End of topic questions

Topic review

1. Using your knowledge from the *Reactivity 2.1* topic, answer the guiding question as fully as possible:

   How are chemical equations used to calculate reacting ratios?

Exam-style questions

Multiple-choice questions

2. Pyrite, FeS_2, reacts with oxygen according to the following equation:

   $4FeS_2(s) + 11O_2(g) \rightarrow 2Fe_2O_3(s) + 8SO_2(g)$

   How many grams of $SO_2(g)$ will be produced from 0.25 mol of FeS_2?

   A. 16
   B. 32
   C. 64
   D. 128

3. In which mixture is sulfuric acid the limiting reactant?

   A. 0.10 mol H_2SO_4 + 0.20 mol KOH
   B. 0.20 mol H_2SO_4 + 0.10 mol KOH
   C. 0.10 mol H_2SO_4 + 0.20 mol $Ca(OH)_2$
   D. 0.20 mol H_2SO_4 + 0.10 mol $Ca(OH)_2$

4. What is the percentage yield when 18 dm^3 of ethane, $C_2H_6(g)$, is produced from 20 dm^3 of ethene, $C_2H_4(g)$? All volumes are measured at STP.

   $C_2H_4(g) + H_2(g) \rightarrow C_2H_6(g)$

   A. 10%
   B. 20%
   C. 80%
   D. 90%

5. Which of the following expressions gives the atom economy of the synthesis of methanal, HCHO(g), from methanol, $CH_3OH(l)$, if the experimental yield is 100%?

   $CH_3OH(l) + 0.5O_2(g) \rightarrow HCHO(g) + H_2O(l)$

   I $\dfrac{M(\text{HCHO})}{M(\text{CH}_3\text{OH}) + M(\text{HCHO})}$

   II $\dfrac{M(\text{HCHO})}{M(\text{CH}_3\text{OH}) + 0.5 \times M(\text{O}_2)}$

   III $\dfrac{M(\text{HCHO})}{M(\text{HCHO}) + M(\text{H}_2\text{O})}$

   A. I and II only
   B. I and III only
   C. II and III only
   D. I, II and III

Extended-response questions

6. Potassium superoxide, $KO_2(s)$, is used to regenerate oxygen from the carbon dioxide exhaled by the crew of a submarine or spacecraft.

   a. Formulate the balanced equation for the reaction between potassium superoxide and carbon dioxide that produces oxygen and potassium carbonate, $K_2CO_3(s)$.
   b. Deduce the limiting reactant in the reaction of 28.44 g of potassium superoxide and 6.81 dm^3 (STP) of carbon dioxide.
   c. Calculate the mass, in g, of potassium carbonate and the volume, in dm^3 at STP, of oxygen produced in this reaction.

7. Chlorine gas is produced in the laboratory by the reaction of hydrochloric acid, HCl(aq), with manganese(IV) oxide, $MnO_2(s)$:

   $MnO_2(s) + 4HCl(aq) \rightarrow MnCl_2(aq) + Cl_2(g) + 2H_2O(l)$

   A 17.4 g sample of manganese(IV) oxide was added to 0.100 dm^3 of 10.0 mol dm^{-3} hydrochloric acid, and the mixture was heated until the reaction was complete.

   a. Deduce the limiting reactant in this experiment.
   b. Calculate the volume, in dm^3 at STP, of chlorine gas produced.
   c. Calculate the molar concentrations, in mol dm^{-3}, of all solutes in the final solution. Assume that the volume of the solution did not change during the reaction.

8. A 10.0 cm^3 sample of a solution with unknown concentration of barium hydroxide, $Ba(OH)_2(aq)$, was titrated with 0.100 mol dm^{-3} hydrochloric acid, HCl(aq), in the presence of an acid–base indicator. The colour change was observed when 11.7 cm^3 of the standard solution was added.
   a. Formulate the balanced equation for the neutralization if the reaction products are barium chloride, $BaCl_2(aq)$, and water.
   b. Determine the concentration, in mol dm^{-3}, of barium hydroxide in the analysed solution.

9. The thermal decomposition of sodium hydrogencarbonate, $NaHCO_3(s)$, produces sodium carbonate, $Na_2CO_3(s)$, carbon dioxide and water.
   a. Formulate the balanced equation for this reaction.
   b. Calculate the theoretical yield, in g, of carbon dioxide produced by the decomposition of 10.0 g of sodium hydrogencarbonate.
   c. The decomposition of 10.0 g of sodium hydrogencarbonate produced 1.20 dm^3 (STP) of carbon dioxide. Calculate the theoretical yield, in dm^3, of carbon dioxide and its percentage yield in this reaction.
   d. Calculate the masses of solid substances in the final mixture obtained in part **c**.

10. Copper(I) sulfide, Cu_2S, is found in nature as the mineral *chalcocite*, which is a major component of copper ores. At high temperatures, chalcocite reacts with oxygen to produce copper metal and sulfur dioxide, $SO_2(g)$.
   a. Formulate the balanced equation for the reaction of copper(I) sulfide with oxygen.
   b. Determine the theoretical yield, in kg, of copper metal that could be obtained from 1.00 ton (1000 kg) of an ore that contains 75.3% of chalcocite. Assume that other components of the ore are unreactive.
   c. Using your answer to part **b**, determine the percentage yield of copper metal if its practical yield is 506 kg.

11. Calculate the atom economy for the following reactions, assuming that the organic compound is the target product in each case.
   a. $CH_3CH_2OH(l) \rightarrow H_2C{=}CH_2(g) + H_2O(l)$
   b. $6CO_2(g) + 6H_2O(l) \rightarrow C_6H_{12}O_6(aq) + 6O_2(g)$
   c. $nH_2C{=}CH_2(g) \rightarrow \left[CH_2{-}CH_2\right]_n(s)$

12. Nitrogen dioxide, $NO_2(g)$, can be synthesized from nitrogen monoxide, NO(g), and oxygen.
   a. Formulate the balanced equation for this reaction.
   b. Calculate the theoretical atom economy for the equation from part **a**.
   c. In a particular experiment, 1.00 dm^3 of nitrogen monoxide was mixed with 1.00 dm^3 of oxygen to produce 0.700 dm^3 of nitrogen dioxide. Calculate the theoretical yield, in dm^3, and the percentage yield of nitrogen dioxide.
   d. Calculate the actual atom economy for the synthesis in part **c**.

End of topic questions

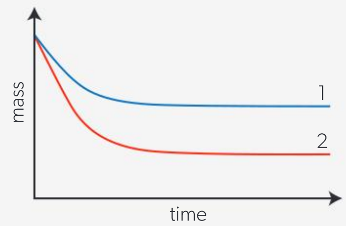
Topic review

1. Using your knowledge from the *Reactivity 2.2* topic, answer the guiding question as fully as possible:
   How can the rate of a reaction be controlled?

Exam-style questions

Multiple-choice questions

2. Excess magnesium powder was added to a beaker containing dilute hydrochloric acid. The mass of the beaker and its contents was recorded and plotted against time (figure 27, curve 1).



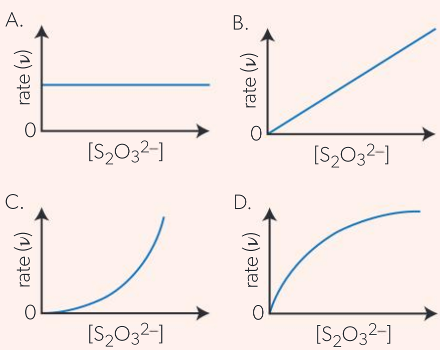
◀ Figure 27 Mass of the beaker as a function of time

Which change could produce curve 2 in figure 27?

A. Increasing the temperature
B. Using the same mass of Mg ribbon
C. Doubling the mass of powdered Mg
D. Using the same volume of concentrated HCl(aq)

AHL

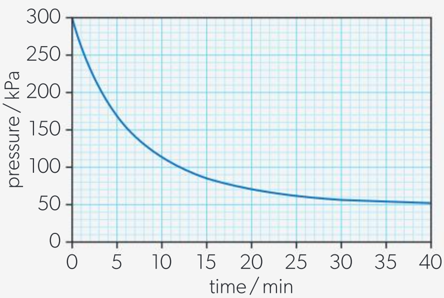
3. Thiosulfate ions, $S_2O_3^{2-}$(aq), are oxidized by hydrogen peroxide, H_2O_2(aq), as follows:
   $H_2O_2(aq) + 2S_2O_3^{2-}(aq) + 2H^+(aq) \rightarrow S_4O_6^{2-}(aq) + 2H_2O(l)$
   Which graph is consistent with the experimentally determined rate equation, $v = k[H_2O_2][S_2O_3^{2-}]$?



Extended-response questions

4. The questions below refer to the experiments described in question 2.
   a. Explain the shape of curve 1 from figure 27 in terms of the collision theory.
   b. Using the same graph, sketch the third curve that would be produced if the original experiment were run at a lower temperature.
   c. Using a different graph, sketch the concentration of Mg^{2+}(aq) ions against time for experiments 1 and 2.

5. Calcium oxide reacts with carbon dioxide as follows:
   $CaO(s) + CO_2(g) \rightarrow CaCO_3(s)$
   Excess calcium oxide was placed into a pressurized vessel with a volume of 1.00 dm^3. The vessel was filled with gaseous carbon dioxide and sealed off. A constant temperature of 25.0 °C was maintained during the whole experiment. The plot of the pressure inside the vessel against time is shown below.



   a. Using the ideal gas law (*Structure 1.5*), calculate the concentrations of CO_2(g) in the vessel at $t = 0, 5, 10, \ldots, 40$ min. Assume that the volume occupied by solid substances is negligible.
   b. Calculate the average reaction rate, in mol dm^{-3} min^{-1}, for the period between 0 and 20 min.
   c. Plot the concentration of carbon dioxide against time on graph paper.
   d. Using the tangent line method, determine the initial reaction rate and the instantaneous reaction rate at $t = 10$ min.

6. Consider the following process:
   $3I^-(aq) + H_2O_2(aq) + 2H^+(aq) \rightarrow I_3^-(aq) + 2H_2O(l)$
   Over a period of 2.0 min, the concentration of iodide ions in the solution decreased from 0.050 to 0.020 mol dm^{-3}.

a. Calculate:
   i. average reaction rates, in $mol\,dm^{-3}\,s^{-1}$, with respect to $I^-(aq)$ and $H_2O_2(aq)$
   ii. overall average reaction rate expressed in the same units.

b. Sketch a graph to show the changes in concentrations of $I^-(aq)$, $H_2O_2(aq)$ and $I_3^-(aq)$ over time. Assume that the initial concentrations of $I^-(aq)$ and $H_2O_2(aq)$ were equal, and the initial concentration of $I_3^-(aq)$ was zero.

c. Suggest how the change in concentration of iodine, $I_2(aq)$, could be monitored.

d. The experiment was repeated with the following changes:
   i. the concentration of $H_2O_2(aq)$ was doubled at constant temperature
   ii. the reaction was carried out in a pressurized vessel at 200 kPa instead of 100 kPa
   iii. the temperature of the reaction mixture was lowered by 5 °C
   iv. the solution of iodide ions, $I^-(aq)$, was prepared from a fine powder of sodium iodide, NaI(s), instead of large crystals of this compound.

For each of the changes, predict, stating a reason, its effect on the rate of reaction.

7. Phosgene, $COCl_2$, is usually produced by the reaction between carbon monoxide, CO, and chlorine, Cl_2, according to the equation:

$CO(g) + Cl_2(g) \rightarrow COCl_2(g) \quad \Delta H_r = -108\ kJ\,mol^{-1}$

a. Sketch the potential energy profile for the synthesis of phosgene, indicating both the enthalpy of reaction and the activation energy.

b. This reaction is normally carried out using a catalyst. Sketch a second curve labelled “catalysed” on the diagram to indicate the effect of the catalyst.

c. Sketch a Maxwell–Boltzmann energy distribution curve for gaseous reactants at a certain temperature.

d. Using your sketch from part **c**, explain the effect of catalyst on the reaction rate.

AHL

8. Nitrogen(II) oxide reacts with chlorine as follows:

$2NO(g) + Cl_2(g) \rightarrow 2NOCl(g)$

The following experimental data were obtained for this reaction at 260 K:

[NO] / $mol\,dm^{-3}$	$[Cl_2]$ / $mol\,dm^{-3}$	ν_{init} / $mol\,dm^{-3}\,min^{-1}$
1.50×10^{-2}	1.50×10^{-2}	5.30×10^{-3}
1.50×10^{-2}	3.00×10^{-2}	1.06×10^{-2}
3.00×10^{-2}	3.00×10^{-2}	4.24×10^{-2}

a. Deduce the reaction orders with respect to $Cl_2(g)$ and NO(g).

AHL

b. State the rate equation and the overall reaction order.

c. Calculate the value of the rate constant at 260 K.

The reaction proceeds in two steps:

step 1 $\quad 2NO(g) \rightarrow N_2O_2(g)$

step 2 $\quad N_2O_2(g) + Cl_2(g) \rightarrow 2NOCl(g)$

d. Using the rate equation deduced in part (b), identify the rate-determining step (RDS) in this reaction.

9. Consider the following two-step reaction mechanism:

step 1 (slow) $\quad N_2O(g) \rightarrow N_2(g) + O(g)$

step 2 (fast) $\quad N_2O(g) + O(g) \rightarrow N_2(g) + O_2(g)$

a. Formulate the equation for the overall reaction.

b. Identify the role (reactant, product or intermediate) of each species involved in the reaction mechanism.

c. Identify the molecularity of the rate-determining step.

d. Deduce the rate equation of the overall reaction and state the overall reaction order.

e. The overall reaction has a ΔH_r value of $-164.1\ kJ\,mol^{-1}$. Sketch the energy profile for this reaction.

10. The rate constants of a certain reaction at 30 and 60 °C are 0.183 and 5.45 $dm^3\,mol^{-1}\,s^{-1}$, respectively.

a. Identify the overall order of this reaction.

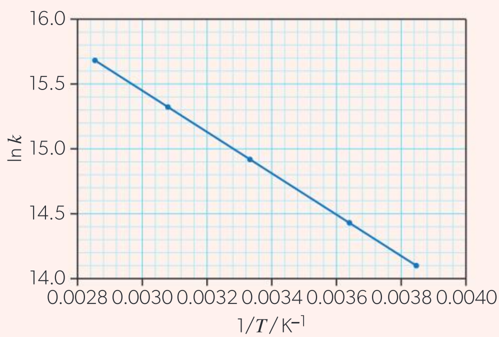
b. Determine the activation energy, in $kJ\,mol^{-1}$, of the reaction.

c. Calculate the rate constant, in $dm^3\,mol^{-1}\,s^{-1}$, of this reaction at 45 °C.

11. Chlorine monoxide, ClO•, is an unstable radical that plays an important role in the process of ozone depletion. In the absence of ozone, chlorine monoxide decomposes as follows:

$2ClO\bullet(g) \rightarrow Cl_2(g) + O_2(g)$

Kinetics studies show that this reaction has the second order with respect to ClO•(g). The plot of ln k against $1/T$ for this reaction is shown below.



a. Determine the activation energy, E_a, in $kJ\,mol^{-1}$, for this reaction.

b. Determine the Arrhenius factor, A, for this reaction and state its units.

End of topic questions

Topic review

1. Using your knowledge from the *Reactivity 2.3* topic, answer the guiding question as fully as possible:

   How can the extent of a reversible reaction be influenced?

Exam-style questions

Multiple-choice questions

2. Which of the following statements is correct?
   A The changes at equilibrium stop only at the microscopic level but not at the macroscopic level.
   B The changes at equilibrium stop at both the macroscopic level and the microscopic level.
   C The rates of both forward and reverse reactions at equilibrium are equal to zero.
   D The equilibrium constant expression can be deduced from the reaction stoichiometry.

3. Which factors increase the rates of both forward and reverse reactions in any system at equilibrium?
   I. Increase in temperature
   II. Increase in pressure
   III. Addition of a catalyst
   A I and II only
   B I and III only
   C II and III only
   D I, II and III

4. What will happen in the following reaction mixture at equilibrium if the pressure decreases?
   $SO_2(g) + H_2O(l) \rightleftharpoons H^+(aq) + HSO_3^-(aq)$
   A The equilibrium position will shift to the left and $[H^+]$ will increase
   B The equilibrium position will shift to the right and $[H^+]$ will increase
   C The equilibrium position will shift to the left and $[H^+]$ will decrease
   D The equilibrium position will shift to the right and $[H^+]$ will decrease

AHL

5. What is true for any system at equilibrium?
   A $K = 1$
   B $Q = 1$
   C $Q = K$
   D $\Delta G^\ominus = 0$

6. For a certain reversible reaction in a closed system, $Q > K$. Which changes will occur when the system will be approaching equilibrium at constant temperature?
   A Q will decrease
   B K will increase
   C Concentrations of reactants will decrease
   D Concentrations of products will increase

7. At 1000 K, the forward reaction has a negative $\Delta G^\ominus$ value:
   $2NO_2(g) \rightleftharpoons 2NO(g) + O_2(g)$
   Which expression is correct for the equilibrium at this temperature?
   A $[NO_2]^2 > [NO]^2[O_2]$
   B $[NO_2] < [NO]$
   C $[NO] = 2[O_2]$
   D $K > 1$

AHL

Extended-response questions

8. Deduce the equilibrium constant expressions for the following reactions.
   a. $3O_2(g) \rightleftharpoons 2O_3(g)$
   b. $2NO_2(g) \rightleftharpoons 2NO(g) + O_2(g)$
   c. $NO_2(g) \rightleftharpoons NO(g) + 0.5O_2(g)$
   d. $CH_3COOH(aq) \rightleftharpoons CH_3COO^-(aq) + H^+(aq)$
   e. $NH_3(aq) + H_2O(l) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$
   f. $CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$

9. At a certain temperature, the K value for reaction **b** from the previous problem is 0.81. Deduce the K value for reaction **c** from the same problem.

10. Consider the following reaction:
    $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$
    The equilibrium concentrations of hydrogen, iodine and hydrogen iodide in the reaction mixture at 760 K were found to be 0.012, 0.015 and 0.091 mol dm^{-3}, respectively.
    a. Deduce the equilibrium constant expression and determine the K value for this reaction at 760 K.
    b. The K value for the same reaction at 715 K is 48.0. Deduce the sign of the standard enthalpy change for the forward reaction.

11. Consider the following reaction:

$$2CO(g) + O_2(g) \rightleftharpoons 2CO_2(g) \quad \Delta H^{\ominus} = -566\ \text{kJ mol}^{-1}$$

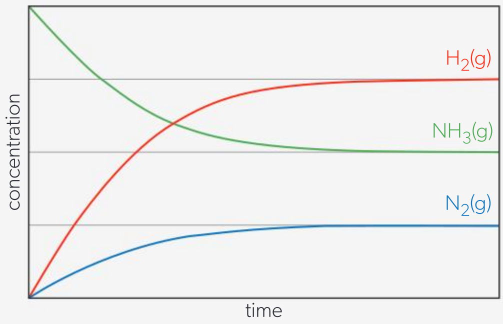
Outline how the following changes will affect the equilibrium position and the K value of this reaction:

a. decrease in pressure
b. increase in temperature
c. increase in concentration of oxygen gas
d. decrease in concentration of carbon monoxide
e. addition of a catalyst

12. At high temperature, ammonia decomposes into nitrogen and hydrogen:

$$2NH_3(g) \rightleftharpoons N_2(g) + 3H_2(g)$$

The progress of this reaction under certain conditions without a catalyst is shown in the graph below.



On a copy of the same graph, sketch the changes in concentrations of $NH_3(g)$, $N_2(g)$ and $H_2(g)$ over time for the same reaction under the same conditions in the presence of a catalyst.

AHL

13. The esterification reaction between ethanoic acid and ethanol proceeds as follows:

$$CH_3COOH(org) + CH_3CH_2OH(org) \rightleftharpoons CH_3COOCH_2CH_3(org) + H_2O(org)$$

A mixture of 1.00 mol of ethanoic acid and 2.00 mol of ethanol was dissolved in an inert organic solvent (designated as "org") to produce 1.00 dm^3 of the solution and heated at 50 °C in the presence of an acid catalyst until equilibrium was reached. The equilibrium mixture contained 1.40 mol of ethanol.

a. Calculate the K value for this equilibrium at 50 °C.
b. Determine the direction of the spontaneous reaction at 50 °C in the mixture containing equal concentrations of all four species participating in this equilibrium.

AHL

14. Benzoic acid, C_6H_5COOH, dissociates in aqueous solutions as follows:

$$C_6H_5COOH(aq) \rightleftharpoons C_6H_5COO^-(aq) + H^+(aq)$$

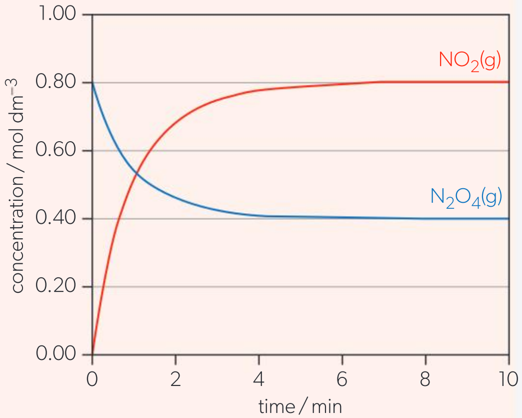
At 298 K, the K value for this equilibrium is 6.31×10^{-5}.

a. Determine the equilibrium concentration, in mol dm^{-3}, of $H^+(aq)$ ions in a 0.0200 mol dm^{-3} solution of benzoic acid at 298 K.
b. Calculate the $\Delta G^{\ominus}$ value, in kJ mol^{-1}, for the forward reaction at 298 K.

15. Consider the equilibrium between two oxides of nitrogen:

$$N_2O_4(g) \rightleftharpoons 2NO_2(g) \quad \Delta H^{\ominus} = +58\ \text{kJ mol}^{-1}$$

The graph below shows the concentrations of both oxides at 320 K as a function of time.



a. State the K expression for this equilibrium and determine the K value at 320 K.
b. Calculate the $\Delta G^{\ominus}$ value, in kJ mol^{-1}, for the forward reaction at 320 K.
c. Determine the direction of the spontaneous reaction at 320 K in the mixture containing 0.50 mol dm^{-3} of $N_2O_4(g)$ and 0.10 mol dm^{-3} of $NO_2(g)$.