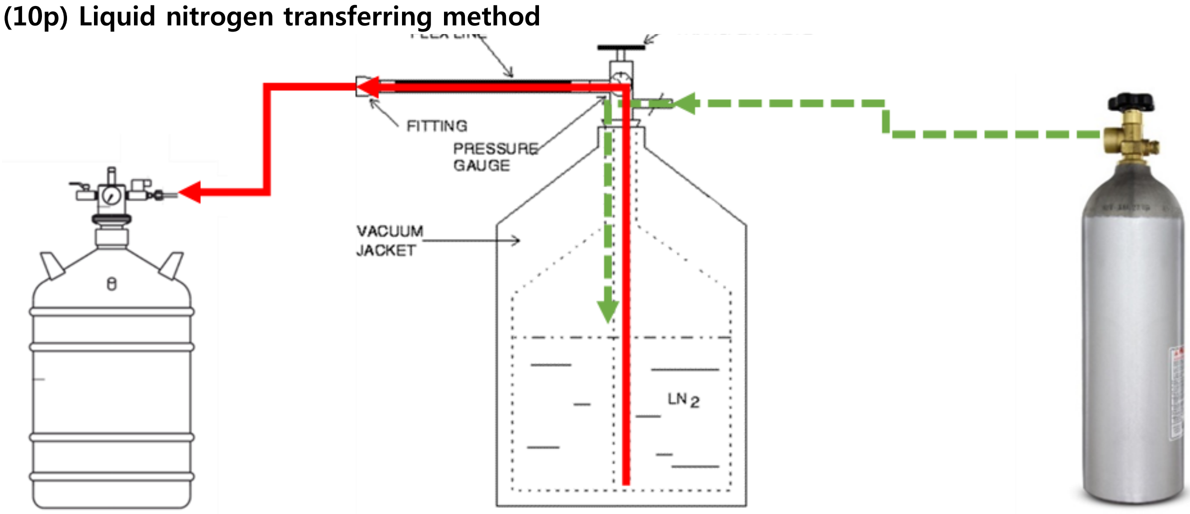


(3) **(3p)**If the regenerator were less than 100 percent effective, **the temperature of the gas leaving the regenerator at point 3 in Fig. 5.21 would be somewhat higher than ideal.** This means that some of the energy that could have been absorbed from the low-temperature region.

5. **(10p) Thermodynamic liquid-level probes**

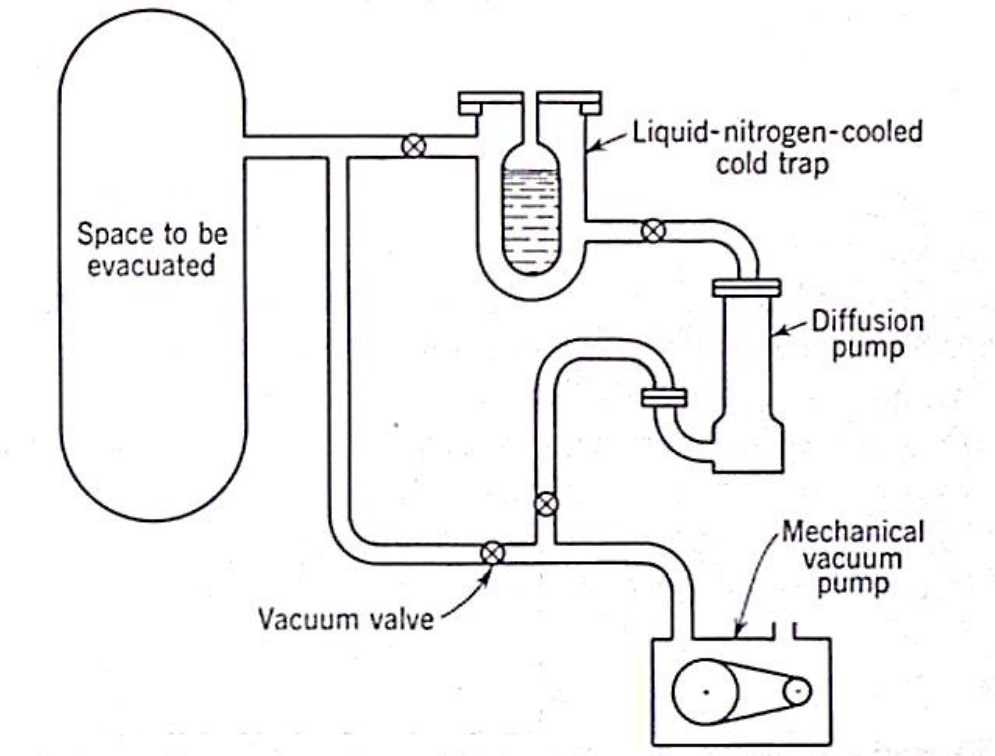
As the capillary tube is immersed in the cryogenic liquid, (5p) the gas that is in the immersed portion of the tube will be condensed. (5p)The change in volume of the gas during condensation reduces the pressure of the gas within the dead volume may then be used as an indication of the liquid level.

6. **(10p) Liquid nitrogen transferring method**



(5p)Tube connection is seen in above schematic diagram. The compressed nitrogen gas is injected into the nitrogen supply tank. **(5p)High pressure gas push the liquid nitrogen to get out of the supply tank** and it is transferred to the small Dewar.

7. **(10p) Vacuum system**



(3p)A mechanical pump is used as a forepump or roughing pump to reduce the system pressure to approximately 1.0 Pa (about 10^-2 torr) through a by-pass line. Once the pressure has been reduced to about 1 Pa, the **diffusion pump is turned on and the valve in the by-pass line is closed.** The diffusion pump cannot operate if the pump exhaust pressure is much above about 10 Pa (about 10^-1 torr), **(3p)so the forepump is necessary** for the operation of the diffusion pump. In addition, **(3p)the valving shown above is such that the diffusion pump may be isolated from the remainder of the system**. This arrangement is important if the vacuum must be broken for any reason because the diffusion pump oil could deteriorate if atmospheric air came in contact with the hot oil in the pump. **(1p)A cold trap or baffle** is provided near the inlet of the diffusion pump to prevent back streaming of oil vapor and to freeze out condensable gases such as water vapor before the gas reaches the diffusion pump.

8. **(5p) Refrigeration purification**

$\ln(p/p_0) = 6.1 - 2816/150 - (-1.587) * \ln(150)$

➔ $p/p_0 = \exp(6.1 - 2816/150 - (-1.587) * \ln(150))$

➔ $p/p_0 = \exp(-4.72)$

➔ $p/p_0 = 0.0089$

➔ $p = 0.89\ \text{kPa}$