AP Chemistry

Exercise 13.5

Equilibrium & ICE Tables

Name: KEY

Date:________________ Per:________

The equilibrium constant (K) is the ratio of the equilibrium concentration (or pressure) of product(s) to the equilibrium concentration (or pressure) of reactant(s). The same expression can be used to calculate the reaction quotient, (Q):

$$2\,NO_{2\,(g)} + 7\,H_{2\,(g)} \rightleftharpoons 2\,NH_{3\,(g)} + 4\,H_2O_{\,(l)}$$

$$K_C = \frac{[NH_3]_{eq}^2}{[NO_2]_{eq}^2[H_2]_{eq}^7}\ \ (at\ equilibrium)\ \ ;\ \ \ Q = \frac{[NH_3]^2}{[NO_2]^2[H_2]^7}\ \ (at\ any\ moment/point)$$

The coefficients from the balanced equation become exponents. Liquids and solids never appear in the expressions, because their concentrations (or pressures) do not change throughout the reaction.

DIRECTIONS: Write an equilibrium expression for each of the following. Not all equations are balanced.

1. $CaSO_4\,(s) \rightleftharpoons Ca^{2+}\,(aq) + SO_4^{2-}\,(aq)$

   $K_c = [Ca^{2+}][SO_4^{2-}]$

2. $\underline{4}\,HCl\,(g) + \underline{\ \ }\,O_2\,(g) \rightleftharpoons \underline{2}\,H_2O\,(l) + \underline{2}\,Cl_2\,(g)$

   $K_c = \frac{[Cl_2]^2}{[HCl]^4[O_2]}$

3. $Sn\,(s) + 2CO_2\,(g) \rightleftharpoons SnO_2\,(g) + 2CO\,(g)$

   $K_c = \frac{[SnO_2][CO]^2}{[CO_2]^2}$

4. $\underline{2}\,SO_3\,(g) \rightleftharpoons \underline{2}\,SO_2\,(g) + \underline{1}\,O_2\,(g)$

   $K_c = \frac{[SO_2]^2[O_2]^1}{[SO_3]^2}$

5. $Mg(s) + 2Ag^+\,(aq) \rightleftharpoons Mg^{2+}\,(aq) + 2Ag\,(s)$

   $K_c = \frac{[Mg^{2+}]}{[Ag^+]^2}$

6. $\underline{2}\,NO\,(g) + \underline{1}\,Cl_2\,(g) \rightleftharpoons \underline{2}\,NOCl\,(g)$

   $K_c = \frac{[NOCl]^2}{[NO]^2[Cl_2]^1}$

7. $2HBr\,(g) \rightleftharpoons H_2\,(g) + Br_2\,(l)$

   $K_c = \frac{[H_2]}{[HBr]^2}$

8. $C\,(s) + H_2O\,(g) \rightleftharpoons CO\,(g) + H_2\,(g)$

   $K_c = \frac{[CO][H_2]}{[H_2O]}$

9. $\underline{2}\,O_3\,(g) \rightleftharpoons \underline{3}\,O_2\,(g)$

   $K_c = \frac{[O_2]^3}{[O_3]^2}$

10. $O_2\,(g) + NO_2\,(g) \rightleftharpoons O_3\,(g) + NO\,(g)$

    $K_c = \frac{[O_3][NO]}{[O_2][NO_2]}$

Calculating K_c (or K_p) from a known set of equilibrium concentrations (or pressures) simply requires substituting the equilibrium concentrations (or pressures) into the equilibrium expression. If K_c (or K_p) is known, the concentration (or pressure) of one missing species may be found if the others are known.

DIRECTIONS: Complete the following in the space provided:

11. Determine the equilibrium constant (K_c) for the following reaction if the equilibrium concentrations of $[N_2O_4] = 0.00150$ and $[NO_2] = 0.571$. Write the equilibrium expression and solve for the value of K_c.

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

    $$K_c = \frac{[NO_2]^2}{[N_2O_4]} = \frac{[0.571]^2}{[0.00150]} = 217.3$$

    $\boxed{K_c = 217}$

12. For the reaction $CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2\,(g)$ at 1500°C, an equilibrium mixture of these gases was found to have the following concentrations $[CO] = 0.300M$, $[H_2] = 0.800M$ and $[CH_4] = 0.400M$. K_c at 1500°C = 5.67. Determine the equilibrium concentration of H_2O in this mixture.

    $$K_c = \frac{[CO][H_2]^3}{[CH_4][H_2O]} = \frac{[0.300][0.800]^3}{[0.400][x]} = 5.67 \rightarrow [x] = \frac{[0.300][0.800]^3}{[0.400]5.67} = 0.06772$$

    $\boxed{[H_2O] = 0.0677}$

Answers: 11) 217 12) 0.0677 M 13) 305 14) 1.84×10^{-2} 15) 29 17) 2.9×10^{27} 19) 1.79×10^{-5} 20) 66.7 21) 6.94×10^{-3} 23) 3.7×10^{-3} 24) $N_2O_4] = 0.0307M$, $[NO_2] = 0.0120M$ 25) $[CO] = 0.260M$, $[H_2O] = 0.234M$, $[H_2] = [CO_2] = 0.500M$ 26) 0.80 27) $[H_2] = [I_2] = 0.0670M$, $[HI] = 0.766M$ 28) $[CO] = 0.0807M$, $[Br_2] = 0.0607M$, $[COBr_2] = 0.0033M$

Exercise 13.5
Equilibrium & ICE Tables

Name: ______________________

Date: ________________ Per: ________

13. Nitrogen and hydrogen react together in a 4.00 liter container at 450°C. At equilibrium, $[N_2] = 0.130$, $[H_2] = 0.220$, and $[NH_3] = 0.650$. Calculate the equilibrium constant (K_c) for this reaction.

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

$$K_c = \frac{[NH_3]^2}{[N_2][H_2]^3} = \frac{[0.650]^2}{[0.130][0.220]^3} = 305.2$$

$\boxed{K_c = 305}$

14. A reaction vessel is charged with hydrogen iodide, which partially decomposes to molecular hydrogen and iodine according to the equation:

$$2HI(g) \rightleftharpoons H_2(g) + I_2(g)$$

When the system comes to equilibrium at 425 °C, $P_{HI} = 0.708$ atm, and $P_{H_2} = P_{I_2} = 0.0960$ atm. Calculate the value of K_p.

$$K_p = \frac{(pH_2)(pI_2)}{(pHI)^2} = \frac{(0.0960)(0.0960)}{(0.708)^2} = 0.01838$$

$\boxed{K_c = 0.0184 \text{ or } 1.84 \times 10^{-2}}$

15. For the reaction $H_2(g) + Cl_2(g) \rightleftharpoons 2HCl(g)$, the following equilibrium concentrations are determined: $[H_2] = 0.42\ M$, $[Cl_2] = 0.075\ M$, and $[HCl] = 0.95\ M$. Calculate the value of K_c.

$$K_c = \frac{[HCl]^2}{[H_2][Cl_2]} = \frac{[0.95]^2}{[0.42][0.075]} = 28.65$$

$\boxed{K_c = 29}$

16. Write the equilibrium expression K_p for the reaction: $N_2(g) + O_2(g) \rightleftharpoons 2NO(g)$.

$$K_p = \frac{(pNO)^2}{(pN_2)(pO_2)}$$

17. The K_{eq} for the equilibrium of $2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)$ is 5.4×10^{13} at 480.0°C. What is the value of K_{eq} for the reaction $4NO(g) + 2O_2(g) \rightleftharpoons 4NO_2(g)$?

$4NO(g) + 2O_2(g) \rightleftharpoons 4NO_2(g) = 2(2NO(g) + O_2(g) \rightleftharpoons 2NO_2(g)) \therefore K'_{eq} = K^2$

$K'_{eq} = (5.4 \times 10^{13})^2 = \boxed{2.9 \times 10^{27}}$

18. Write the expression for K_p for the reaction $4CuO(s) + CH_4(g) \rightleftharpoons CO_2(g) + 4Cu(s) + 2H_2O(g)$.

$$K_p = \frac{(pCO_2)(pH_2O)^2}{(pCH_4)}$$

19. Acetic acid is a weak acid that dissociates into the acetate ion and a proton in aqueous solution:

$$HC_2H_3O_2(aq) \rightleftharpoons C_2H_3O_2^-(aq) + H^+(aq)$$

At equilibrium at 25 °C a 0.100 M solution of acetic acid has the following concentrations: $[HC_2H_3O_2]_{eq} = 0.0990$ M, $[C_2H_3O_2^-]_{eq} = 1.33 \times 10^{-3}$ M, and $[H^+]_{eq} = 1.33 \times 10^{-3}$ M. Calculate the equilibrium constant, K_{eq}, for the ionization of acetic acid at 25°C.

$$K_{eq} = \frac{[C_2H_3O_2^-][H^+]}{[HC_2H_3O_2]} = \frac{[1.33 \times 10^{-3}][1.33 \times 10^{-3}]}{[0.0990]} = 1.786 \times 10^{-5}$$

or K_c

$\boxed{K_{eq} = 1.79 \times 10^{-5}}$

Answers: 11) 217 12) 0.0677 M 13) 305 14) 1.84×10^{-2} 15) 29 17) 2.9×10^{27} 19) 1.79×10^{-5} 20) 66.7 21) 6.94×10^{-3} 23) 3.7×10^{-3} 24) $[N_2O_4] = 0.0307$M, $[NO_2] = 0.0120$M 25) $[CO] = 0.260M$, $[H_2O] = 0.234M$, $[H_2] = [CO_2] = 0.500M$ 26) 0.80 27) $[H_2] = [I_2] = 0.0670M$, $[HI] = 0.766M$ 28) $[CO] = 0.0807M$, $[Br_2] = 0.0607M$, $[COBr_2] = 0.0033M$

Exercise 13.5

Equilibrium & ICE Tables

Name: ______________________

Date: ________________ Per: ________

20. Phosphorus trichloride and phosphorus pentachloride equilibrate in the presence of molecular chlorine according to the reaction: $PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$. If an equilibrium mixture at 450 K contains $PPCl_3 = 0.124$ atm, $PCl_2 = 0.157$ atm, and $PPCl_5 = 1.30$ atm. What is the value of K_p at this temperature?

$$K_p = \frac{(pPCl_5)}{(pPCl_3)(pCl_2)} = \frac{(1.30)}{(0.124)(0.157)} = 66.77$$

$K_p = 66.8$ — wrong rounding at bottom.

21. Dinitrogen tetroxide partially decomposes according to the equilibrium: $N_2O_4(g) \rightleftharpoons 2NO_2(g)$. A 1.000-L flask is charged with 3.00×10^{-2} mol of N_2O_4. At equilibrium, 2.36×10^{-2} mol of N_2O_4 remains. K_{eq} for this reaction is __________.

$$K_c = \frac{[NO_2]^2}{[N_2O_4]}$$

	$1N_2O_4(g)$	$\rightleftharpoons 2NO_2(g)$
I	$[3.00 \times 10^{-2}]_0$	0
C	$-[6.4 \times 10^{-3}]$	$+[1.28 \times 10^{-2}]$
E	$[2.36 \times 10^{-2}]_{eq}$	$[1.28 \times 10^{-2}]$

$$K_c = \frac{[1.28 \times 10^{-2}]^2}{[2.36 \times 10^{-2}]} = 6.942 \times 10^{-3}$$

$K_c = 6.94 \times 10^{-3}$

ICE Tables

If equilibrium concentrations are not known, the problem requires using stoichiometric relationships to determine the equilibrium concentrations from given information. These are organized using an ICE table.

For the reaction $CO(g) + H_2O(g) \rightleftharpoons CO_2(g) + H_2(g)$ calculate the equilibrium concentrations of all species if 1.000 mol of each reactant is mixed in a 1.000L flask. $K_c = 5.10$ at the temperature of this reaction.

		$CO(g)$	$H_2O(g)$	$CO_2(g)$	$H_2(g)$
[Initial]	I	1.000	1.000	0.000	0.000
[Change]	C	–x	–x	+x	+x
[Equilibrium]	E	1.000 – x	1.000 – x	x	x

$K_c = \frac{[CO_2][H_2]}{[CO][H_2O]}$ $\quad 5.10 = \frac{x^2}{(1.000 - x)^2}$ $\quad 2.26 = \frac{x}{1.000 - x}$ $\quad 2.26 - 2.26\,x = x$ $\quad x = 0.693$

		$CO(g)$	$H_2O(g)$	$CO_2(g)$	$H_2(g)$
[Equilibrium]	E	1.000 – 0.693 = 0.307*M*	1.000 – 0.693 = 0.307 *M*	0.693 *M*	0.693 *M*

22. When wine spoils, ethanol is oxidized to acetic acid as O_2 from the air dissolves in the wine: $C_2H_5OH(aq) + O_2(aq) \rightleftharpoons CH_3COOH(aq) + H_2O(l)$ The value of K_c for this reaction at 25°C is 1.2×10^{82}. Will much ethanol remain when the reaction has reached equilibrium? Explain.

1.2×10^{82} IS AN EXTREMELY LARGE NUMBER MEANING THE RXN GOES TO COMPLETION (BASICALLY), SO NOT MUCH IF ANY OF THE C_2H_5OH WILL REMAIN. ESSENTIALLY ALL C_2H_5OH IS CONVERTED TO PRODUCTS.

23. An equilibrium mixture of O_2, SO_2 and SO_3 contains equal concentrations of SO_2 and SO_3. Calculate the concentration of O_2 if $K_c = 270.$ for the reaction: $2\,SO_2(g) + O_2(g) \rightleftharpoons 2\,SO_3(g)$

$$K_c = \frac{[SO_3]^2}{[SO_2]^2[O_2]}$$

$[SO_3] = [SO_2] = x$

$$K_c = \frac{[x]^2}{[x]^2[O_2]} = 270. = \frac{[x]^2}{[x]^2[O_2]} = 270. = \frac{1}{[O_2]}$$

$[O_2] = 3.703 \times 10^{-3}$

$[O_2] = 3.70 \times 10^{-3}$ — wrong SF at bottom.

Answers: 11) 217 12) 0.0677 *M* 13) 305 14) 1.84×10^{-2} 15) 29 17) 2.9×10^{27} 19) 1.79×10^{-5} 20) 66.7 21) 6.94×10^{-3} 23) 3.7×10^{-3} 24) N_2O_4] = 0.0307M, [NO_2] = 0.0120M 25) [CO] = 0.260*M*, [H_2O] = 0.234*M*, [H_2] = [CO_2] = 0.500*M* 26) 0.80 27) [H_2] = [I_2] = 0.0670*M*, [HI] = 0.766*M* 28) [CO] = 0.0807*M*, [Br_2] = 0.0607*M*, [$COBr_2$] = 0.0033*M*

Exercise 13.5

Equilibrium & ICE Tables

Name: ____________________

Date: ________________ Per: ________

24. The value of K_c for the equilibrium $N_2O_4(g) \rightleftharpoons 2NO_2(g)$ is 4.64×10^{-3} at 25°C. If the initial concentrations of N_2O_4 is 0.0367M and the initial concentration of NO_2 is zero, what will be the concentration of both gases at equilibrium?

	$N_2O_4(g)$	$\rightleftharpoons 2NO_2(g)$
R	$N_2O_4(g)$	$2NO_2(g)$
I	0.0367	0
C	$-x$	$+2x$
E	$0.0367-x$	$2x$

$K_c = \frac{[NO_2]^2}{[N_2O_4]}$

$4.64 \times 10^{-3} = \frac{[2x]^2}{[0.0367-x]}$

$1.702 \times 10^{-4} - 4.64 \times 10^{-3}x = 4x^2$

$4x^2 + 4.64 \times 10^{-3}x - 1.702 \times 10^{-4} = 0$

$x = \frac{-4.64 \times 10^{-3} \pm \sqrt{(4.64 \times 10^{-3})^2 - 4 \cdot 4 \cdot (-1.702 \times 10^{-4})}}{2(4)}$

$x = 5.968 \times 10^{-3}$ or -7.128×10^{-3}

$[NO_2] = 2x = 2(5.968 \times 10^{-3}) = 0.01193 =$ **0.0119**

$[N_2O_4] = 0.0367 - x = 0.0367 - 5.968 \times 10^{-3} = 0.03073 =$ **0.0307**

25. At 650°C, the reaction below has a K_{eq} value of 0.771. If 2.00 mol of both hydrogen and carbon dioxide are placed in a 4.00 L container and allowed to react, what will be the equilibrium concentrations of all four gases?

R	$H_2(g)$ +	$CO_2(g)$ $\rightleftharpoons$	$CO(g)$ +	$H_2O(g)$
I	[0.500]	[0.500]	0	0
C	$-x$	$-x$	$+x$	$+x$
E	[0.500−x]	[0.500−x]	x	x

$K_c = \frac{[CO][H_2O]}{[H_2][CO_2]}$

$K_c = \frac{[x][x]}{[0.500-x][0.500-x]}$

$\sqrt{K_c} = \frac{[x]}{[0.500-x]} \rightarrow \sqrt{0.771} = \frac{[x]}{[0.500-x]} \rightarrow 0.8780 = \frac{[x]}{[0.500-x]}$

$0.439 - 0.8780x = x$

$0.439 = 1.8780x$

$x = 0.2337$

$[CO] = [H_2O] = 0.234\,M$

$[H_2] = [CO_2] = (0.500 - 0.234) = 0.266\,M$

$[H_2] = [CO_2] = 0.266\,M$

26. Find the equilibrium constant, K_{eq}, for the following equilibrium. The initial concentrations of AB and A_2D are 0.30 M before they are mixed and when equilibrium is reached, the equilibrium concentration of A_2D is 0.20 M. Be sure to show an ICE table for your calculation.

R	$2AB(g)$ + $C_2D(s)$ $\rightleftharpoons$	$1A_2D(g)$ + $2CB(s)$
I	0.30	0.30
C	+0.20	−0.10
E	0.50	0.20

$K_c = \frac{[A_2D]}{[AB]^2} = \frac{0.20}{[0.50]^2} =$ **0.80**

Since reactants & products are present Q must be calculated to find direction.

27. A 5.00 L reaction vessel is filled with 1.00 mol of H_2, 1.00 mol of I_2 and 2.50 mol of HI. K_c (at 500K) is 129. Calculate the equilibrium concentrations of H_2, I_2 and HI at 500K given the reaction: $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$.

R $H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$

I [0.200] [0.200] [0.500]

$K_c = \frac{[HI]^2}{[H_2][I_2]}$

$Q = \frac{[0.500]^2}{[0.200][0.200]} = 6.25$ (Rxn goes forward)

R	$H_2(g)$ +	$I_2(g)$ $\rightleftharpoons$	$2HI(g)$
I	[0.200]	[0.200]	[0.500]
C	$-x$	$-x$	$+2x$
E	[0.200−x]	[0.200−x]	[0.500+2x]

$K_c = \frac{[0.500+2x]^2}{[0.200-x]^2}$

$\sqrt{K_c} = \frac{0.500+2x}{0.200-x}$

$\sqrt{129} = \frac{0.500+2x}{0.200-x}$

$11.35 = \frac{0.500+2x}{0.200-x}$

$2.271 - 11.35x = 0.500 + 2x$

$1.77 = 13.35x$

$x = 0.132$

$[H_2] = [I_2] = 0.200 - 0.132$ **= 0.068M**

$[HI] = 0.500 - 2(0.132)$ **= 0.764M**

28. Carbonyl bromide, $COBr_2$, can be formed by reacting CO with Br_2. A mixture of 0.400 mol CO, 0.300 mol Br_2, and 0.0200 mol $COBr_2$ is sealed in a 5.00L flask. Calculate equilibrium concentrations for all gases. $K_c = 0.680$

$CO(g) + Br_2(g) \rightleftharpoons COBr_2(g)$

[0.0800] [0.0600] [0.00400]

$K_c = \frac{[COBr_2]}{[CO][Br_2]}$

$Q = \frac{[0.00400]}{[0.0800][0.0600]}$

$Q = 0.833$

Q>K, RXN GOE IN REVERSE

R	$CO(g)$ +	$Br_2(g)$ $\rightleftharpoons$	$COBr_2(g)$
I	[0.0800]	[0.0600]	[0.00400]
C	$+x$	$+x$	$-x$
E	$0.0800+x$	$0.0600+x$	$0.00400-x$

$K_c = \frac{[COBr_2]}{[CO][Br_2]}$

$0.680 = \frac{[0.00400-x]}{[0.0800+x][0.0600+x]}$

$0.680 = \frac{[0.00400-x]}{0.00480 + 0.140x + x^2}$

$0.003264 + 0.0952x + 0.680x^2 = 0.00400 - x$

$0.680x^2 + 1.0952x - 0.000736 = 0$

$x = \frac{-1.0952 \pm \sqrt{(1.0952)^2 - 4(0.680)(-0.000736)}}{2(0.680)}$

$x = 6.717 \times 10^{-4}$ or -1.61 x cannot be negative

$[CO] = 0.0800 + 6.717 \times 10^{-4} = 0.0807\,M$

$[Br_2] = 0.0600 + 6.717 \times 10^{-4} = 0.0607\,M$

$[COBr_2] = 0.0400 - 6.717 \times 10^{-4} = 0.0033\,M$

Answers: 11) 217 12) 0.0677 *M* 13) 305 14) 1.84×10^{-2} 15) 29 17) 2.9×10^{27} 19) 1.79×10^{-5} 20) 66.7 21) 6.94×10^{-3} 23) 3.7×10^{-3} 24) $[N_2O_4] = 0.0307$M, $[NO_2] = 0.0120$M 25) $[CO] = 0.260M$, $[H_2O] = 0.234M$, $[H_2] = [CO_2] = 0.500M$ 26) 0.80 27) $[H_2] = [I_2] = 0.0670M$, $[HI] = 0.766M$ 28) $[CO] = 0.0807M$, $[Br_2] = 0.0607M$, $[COBr_2] = 0.0033M$