# National Exams December 2018

## 10-Met-A1, Metallurgical Thermodynamics

### 3 hours duration

**NOTES:**

1. Answer only **five** questions. Any five questions (out of seven) constitute a complete paper. Only the first five questions as they appear in your answer book will be marked.

2. All questions are of equal value (20 marks each out of 100).

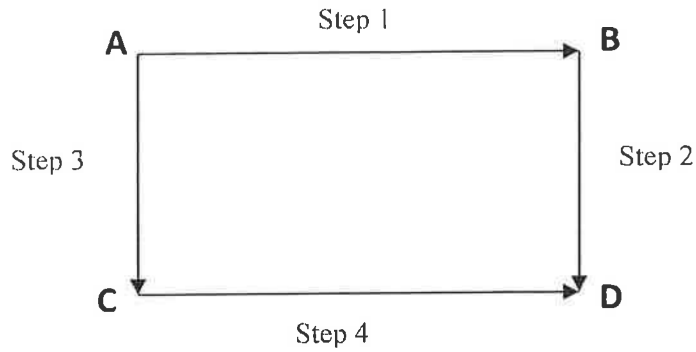
3. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper a clear statement of any assumptions made.

4. Candidates may use one of two calculators, the Casio or Sharp approved models. This is a closed book exam.

5. The exam consists of 5 pages including Ellingham diagram.

Question 1: (a) 4, (b) 4, (c) 4, (d) 4, (e) 2, (f) 2
Question 2: 20
Question 3: (a) 10, (b) 10
Question 4: (a) 8, (b) 12
Question 5: (a) 4, (b) 4, (c) 4, (d) 4, (e) 4
Question 6: (a) 5, (b) 5, (c) 5, (d) 5
Question 7: (a) 4, (b) 4, (c) 4, (d) 4, (e) 2, (f) 2

**Problem No. 1 (20 marks):** 1 mol of a monatomic ideal gas is taken from state A ($P_A$ = 100 kPa, $V_A$= 10 L) to state D ($P_D$ = 50 kPa, $V_D$ = 30 L) by two different paths as shown below:




Path 1: Step 1: State A ($P_A$ = 100 kPa, $V_A$= 10 L) to state B ($P_B$ = 100 kPa, $V_B$= 30 L)
Step 2: State B ($P_B$ = 100 kPa, $V_B$= 30 L) to state D ($P_D$ = 50 kPa, $V_D$ = 30 L)

Path 2: Step 3: State A ($P_A$ = 100 kPa, $V_A$= 10 L) to state C ($P_C$ = 50 kPa, $V_C$ = 10 L)
Step 4: State C ($P_C$ = 50 kPa, $V_C$ = 10 L) to state D ($P_D$ = 50 kPa, $V_D$ = 30 L)

(a) Calculate heat flow in the system (q), work done on the system (w), change in internal energy of the system ($\Delta E$) and change in enthalpy of the system ($\Delta H$) for Step 1. (4 marks)
(b) Calculate heat flow in the system (q), work done on the system (w), change in internal energy of the system ($\Delta E$) and change in enthalpy of the system ($\Delta H$) for Step 2. (4 marks)
(c) Calculate heat flow in the system (q), work done on the system (w), change in internal energy of the system ($\Delta E$) and change in enthalpy of the system ($\Delta H$) for Step 3. (4 marks)
(d) Calculate heat flow in the system (q), work done on the system (w), change in internal energy of the system ($\Delta E$) and change in enthalpy of the system ($\Delta H$) for Step 4. (4 marks)
(e) Calculate heat flow in the system (q), work done on the system (w), change in internal energy of the system ($\Delta E$) and change in enthalpy of the system ($\Delta H$) for Path 1. (2 marks)
(f) Calculate heat flow in the system (q), work done on the system (w), change in internal energy of the system ($\Delta E$) and change in enthalpy of the system ($\Delta H$) for Path 2. (2 marks)

**Problem No. 2 (20 marks):**

Calculate $\Delta S^o_R$ for the reaction $CO(g) + \frac{1}{2} O_2(g) = CO_2(g)$ at 500 K given the following data:

$S^o_{298K}$ (CO, g) = 197.7 J $K^{-1}$ $mol^{-1}$

$S^o_{298K}$ ($CO_2$, g) = 213.7 J $K^{-1}$ $mol^{-1}$

$S^o_{298K}$ ($O_2$, g) = 205.1 J $K^{-1}$ $mol^{-1}$

$C_p$ (CO, g) in J $K^{-1}$ $mol^{-1}$ = $31.1 - 1.5 \times 10^{-2}\, T + 3.1 \times 10^{-5}\, T^2 - 1.5 \times 10^{-8}\, T^3$

$C_p$ ($CO_2$, g) in J $K^{-1}$ $mol^{-1}$ = $18.9 + 7.9 \times 10^{-2}\, T - 6.8 \times 10^{-5}\, T^2 + 2.4 \times 10^{-8}\, T^3$

$C_p$ ($O_2$, g) in J $K^{-1}$ $mol^{-1}$ = $30.8 - 1.2 \times 10^{-2}\, T + 2.4 \times 10^{-5}\, T^2$

Assume that T is in K for heat capacity data.

**Problem No. 3 (20 marks):**

Assume that $(\partial U/\partial V)_T = 0$ and $(\partial H/\partial P)_T = 0$ for an ideal gas.

(a) Prove that $C_v$ is independent of volume at constant temperature. (10 marks)

(b) Prove that $C_p$ is independent of pressure at constant temperature. (10 marks)

**Problem No. 4 (20 marks):**

(a) A tank contains pure oxygen at a total pressure of 1 atmosphere. Oxygen exists primarily in the diatomic form, but it can exist in monatomic state as well. The equilibrium is governed by the following reaction:

$$\frac{1}{2} O_2 = O$$

If the standard Gibbs energy for the reaction is 187,800 J/mol of monatomic oxygen at 1000 K, what is the composition of the gas at 1000 K? (8 marks)

(b) A tank contains oxygen, hydrogen and water vapor at a total pressure of 1 atmosphere. The equilibrium is governed by the following reaction:

$$H_2 + \frac{1}{2} O_2 = H_2O; \ \Delta G^{o} = -246{,}000 + 54.84T$$

If partial pressure of oxygen is maintained at $1 \times 10^{-10}$ atmosphere at 1750 K, what is the composition of the gas at 1750 K? (12 marks)

**Problem No. 5 (20 marks):**

Given the following data for standard enthalpy of formation at 25 °C:

| Compound | Standard enthalpy of formation |
|---|---|
| $CH_4$ | -75 kJ/mol |
| $C_3H_8$ | -105 kJ/mol |
| $C_6H_{14}$ | -199 kJ/mol |
| $C_8H_{18}$ | -259 kJ/mol |
| $CO_2$ | -394 kJ/mol |
| $H_2O$ | -286 kJ/mol |

(a) Calculate the heat of combustion per mole of $CH_4$. (4 marks)

(b) Calculate the heat of combustion per mole of $C_3H_8$. (4 marks)

(c) Calculate the heat of combustion per mole of $C_6H_{14}$. (4 marks)

(d) Calculate the heat of combustion per mole of $C_8H_{18}$. (4 marks)

(e) Which fuel generates highest amount of heat per unit weight of the fuel. (4 marks)

**Problem No. 6 (20 marks)**

Consider a galvanic cell based on the following reaction:

$$Zn\ (s) + Fe^{2+}\ (aq) \longrightarrow Zn^{2+}\ (aq) + Fe\ (s) \qquad (1)$$

(a) Calculate the standard cell potential (E°) at 25°C (5 marks)

(b) Calculate the standard free energy ($\Delta G^o$) for the cell at 25°C. (5 marks)

(c) Calculate the equilibrium constant for the redox reaction at 25°C. (5 marks)

(d) Calculate the cell potential (E) at 25°C, if concentration of $Fe^{2+}$ is 0.5 M and concentration of $Zn^{2+}$ is 2.0 M. (5 marks)

Given: Standard reduction potentials at 25°C for half reactions:

$Zn^{2+} + 2\,e^- \longrightarrow Zn\ (s)$ -0.76 V

$Fe^{2+} + 2\,e^- \longrightarrow Fe\ (s)$ -0.44 V

**Problem No. 7 (20 marks)**

Use the attached Ellingham Diagram to answer the following questions:

a) What is the partial pressure of oxygen in equilibrium with Mn and MnO at 900 °C? (4 marks)

b) What is the ratio of partial pressures of CO to $CO_2$ for equilibrium of Mn and MnO in a CO-$CO_2$ atmosphere at 900 °C? (4 marks)

c) What is the ratio of partial pressures of $H_2$ to $H_2O$ for equilibrium of Mn and MnO in a $H_2$-$H_2O$ atmosphere at 900 °C? (4 marks)

d) What is $\Delta G^o$ (kJ/mol) at 800 °C for the reaction: Ca + MgO = CaO + Mg? (4 marks)

e) What is the melting point of Ca? (2 marks)

f) What is the boiling point of Ca? (2 marks)

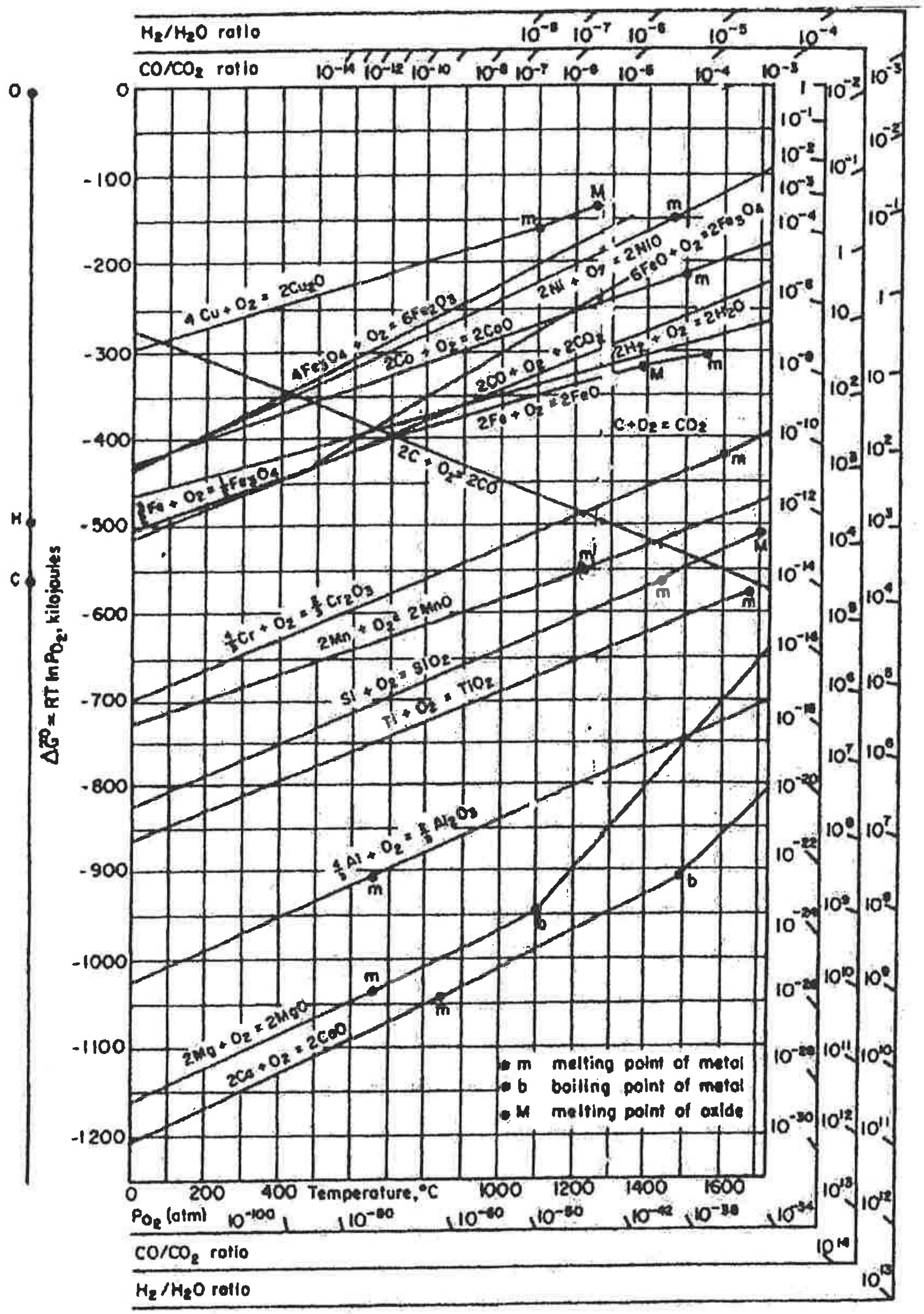



Figure 9–3. Ellingham diagram for some oxides; Richardson nomographic scales are included. (Adapted from D. R. Gaskell, *Introduction to Metallurgical Thermodynamics*, 2nd ed., Hemisphere Publishing, New York, 1981.)