K_P VERSUS K_C

1. What are the units of K_p and K_c for each of the following?

a) $2H_2S(g) \rightleftharpoons 2H_2(g) + S_2(g)$

b) $4NH_3(g) + 3O_2(g) \rightleftharpoons 2N_2(g) + 6H_2O(g)$

2. What are the units of K_p and K_c for each of the following?

a) $NH_4HS(s) \rightleftharpoons NH_3(g) + H_2S(g)$

b) $P_4(g) + 5O_2(g) \rightleftharpoons P_4O_{10}(s)$

3. Determine K_c values for the following at 298 K:

a) $N_2O_4(g) \rightleftharpoons 2NO_2(g)$ $K_p = 0.15$ atm

b) $NO_2(g) + NO(g) \rightleftharpoons N_2O_3(g)$ $K_p = 0.86\ atm^{-1}$

4. Determine the value of K_c for each of the following:

a) $SO_2Cl_2(g) \rightleftharpoons SO_2(g) + Cl_2(g)$ $K_p = 2.9\times10^{-2}$ atm at 30 °C

b) $2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$ $K_p = 1.48\times10^{4}\ atm^{-1}$ at 184 °C

5. Determine the value of K_p for each of the following:

a) $CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$ $K_c = 23.2$ at 600 K

b) $2H_2S(g) \rightleftharpoons 2H_2(g) + S_2(g)$ $K_c = 2.3\times10^{-4}$ M at 1405 K

PROPERTIES OF THE EQUILIBRIUM CONSTANT

6. If equal number of moles of reactants are used, do the following equilibrium mixtures contain primarily reactants or products?

a) $HCN(aq) + H_2O(l) \rightleftharpoons CN^{1-}(aq) + H_3O^{1+}(aq)$ $K = 6.2\times10^{-10}$

b) $H_2(g) + Cl_2(g) \rightleftharpoons 2\ HCl(g)$ $K = 2.51\times10^{4}$

7. **a)** Determine K for: $HI(g) \rightleftharpoons {}^1/_2H_2(g) + {}^1/_2I_2(s)$, given $H_2(g) + I_2(s) \rightleftharpoons 2\ HI(g)$ $K = 8.6$

b) Determine K_c for: $2\ SO_2(g) + O_2(g) \rightleftharpoons 2\ SO_3(g)$, given $SO_2(g) + {}^1/_2O_2(g) \rightleftharpoons SO_3(g)$ $K_c = 3.61\ M^{-1/2}$

8. Use the K_p values in Exercise 3 to determine K_p values of the following.

a) $2NO_2(g) \rightleftharpoons N_2O_4(g)$

b) $NO_2(g) \rightleftharpoons {}^1/_2N_2O_4(g)$

c) $2\ NO_2(g) + 2\ NO(g) \rightleftharpoons 2\ N_2O_3(g)$

d) $N_2O_4(g) + 2\ NO(g) \rightleftharpoons 2\ N_2O_3(g)$

9. Given the following:

$2\ NO(g) \rightleftharpoons N_2(g) + O_2(g)$ $K = 2.4\times10^{30}$

$NO(g) + {}^1/_2Br_2(g) \rightleftharpoons NOBr(g)$ $K = 1.4$

Determine K for

${}^1/_2N_2(g) + {}^1/_2O_2(g) + {}^1/_2Br_2(g) \rightleftharpoons NOBr(g)$

10. Given the following information at 1000 K:

$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$ $K_1 = 0.039$

$C(s) + CO_2(g) \rightleftharpoons 2\ CO(g)$ $K_2 = 1.9$

Determine the equilibrium constant at 1000 K for:

$CaCO_3(s) + C(s) \rightleftharpoons CaO(s) + 2\ CO(g)$

11. Lead fluoride dissolves in strong acid by the following reaction:

$PbF_2(s) + 2H_3O^{1+}(aq) \rightleftharpoons Pb^{2+}(aq) + 2HF(aq) + 2H_2O(l)$

a) What is the equilibrium constant *expression* for the reaction?

b) Use the following equilibrium constants to determine the value of the equilibrium constant of the above reaction:

$PbF_2(s) \rightleftharpoons Pb^{2+}(aq) + 2F^{1-}(aq)$ $K_1 = 3.7x10^{-8}$

$HF(aq) + H_2O(l) \rightleftharpoons H_3O^{1+} + F^{1-}(aq)$ $K_2 = 7.2x10^{-4}$

12. Aluminum hydroxide dissolves in strong acid by the following reaction:

$Al(OH)_3(s) + 3H_3O^{1+}(aq) \rightleftharpoons Al^{3+}(aq) + 6H_2O(l)$

a) What is the equilibrium constant *expression* for the reaction?

b) Use the following equilibrium constants to calculate the value of K for the above reaction

$H_3O^{1+}(aq) + OH^{1-}(aq) \rightleftharpoons 2H_2O(l)$ $K_1 = 1.0x10^{+14}$

$Al(OH)_3(s) \rightleftharpoons Al^{3+}(aq) + 3OH^{1-}(aq)$ $K_2 = 1.9x10^{-33}$

13. Equal numbers of moles of Cl_2 and NO are placed in a vessel at some temperature where they reach the following equilibrium:

$2\,NO(g) + Cl_2(g) \rightleftharpoons 2\,ClNO(g)$

Indicate whether each of the following statements about the resulting equilibrium mixture is true, false, or depends upon the value of the equilibrium constant.

a) $[NO] > [ClNO]$ **b)** $[Cl_2] < [NO]$ **c)** $[Cl_2] > [ClNO]$

14. Equal number of moles of NH_3 and N_2 are added to a flask where they equilibrate according to: $2NH_3(g) \rightleftharpoons N_2(g) + 3H_2(g)$. Indicate whether each of the following statements about the resulting equilibrium mixture is true, false, or depends upon the value of the equilibrium constant.

a) $[NH_3] < [H_2]$ **b)** $[H_2] > [N_2]$ **c)** $[NH_3] > [N_2]$

LE CHÂTELIER'S PRINCIPLE

15. What effect (increase, decrease, or no effect) does increasing the volume of the following equilibrium mixtures at constant temperature have on *Q?* What effect does each have on K?

a) $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$ $\Delta H^o = +53$ kJ

b) $3H_2(g) + N_2(g) \rightleftharpoons 2NH_3(g)$ $\Delta H^o = -92$ kJ

c) $N_2O_4(g) \rightleftharpoons 2NO_2(g)$ $\Delta H^o = +58$ kJ

16. What effect does increasing the temperature at constant volume of each of the equilibrium mixtures in Exercise 15 have on *Q* and K?

17. Does increasing the volume of each of the equilibria in Exercise 15 increase the number of moles of reactant, product, or neither?

18. Does increasing the temperature of each of the equilibria in Exercise 15 increase the number of moles of reactant or product?

19. Consider the equilibrium, $NH_3(g) + H_2S(g) \rightleftharpoons NH_4HS(s)$, $\Delta H^o < 0$. Which of the following would *increase* the number of moles of ammonia in the equilibrium mixture?

a) increasing the temperature

b) increasing the volume of the container

c) adding more H_2S gas

d) adding more NH_4HS solid

20. Methanol is manufactured by the following reaction:

$CO(g) + 2\,H_2(g) \rightleftharpoons CH_3OH(g)$ $\Delta H° = -91$ kJ

Does the amount of methanol increase, decrease, or remain the same when an equilibrium mixture is subjected to the following changes?

a) the temperature is increased

b) the volume of the container is decreased

c) CO is added

d) CH_3OH is added

21. Consider the following: $P_4(s) + 6Cl_2(g) \rightleftharpoons 4PCl_3(l)$ $\Delta H < 0$

What happens to the mass of phosphorus in each of the following?

a) the volume is increased **b)** chlorine is removed

c) phosphorus trichloride is added **d)** the mixture is cooled

22. Predict how an increase in temperature will change K for the following chemical reactions:

a) $N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$ $\Delta H° = 181$ kJ

b) $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$ $\Delta H° = -198$ kJ

SOLVING FOR AN UNKNOWN EQUILIBRIUM CONCENTRATION

23. What is the concentration of ammonia in an equilibrium mixture that is 0.015 M in H_2 and 0.250 M in N_2?

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ $K_c = 473\ M^{-2}$

24. What is the equilibrium concentration of hydronium ion in a solution that 0.0867 M HF and 0.108 M F^{1-}?

$HF(aq) + H_2O(l) \rightleftharpoons H_3O^{1+}(aq) + F^{1-}(aq)$ $K_c = 7.2 \times 10^{-4}$ M

25. What is the partial pressure of H_2 if the equilibrium partial pressures of I_2 and HI are 485 torr and 1293 torr, respectively?

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$ $K = 12.0$

26. What is the equilibrium concentration of Pb^{2+} in a solution of $PbCl_2$ that is 0.11 M in chloride ion?

$PbCl_2(s) \rightleftharpoons Pb^{2+}(aq) + 2Cl^{1-}(aq)$ $K_c = 1.7 \times 10^{-5}\ M^3$

DETERMINING THE VALUE OF K

27. A mixture that contains 1.00 mol of NH_3 and 0.400 mol of N_2 in a 5.00-L container is left to equilibrate. At equilibrium, it contains only 0.780 mol of NH_3. The reaction is $2NH_3(g) \rightleftharpoons 3H_2(g) + N_2(g)$

a) What are the equilibrium concentrations of the gases?

b) What is the value of K_c for the reaction shown above?

28. At a particular temperature, a 3.0-L flask contains 3.0 mol HI, 4.0 mol H_2 and 0.25 mol I_2 at equilibrium. Calculate K at this temperature for the reaction: $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

29. Phosgene, a toxic gas used in the synthesis of many organic compounds, decomposes according to the reaction:

$COCl_2(g) \rightleftharpoons CO(g) + Cl_2(g)$

Phosgene is heated in a flask. At a certain temperature, the equilibrium mixture is found to contain 0.050 M CO, 0.050 M Cl_2, and 0.50 M $COCl_2$. What is the value of K_c at this temperature?

30. A sealed container is filled with 5.00 atm of NH_3. What is the equilibrium constant for the following reaction at the temperature of the experiment if the total pressure of all gases is 8.54 atm at equilibrium?

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

31. A sealed container is filled with 1.40 atm of PCl_5 and heated until the PCl_5 decomposes. What is the equilibrium constant for the following reaction at the temperature of the experiment if the total pressure inside the container is 2.60 atm at equilibrium? $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$

32. 8.0 mol NH_3 are placed in a 10.0-L container at some temperature and allowed to equilibrate. At equilibrium, 2.0 moles remained. What is the value of K_c for the following reaction at the temperature of the experiment?

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

33. At some temperature, 0.400 mol NO, 0.300 mol Cl_2 and 0.700 mol ClNO are introduced into a 20.0-L flask and allowed to react. What is the value of K_c for the following reaction at this temperature if the equilibrium mixture contained 0.900 mol ClNO? $2NO(g) + Cl_2(g) \rightleftharpoons 2ClNO(g)$

34. Iron(III) oxalate decomposes as follows:

$Fe_2(C_2O_4)_3 \rightleftharpoons Fe_2O_3(s) + 3CO(g) + 3CO_2(g)$

What is the value of K_p at a temperature where the total pressure of an equilibrium mixture is 0.868 atm?

35. What is the value of K_c for the reaction $2SO_3 \rightleftharpoons 2SO_2 + O_2$ at a temperature where 24.0 % of 0.600 mol·L^{-1} SO_3 decomposes?

36. 4.00 mol CO_2 is placed in a 6.00-L container at a temperature where 12.3% of it decomposes. What is the value of K_c for the following at this temperature? $2CO_2(g) \rightleftharpoons 2CO(g) + O_2(g)$

37. At 2000. °C, water decomposes into hydrogen and oxygen. When 3.00 mol H_2O is heated in a sealed, 5.00-L container to 2000 °C, 2.00% of the water decomposes.

a) What is value of K_c for $2H_2O(g) \rightleftharpoons 2H_2(g) + O_2(g)$ at 2000 °C?

b) What is the value of K_p at this temperature?

c) What is the standard free energy of formation of $H_2O(g)$ at 2000 °C?

38. Sulfuric acid has many uses, making it the most produced chemical in the world (over 150 million tons a year). One of the steps in the manufacture of sulfuric acid is $SO_2(g) + {}^1/_2O_2(g) \rightleftharpoons SO_3(g)$. A sealed flask at 627 °C is loaded with 1.48 atm of SO_2 and 0.74 atm of O_2. After reaction, the equilibrium pressure of SO_3 is found to be 1.10 atm. What is the value of K_p for this reaction at 627 °C?

EQUILIBRIUM COMPOSITION

39. For the reaction: $2HI(g) \rightleftharpoons H_2(g) + I_2(g)$ $K_c = 0.0160$ at 520. °C

Calculate the concentration of all of the gases at equilibrium in a 6.00-L container with the following initial conditions:

a) 0.400 mol HI **b)** 0.200 mol H_2 and 0.200 mol I_2

c) 0.200 mol H_2, 0.200 mol I_2, and 0.400 mol HI

d)* 0.200 mol H_2 and 0.300 mol I_2

e)* 0.100 mol H_2, 0.200 mol I_2, and 0.300 mol HI

40. At a certain temperature, $K = 1.0 \times 10^2$ for the reaction: $H_2(g) + F_2(g) \rightleftharpoons 2HF(g)$.

Calculate the equilibrium concentrations (or pressures) of all species in the equilibrium mixtures produced by mixing the following amounts of gas:

a) 3.0 mol H_2 + 3.0 mol F_2 in a 2.0-L container

b)* 0.20 M H_2 + 0.35 M F_2

c)* 0.80 atm H_2 + 0.60 atm F_2 + 1.00 atm HF

41. An equilibrium mixture is found to contain 1.200 mol each CO_2 and H_2 and 0.155 mol each CO and H_2O. Assume that all substances are gases.

a) What is the equilibrium constant for $CO_2 + H_2 \rightleftharpoons CO + H_2O$?

b) What is the value of the reaction quotient immediately after the addition of 0.800 mol of each gas to this equilibrium mixture? How many moles of each gas are present when equilibrium is reestablished?

42. What is the equilibrium concentration of CN^{1-} ion after mixing the following solutions? Hint: Mixing the solutions dilutes the reactants.

a) mixing 50.0 mL of 0.100 M HCN with 50.0 mL of 0.100 M NH_3?
$NH_3(aq) + HCN(aq) \rightleftharpoons NH_4^{1+}(aq) + CN^{1-}(aq)$ $K = 0.71$

b) mixing 50.0 mL of 0.100 M HCN with 50.0 mL of 0.100 M K_2S?
$S^{2-}(aq) + HCN(aq) \rightleftharpoons HS^{1-} + CN^{1-}(aq)$ $K = 3.1 \times 10^3$

c) mixing 50.0 mL of 0.100 M HCN with 50.0 mL of 0.100 M KF?
$F^{1-}(aq) + HCN(aq) \rightleftharpoons HF + CN^{1-}(aq)$ $K = 5.6 \times 10^{-7}$

43. What is the equilibrium concentration of F^{1-} ion after mixing the following solutions? Hint: Mixing the solutions dilutes the reactants.

a) mixing 75.0 mL of 0.100 M HF with 75.0 mL of 0.100 M NH_3?
$NH_3(aq) + HF(aq) \rightleftharpoons NH_4^{1+}(aq) + F^{1-}(aq)$ $K = 1.3 \times 10^7$

b) mixing 75.0 mL of 0.100 M HF with 75.0 mL of 0.100 M KNO_2?
$NO_2^{1-}(aq) + HF(aq) \rightleftharpoons HNO_2 + F^{1-}(aq)$ $K = 1.8$

c) mixing 75.0 mL of 0.100 M HF with 75.0 mL of 0.100 M K_2SO_4?
$SO_4^{2-}(aq) + HF(aq) \rightleftharpoons HSO_4^{1-} + F^{1-}(aq)$ $K = 0.060$

44.* An aqueous solution is made 1.00 M in $AgNO_3$ and 1.00 M in $Fe(NO_3)_2$ and allowed to come to equilibrium. What are the concentrations of the ions present when equilibrium is established?

$$Ag^{1+}(aq) + Fe^{2+}(aq) \rightleftharpoons Ag(s) + Fe^{3+}(aq) \qquad K = 2.98$$

45.* Consider the following equilibrium at a temperature near 500 K:

$$PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g) \qquad K = 0.650$$

How many moles of PCl_3 would be in the equilibrium mixture produced by

a) placing 3.36 mol PCl_5 into an empty 4.82-L flask?

b) placing 2.68 mol PCl_3 and 3.65 mol Cl_2 into an empty 6.15-L flask?

Use the following equilibrium for Exercises 46 - 49

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g) \qquad K = 0.64$$

46. What are the partial pressures of the gases in an equilibrium mixture produced by the decomposition of HI with an initial pressure of 2.86 atm?

47. What is the concentration of H_2 in an equilibrium mixture formed by the decomposition of 0.100 M HI?

48. 0.40 mol of H_2 and 0.40 mol of I_2 are placed in 1.0-L container and allowed to react. How many moles of HI are in the equilibrium mixture?

49.* How many moles of I_2 are in the equilibrium mixture produced by 0.20 mol H_2 and 0.40 mol HI in a 2.0-L flask?

Use the following equilibrium for Exercises 50 - 53

$$H_2(g) + CO_2(g) \rightleftharpoons H_2O(g) + CO(g) \qquad K = 16.0$$

50. The initial partial pressures of H_2 and CO_2 in a reaction flask are each 1.64 atm. What is the equilibrium pressure of CO? What is the total pressure at equilibrium?

51. If a reaction mixture is 0.200 M H_2, 0.200 M CO_2, 0.400 M CO and 0.400 M H_2O, what will the equilibrium concentrations be?

52. How many moles of CO_2 would be present at equilibrium after 0.200 mol H_2O and 0.200 mol CO equilibrate in a 1.00-L container?

53.* What are the equilibrium concentrations resulting from the equilibration of 0.300 M H_2, 0.500 M CO_2, 0.100 M CO and 0.600 M H_2O?

HOW MUCH TO ADD OR REMOVE

54. An equilibrium mixture is 0.088 M NH_3, 0.088 M H_2, and 0.160 M N_2. How many $mol \cdot L^{-1}$ of N_2 must be removed to increase the equilibrium concentration of H_2 to 0.130 M?

55. An equilibrium mixture contains 0.800 mol HI, 0.200 mol I_2, and 0.200 mol H_2 in a 1.00-L container. How many moles of I_2 must be removed in order to double the number of moles of H_2 at equilibrium?

56. How many $mol \cdot L^{-1}$ of CO must be withdrawn from the equilibrium described in Exercise 29 to triple the equilibrium concentration of chlorine?

57. An equilibrium mixture is 0.117 M NOBr, 0.364 M NO, and 0.205 M Br_2.

a) What is the value of K_c for the reaction $2NOBr(g) \rightleftharpoons 2NO(g) + Br_2(g)$?

b) How many moles per liter of NOBr must be added to the equilibrium mixture to produce an equilibrium mixture that is 0.360 M in Br_2?

c) The equilibrium temperature is 373 K. What is K_p?

d) What is ΔG^o at 373 K?

58. How many moles of H_2 must be added to 0.656 moles of CO_2 in a 6.49-L flask in order to reduce 96.0 % of the CO_2 to CO at a temperature where K = 4.0 for the following: $H_2(g) + CO_2(g) \rightleftharpoons H_2O(g) + CO(g)$?

MISCELLANEOUS

59. At 25 °C, the solubility of I_2 is 3.0×10^{-4} g·mL^{-1} in water and 2.9×10^{-2} g·mL^{-1} in CCl_4. Iodine is readily extracted from water with CCl_4. The amount of I_2 remaining in each solvent after an extraction is dictated by the equilibrium constant for the extraction process: $I_2(H_2O) \rightleftharpoons I_2(CCl_4)$.

a) Use the solubility of I_2 in each solvent to determine the equilibrium constant for the extraction at 25 °C.

b) What mass of I_2 remains in the water when 200. mL of an aqueous solution containing 55.0 mg of I_2 is extracted with 20. mL of CCl_4?

c) What mass of I_2 remains in the water after two extractions of 200. mL of an aqueous solution containing 55.0 mg of I_2 with 10. mL of CCl_4?

d) What volume of CCl_4 would have to be used to extract 50.0 mg of the I_2 from the original aqueous solution (Part c) in one extraction?

60. Consider the following equilibrium: $CS_2(g) \rightleftharpoons S_2(g) + C(s)$ $K = 0.40$

a) How many grams of carbon form in the decomposition of 3.0 mol of CS_2 in a 6.0-L container?

b) What mass of carbon would be present at equilibrium if 0.50 mol $S_2(g)$ is removed from the equilibrium in Part a?

c) What are the partial pressures of the two gases in an equilibrium mixture with a total pressure of 1.8 atm?

61. Consider the following equilibrium at 400 K:

$Br_2(g) + Cl_2(g) \rightleftharpoons 2BrCl(g)$ $K = 7.0$

a) A mixture contains 1.80 mol BrCl, 0.60 mol of Br_2, and 1.40 mol Cl_2 in a 4.26-L container. How many moles of Cl_2 must be removed to obtain an equilibrium mixture that contains 1.00 mol Br_2?

b) How many moles of chlorine should be added to 0.424 moles of bromine at 400 K to produce 0.500 mol of BrCl at equilibrium?

c) What are the partial pressures of the gases in an equilibrium mixture formed from the decomposition of BrCl if the initial pressure of BrCl was 1.84 atm?

62. Consider the following equilibrium at 250 °C:

$NH_3(g) + H_2S(g) \rightleftharpoons NH_4HS(s)$ $K_p = 9.0$ atm^{-2}

a) What is the value of K_c at 250 °C?

b) What would be the total pressure at equilibrium if excess NH_4HS is placed in the container at 250 °C?

c) What minimum mass of NH_4HS is required to achieve equilibrium in a 12.0-L container at 250 °C?

d) 30.0 g of NH_4HS are placed in a container at 250 °C. To what minimum volume would the container have to be adjusted to make all of the solid disappear?

63. PCl_5 is added to a container at some temperature to a total pressure of 1.000 atm where it decompose by the reaction $PCl_5(g) \rightleftharpoons PCl_3(g) + Cl_2(g)$. At equilibrium, the total pressure in the container is 1.544 atm. What is the value of the equilibrium constant for the decomposition at this temperature?

64. An equilibrium mixture contains 0.220 mol $PCl_5(g)$ and 0.120 mol each of $PCl_3(g)$ and $Cl_2(g)$ in a 2.00-L flask. How many moles of each gas would be present in an equilibrium mixture if the volume of the container were changed to 6.00 L? … to 0.200 L?

65. The following equilibrium pressures were measured in a 5.00 L container at 350 K: $P_{N_2O_4} = 0.226$ atm and $P_{NO_2} = 0.914$ atm. What would the equilibrium pressures be if the volume were increased to 20.0 L? … decreased to 1.00 L?

66. Consider the equilibrium described in Exercise 65. What would the partial pressures of the gases be in the equilibrium mixture if the 5.00-L container were heated to 400 K? Assume that ΔH^o and ΔS^o are independent of temperature.