Q.1 | **Question 1**
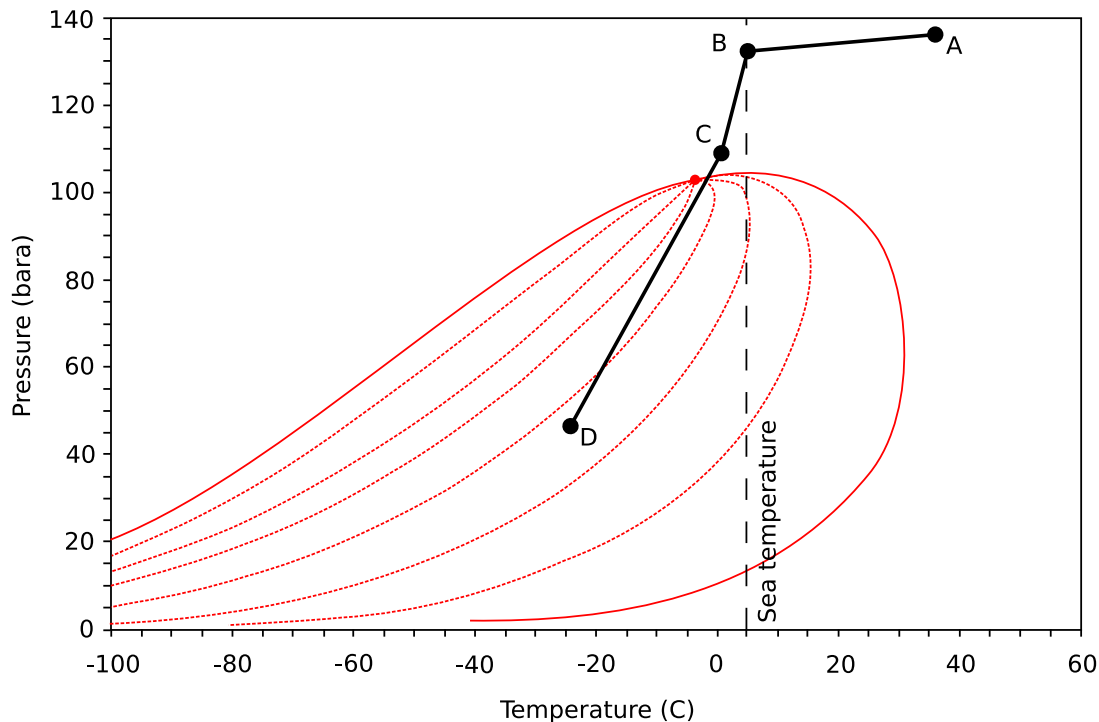**Phase behavior and physical properties**

Figure 1: *The phase diagram for well-fluids produced offshore (point A) and the pressure-temperature path of the subsea pipeline (A→C) and initial treatment at (C→D) the processing plant.*

Consider a subsea well. The wellhead temperature and pressure are indicated by point A on the figure above. The gas processing terminal, which is some distance away, receives the fluids at the conditions indicated by point C.

a) Describe what might be occurring to cause the condition change A→B. Note that the relative pressure drop is small. **[5 marks]**
Solution:

[5/5] Pressure drop is proportional to pipe length, so we are seeing a fast cooling of the well fluids to the sea temperature upon initial entry into the pipeline. ✓/5

b) Describe what might be occurring between points B→C. In particular describe why the fluid is colder than the surrounding sea water. **[5 marks]**
Solution:

The (frictional/accelerational/hydrostatic) pressure drop along the pipeline is causing a Joule-Thomson effect which auto-refrigerates the fluid. This allows it to cool below
[5/5] the surrounding sea temperature. ✓/5

c) Comment on the location of point C. Why is the subsea pipeline exit operated and designed at those conditions? Explain using key properties of the phase diagram. **[5 marks]**

Solution:

Point C is above the cricondenbar, which is the maximum pressure for the multi-phase region of the phase envelope. The pipeline is thus operated in the dense-phase region of the phase diagram which removes any concern over multi-phase issues such as slugging or other intermittent flow as multiple phases cannot exist. It should be noted that this does not avoid issues such as entrained solids or other injected chemicals which are not accounted for in the phase envelope ✓₅

[5/5]

d) Upon arrival to the processing plant, the process C→D is carried out. Explain why this is performed and how the process might be carried out, particularly if energy use is to be minimized. **[5 marks]**

Solution:

The pressure is dropped upon entry to the plant to cause auto-refrigeration into the multi-phase region of the phase diagram. This allows a separation to "lean" the gas phase by knocking out the heavier, less volatile, hydrocarbons. This can be carried out using a Joule-Thomson valve, but for better energy efficiency a turbo-expander system would be used as the gas is typically recompressed for further transport. ✓₅

[5/5]

[Question total: 20 marks]

Q.2   **Question 2**
Fluid flow

a) For a centrifugal compressor describe the condition known as surge. **[4 marks]**
Solution:

Surge is when the compressor reaches its upper limits in pressure ratio and lower limit in flow rate. The compressor blades clear the working gas around themselves and spin free. This prevents the compressors forming a back pressure to inhibit reverse flow. Reverse flow begins and causes an oscillation as it re-enters the compressor which again begins to provide back pressure. ✓₄

[4/4]

b) Describe the concept of equivalent length as used in piping system pressure drop calculations. **[2 marks]**
Solution:

Equivalent length is used to calculate pressure drop arising from fittings and other flow features into an equivalent length of straight pipe pressure drop. ✓₂

[2/2]

c) A polymer gel (density ρ = 1000 kg m^{-3} and viscosity μ = 0.01 Pa s) injection system is sketched below which has an inner diameter of 0.1 m. A volumetric flow of 10,000 barrel day^{-1} is required. This is supplied to each well separately in sequence, so consider the two flow paths separately and at the full flowrate of 10,000 barrel day^{-1}. Calculate the pressure drops required to each well-head (B and C) assuming the pipe walls are smooth. Additional required information is available in Table 1 of the datasheet. **[10 marks]**
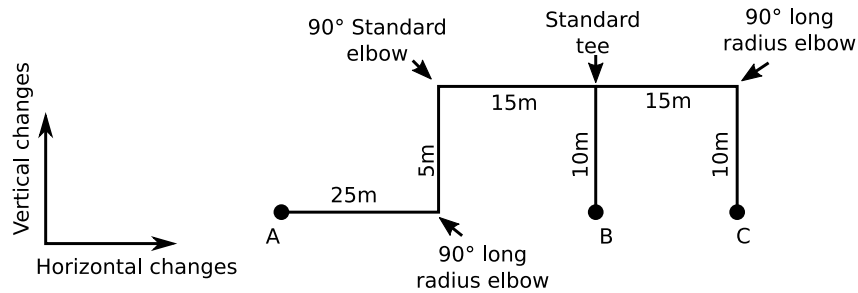

Figure 2: *The flow diagram for the water injection system, and the pipeline. Please note the difference between vertical height changes and horizontal distance changes.*

Solution:

The volumetric flow is

$$10000 \times 0.159/24/3600 = 0.0184 \text{ m}^3 \text{ s}^{-1}$$

[1/10] The pipe cross sectional area is

$$\pi \times 0.1^2/4 = 0.00785 \text{ m}^2$$

[1/10] Thus the average velocity is

$$0.0184/0.00785 = 2.343 \text{ m s}^{-1}$$

[1/10] The Reynolds number is then

$$\text{Re} = 1000 \times 2.343 \times 0.1/0.01 = 23431$$

[1/10]

This is turbulent, thus the blasius correlation is appropriate.

$$f = 0.316 \times 23431^{-0.25} = 0.0255$$

[1/10]

The pipeline lengths are 55 m (A→B) and 70 m (A→C). The connections for (A→B) are 110 L/D giving a total equivalent length of 66 m. The connections for (A→C) are

[1/10] 90 L/D giving a total equivalent length of 79 m.

The frictional pressure loss per length of pipe is as follows:

$$\frac{\Delta p}{L} = 1000 \times 0.0255 \times 2.343^2/2/0.1 = 701 \text{ Pa m}^{-1}$$

[1/10]   ✓
         1

[1/10] This gives an overall frictional pressure loss of $701 \times 66 = 46300$ Pa (A→B) and $701 \times 79 = 55400$ Pa (A→C). ✓
                1

[1/10] The overall height change for both lines is -5 m, thus the hydrostatic pressure loss is $1000 \times 9.81 \times (-5) = -49050$ Pa. ✓
                1

[1/10] In total the pressure requirements are $46300 - 49050 = -2780$ Pa (A→B) and $55400 - 49050 = 6338$ Pa (A→C). ✓
                1

d) What equipment is required to maintain the required flowrate to each well? **[4 marks]**

Solution:

[4/4] Expecting a sensible answer in-line with their results above. For the correct pressure values a pump is required at point A to add an additional 6338 Pa for injection into well C, but a control valve is required at point B to limit the flowrate as siphoning is occuring here. In practice both wells need control valves to control the flow into each well. ✓
              4

[Question total: 20 marks]

Q.3 | **Question 3**
Multi-phase flow

a) Describe how gas introduced into the bottom of a well might increase the flow of oil. **[4 marks]**
   Solution:

   For the flowing oil well, pressure is lost by friction and elevation losses. If the pressure loss can be reduced the oil flow will increase. Introducing gas reduces the density of the fluid column hence elevation losses ($\rho\, g\, h$) are reduced. Provided the effects of increased friction loss due to the extra gas are less than the benefits achieved by reducing density, then overall the pressure loss will be less from the introduced gas hence increased flow.

b) Describe severe slugging and the underlying conditions which promote its appearance in a pipeline with a vertical riser system. **[6 marks]**
   Solution:

   First, there must be a possiblity of forming liquid blocks at the base of the riser. This is only possible if the hydrostatic pressure rise from a blockage is faster than the compression pressure rise for the gas behind the block$\checkmark_2$. This is mathematically expressed as follows,

   $$\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_{riser/hydro.} > \left(\frac{\mathrm{d}p}{\mathrm{d}t}\right)_{flowline/gas-compression}$$

[2/6]

[1/6] $\checkmark_1$The ratio of these two values is also known as the severe slugging number$\checkmark_1$.

[1/6] Second, there must be a low point at the riser foot to allow for liquid accumulation$\checkmark_1$.

[1/6] Third, the pipeline must not already be operating in the slug flow region (as slugs

[1/6] would clear any forming liquid blockages)$\checkmark_1$.

c) A downward sloping, 1000 m long pipeline with an internal diameter of 0.292 m joins a 100 m long vertical pipe (riser) of the same diameter. The pipeline contains oil, gas and water flowing at an average pressure of 20 bara. The flow rates are: Oil = 0.009 m^3 s^{-1}, Water = 0.009 m^3 s^{-1}, and Gas = to be determined.

   The oil and water densities are 800 and 1000 kg m^{-3} respectively. Determine the gas rate at which the system will start the cycle of severe slugging. **[10 marks]**

   Solution:

   At the onset of severe slugging the rate of pressure rise due to vertical pipe filling with liquid will be equal to rate of pressure rise of the gas bubble.

   Calculate the rate of pressure rise in the vertical riser.

[1/10]   Mean liquid density $0.5 \times 1000 + 0.5 \times 800 = 900$ kg m^{-3} $\checkmark_1$.

[1/10]   The volume rate of liquid is $0.009 + 0.009 = 0.018$ m^3 s^{-1} $\checkmark_1$.

[1/10]   CSA of riser is $3.14 \times 0.292^2/4 = 0.067$ m^2 $\checkmark_1$.

[1/10]   Liquid velocity in riser is $0.18/0.067 = 0.27$ m s^{-1} $\checkmark_1$.

[1/10]   Hence dP/dt in riser is $900x9.81x0.27 = 2384$ Pa s^{-1} $\checkmark_1$.

At the onset of severe slugging the dP/dt in riser equals dP/dt of the flowline gas bubble.

[1/10]   Gas rate is X m^3 s^{-1} $\checkmark_1$.

[1/10]   Fraction of gas in flowline is $X/(X + 0.009 + 0.009)$ (assuming no-slip holdup) $\checkmark_1$.

[1/10]   Volume of gas in downward sloping flowline is $V_{slope} = X/(X+0.018) \times 0.067 \times 1000 = 67\,X/(X + 0.018)$ v/v $\checkmark_1$.

Assume ideal gas law. Increase in gas bubble pressure will be proportional to volume percent of gas added (X m^3 s^{-1}).

[1/10] dP/dT gas bubble is $X/V_{slope} \times p = X/(67\,X/(X + 0.018)) \times 20 = (X + 0.018)x20/67$ bar s^{-1} $\checkmark_1$.

At the onset of severe slugging the rate of pressure rise due to vertical pipe filling with liquid will be equal to rate of pressure rise of the gas bubble.

[1/10]   Hence, $(X + 0.018) \times 20/67 \times 100000 = 2384$ and $X = 0.062$ m^3 s^{-1} which is the gas rate at which severe slugging may occur $\checkmark_1$.

[Question total: 20 marks]

Q.4   **Question 4**
Hydrates/dehydration

a) Describe hydrates and the main conditions necessary for hydrate formation. Why is hydrate formation a concern for transportation and process systems? **[4 marks]**
Solution:

[4/4]   Hydrates are formed by a combination of small hydrocarbon molecules - methane to butane, H2S and CO2 - and water. The solid crystals formed can lead to flow restrictions and blockages. This could result in an unsafe situation and/or a loss of production. Their formation is favoured by high pressure and low temperature. $\checkmark_4$

b) Hydrate formation can be calculated using K charts, an example of which is given in Fig. 3.

Explain how these charts could be used to calculate the hydrate formation pressure at a given temperature for a known mixture of methane, ethane, propane and nitrogen. No chart is available for nitrogen.
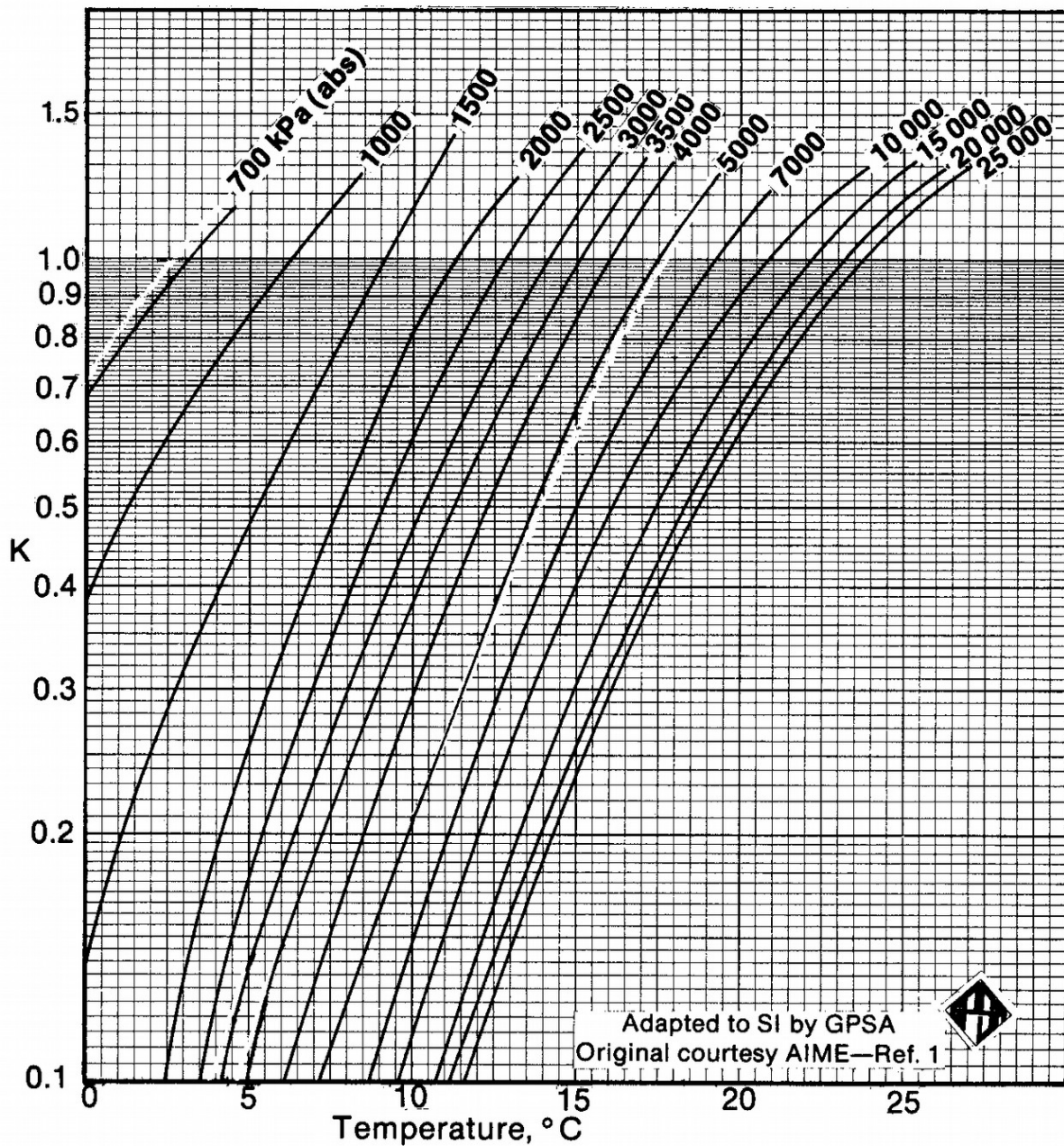
Figure 3: *Hydrate K-value chart for ethane.*

You should note the following relationship for the dewpoint of a hydrocarbon mixture.

$$\sum_{i=1}^{i=N_s} \left(\frac{y_i}{K_{VS,i}} \right) = 1$$

where y_i is the mole fraction of species i and $K_{vs,i}$ is the equilibrium ratio between the gaseous/vapour fraction and the solid hydrate for each component. **[6 marks]**

Solution:

The use of the hydrate charts is analogous to the calculation of a dewpoint for a hydrocarbon mixture. At the dewpoint the above criteria is fulfilled.

Procedure:

(a) Make an initial guess at the hydrate formation pressure.

(b) For methane, ethane and propane estimate the $K_{vs,i}$ from the respective charts

(c) The $K_{vs,i}$ for Nitrogen is infinity as it is not a hydrate former.

(d) Calculate $y_i/K_{vs,i}$ for each component with the term for Nitrogen equal to zero.

(e) Complete the summation, if not equal 1 re-guess formation pressure and repeat.
✓
6

[6/6]

c) To prevent hydrate formation a 2366 Sm^3 h^{-1} gas stream is to be dehydrated using a TEG contactor. The gas enters the dehydrator saturated at 80 bar and 30°C and lean TEG is available at 99% purity. Calculate the exit gas water concentration and the flowrate of TEG required assuming 0.04 m^3 per kg water removed is required. A safety factor of 10°C is also required.

Equilibrium data are available in Fig. 4 and 5.   **[8 marks]**
Solution:

From Fig. 4, saturated gas at 80 bar (8000 kPa) and 30°C has an equilibrium concentration of 550 mg Sm^{-3}. ✓
3

[3/8]

The glycol is available at 99% purity which, according to Fig. 5, has an equilibrium dewpoint of -18°C ✓. Unfortunately a safety factor of 10°C is needed, which implies a
2
equilibrium of -8°C is used for the calculations. ✓
2

[2/8]

[2/8]

Assuming little/no pressure drop in the contactor, the equilibrium wet gas concentration at 80 bar and -8°C is 55 mg Sm^{-3} according to Fig. 4. ✓
1

[1/8]

The total water removal rate is **2366(550 − 55) = 1171170** mg h^{-1}, or 1.17 kg h^{-1} thus **0.04 × 1.17 = 0.0468** m^3 h^{-1} = **1.3 × 10^{-5}** m^3 s^{-1} TEG is required.

d) What TEG purity would be required to dehydrate the gas to 20 mg Sm^{-3}? **[2 marks]**

Solution:

The required dew point is -22.5°C at 8000 kPa. With a safety margin a dewpoint of -32.5°C is required over glycol ✓. At a contactor temperature of **30°C**, this translates
1
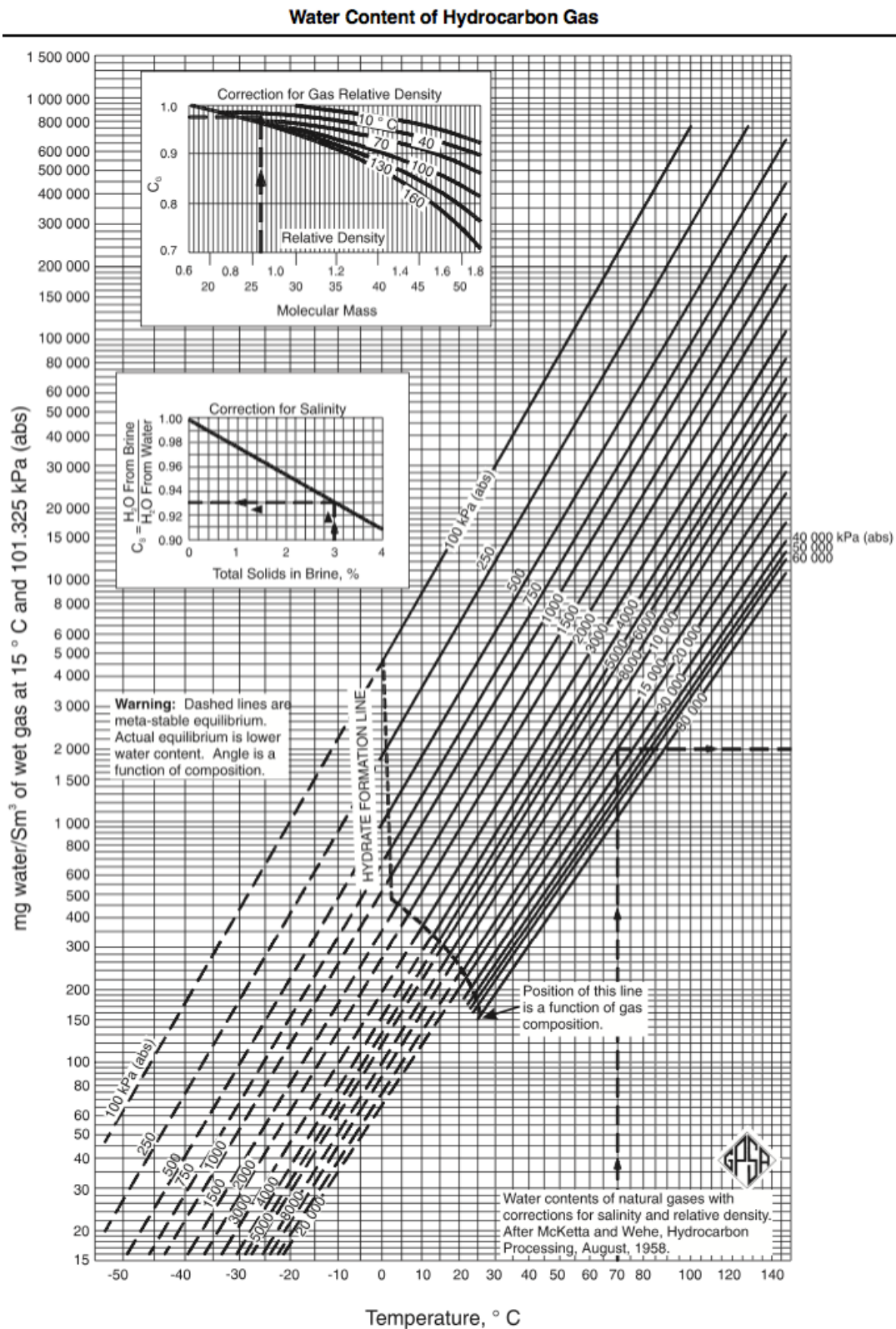to a >99.5% but <99.9% ✓.
1

[1/2]

[1/2]

Figure 4: *Equilibrium chart for wet natural gas including corrections for water salinity and relative molecular weight/density.*

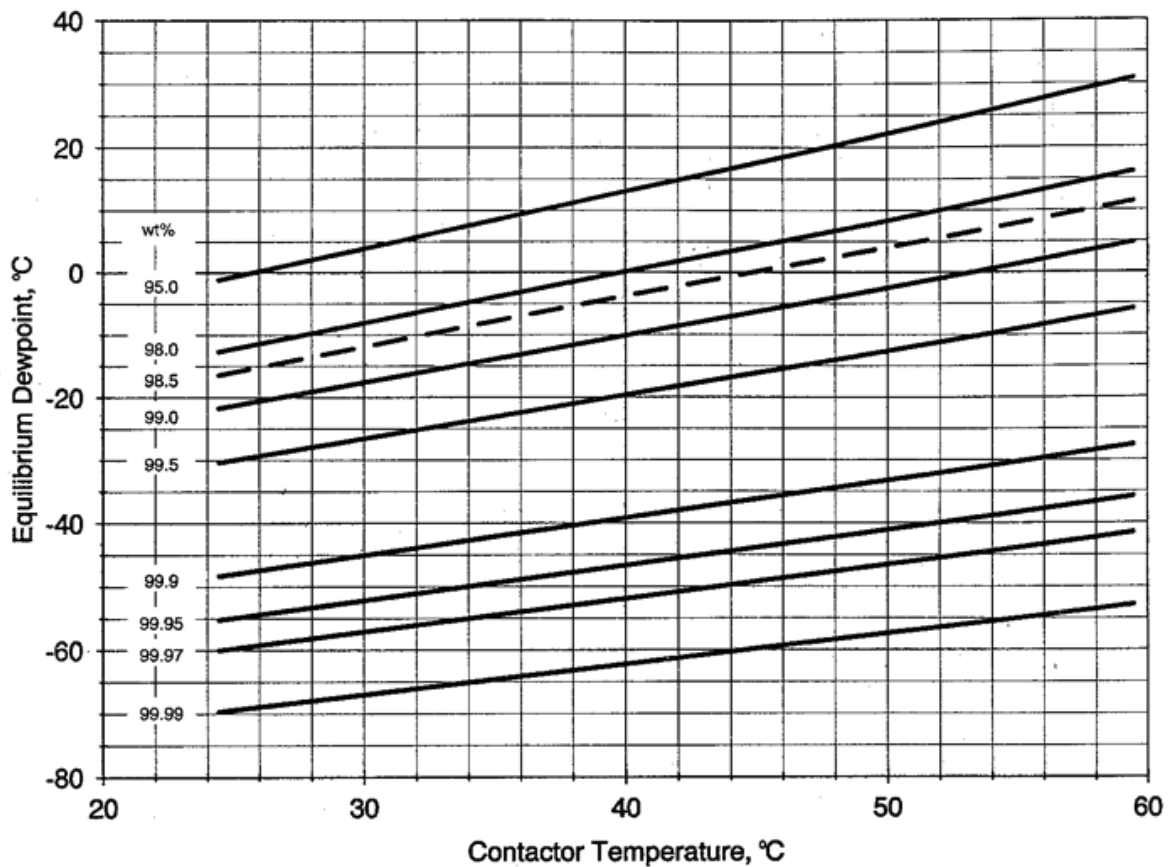**Figure 5:** *Equilibrium correction chart for wet natural gas over TEG solutions.*

[Question total: 20 marks]

Q.5 **Question 5**
Compression/expansion

a) A process gas is to be cooled from 20°C to −35°C using a refrigeration plant. The refrigerant is propane. Using the attached Mollier chart (see Fig. 6) for propane estimate the compressor energy savings between a one and a two stage refrigeration system. Assume air is available at 25°C for condensation. State any other assumptions. Enclose your Mollier chart including your student number with the returned exam booklet. **[14 marks]**
Solution:
Assume a 5°C temperature approach for condensation and evapouration. That means that the propane will have to be compressed to a pressure that corresponds to 25+5 = 30°C. From the Mollier chart that is around 1200 kPa. To cool the process to −35°C requires an evaporator pressure of 120 kPa (−40°C). The Mollier chart can now be
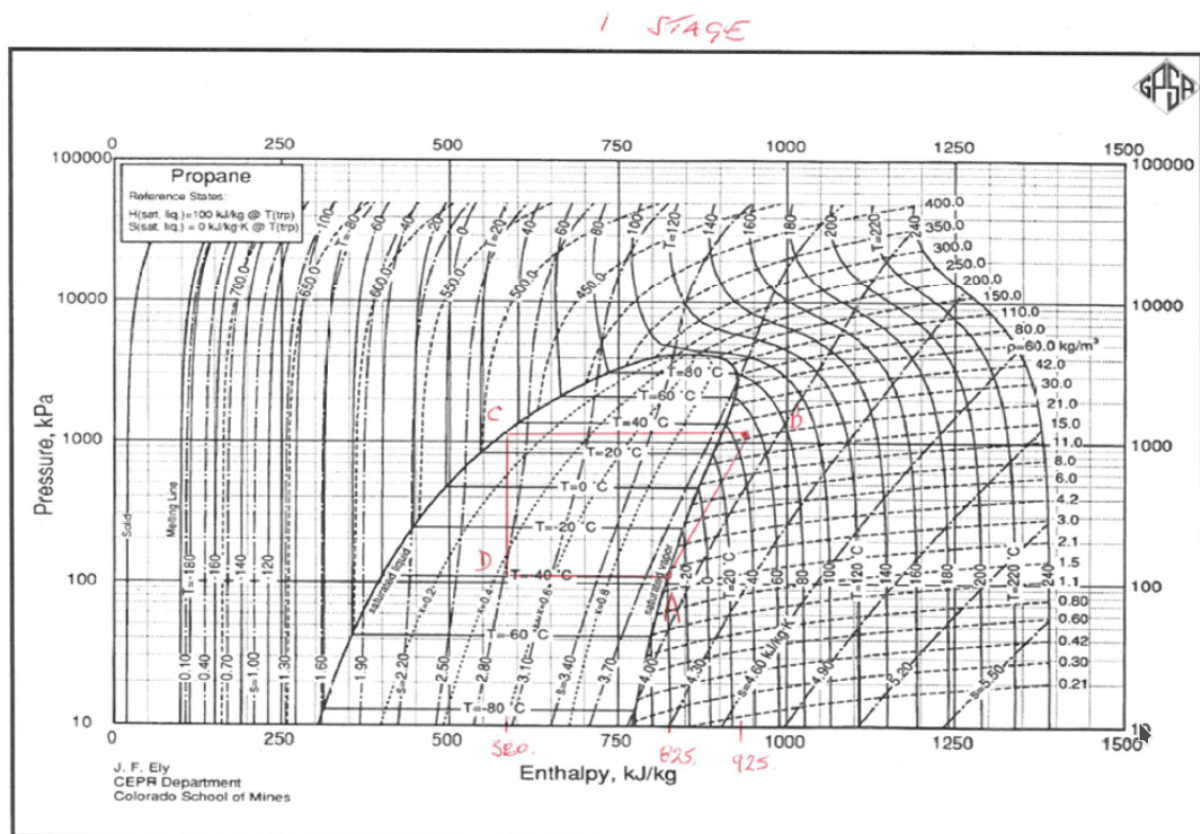**[4/14]** used to complete the one stage refrigeration system$\checkmark_4$.

[1/14] A to B compression - isentropic enthalpy change = $925 - 825 = 100$ kJ kg$^{-1}\checkmark_1$.

[1/14] D to A evapouration duty = 825 − 580 = 245 kJ kg^{-1} $\checkmark_1$.

[1/14] Hence for 1 kJ s^{-1} of heat removed the propane circulation rate will be **1/245** = **0.0041** kg s^{-1} Hence compressor power = **0.0041**x**100** = **0.41** kJ s^{-1} $\checkmark_1$.

Compare to 2 stage refrigeration.

Assume first stage cools process from 20 to −7.5°C.

To cool the process to −7.5°C requires evaporator pressure of 350 kPa (−12.5°C). The Mollier chart can now be used to complete the first stage of the two stage refrigeration

[2/14] system$\checkmark_2$.

[1/14] A to B compression âĂŞ isentropic enthalpy change = 925 − 850 = 75 kJ kg^{-1} $\checkmark_1$.

[1/14] D to A evapouration duty = 850 − 590 = 260 kJ kg^{-1} $\checkmark_1$.

[1/14] Assume each stage of the two stage process removes half the heat of the one stage system 0.5 kJ s^{-1} of heat removed $\checkmark_1$.

Then the propane circulation rate will be **0.5/260** = **0.0019** kg s^{-1}.

Hence compressor power = **0.0019**x**75** = **0.085** kJ s^{-1}.

The second refrigeration stage will be as the one stage process but the heat removed will be **0.5** kJ s^{-1} so the compressor power will be **0.5**x**0.41** = **0.205** kJ s^{-1}.

[1/14] Total power for two stages = 0.205 + 0.085 = 0.29 kJ s^{-1} $\checkmark_1$.

[1/14]   So 2 stages is **0.29/0.41x100 = 70%** of 1 stage power✓.

b) State and explain six factors in deciding whether to use a one or two stage refrigeration system. **[6 marks]**
   Solution:

[6/6]   (1 mark each)✓

(1) Capital cost - two stages more costly - key for economic decision.

(2) Operating cost - two stage uses less energy - key for economic decision.

(3) Availability - two stage is more likely to suffer breakdowns as there is more equipment.

(4) Revenue - key for economic decision.

(5) Safety - two stage has double the amount of leak paths.

(6) Environment - two stage has improved carbon footprint.

[Question total: 20 marks]

If you use this graph, you must attach it to your exam booklet using the provided tag.
<u>**Student ID:**</u>
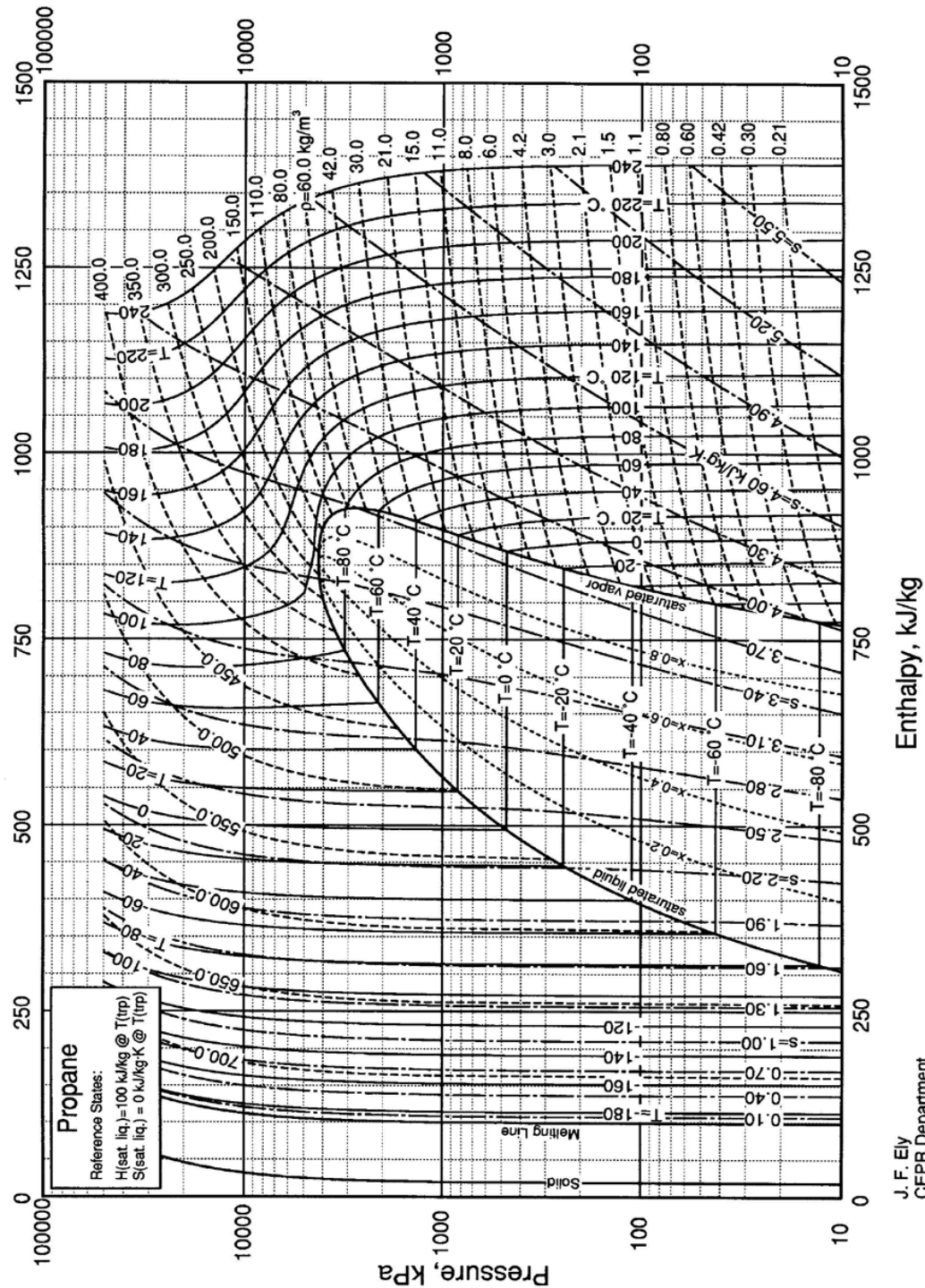
Figure 6: *A Mollier chart for propane.*

END OF PAPER

Total Paper Marks:100

Unit conversions

1 US barrel = 42 US gallons = 0.159 m^3

1 ft = 12 in = 0.3048 m

1 lb = 0.453592 kg

$^\circ$F = ($^\circ$C $\times$ 9/5) + 32

$^\circ$C = ($^\circ$F $-$ 32) 5/9

Physical constants/properties

Air molecular weight = 29 g mol^{-1}

Darcy's equation

$$\Delta p = \frac{\rho\, f\, L\, v^2}{2\, D}$$

Blasius correlation (turbulent flow)

$$f = 0.316\,\mathrm{Re}^{-0.25}$$

Pipe fitting	Equiv. length (L/D)
90° standard elbow	30
45° standard elbow	16
90° long elbow	20
90° street elbow	50
45° street elbow	26
Square corner elbow	57
Standard tee (flow through run)	20
Standard tee (flow through branch)	60
Close pattern return bend	50

Table 1: *A list of equivalent lengths for single phase fluid flow calculations.*