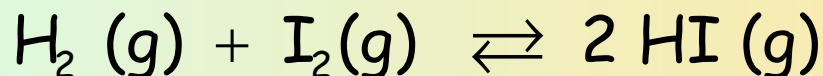


# Chemical Equilibrium: Exercises

1. At 670 °C, a 1 L-flask contains a mixture of gases at equilibrium: 0.003 mol hydrogen, 0.003 mol iodine and 0.024 mol of hydrogen iodide. The reaction is:

Determine:

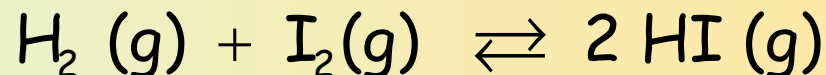


a) The values of  $K_c$  and  $K_p$

b) The total pressure and the partial pressures at equilibrium in the previous conditions

The values of  $K_p$  and  $K_c$  are equal:  $K_p = K_c * (RT)^{\Delta n} \xrightarrow{\Delta n = 0} K_p = K_c$

At equilibrium we have:



$$K_p = K_c = \frac{[\text{HI}]^2}{[\text{H}_2] [\text{I}_2]} = \frac{(0.024)^2}{(0.003)^2} = 64$$

# of moles  
conc.

0.003	0.003	0.024
0.003 M	0.003 M	0.024 M

The total pressure is:

$$P_{\text{tot}} = C_{\text{tot}} * R * T = 0.03 \text{ M} * 0.082 \frac{\text{atm.L}}{\text{K.mol}} * (670 + 273) \text{ K} = 2.32 \text{ atm}$$

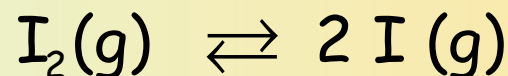
The partial pressures are:

$$P_{\text{H}_2} = P_{\text{I}_2} = 0.003 \text{ M} * 0.082 \frac{\text{atm.L}}{\text{K.mol}} * (670 + 273) \text{ K} = 0.232 \text{ atm}$$

$$P_{\text{HI}} = 0.024 \text{ M} * 0.082 \frac{\text{atm.L}}{\text{K.mol}} * (670 + 273) \text{ K} = 1.856 \text{ atm}$$

# Chemical Equilibrium: Exercises

2. The equilibrium constant for this process



At 1000 K is  $K_c = 3.76 \cdot 10^{-5}$ . If a 2 L-flask that contains  $5 \cdot 10^{-3}$  moles of I is charged with 1 mol of  $\text{I}_2$ , determine the concentrations of both components at equilibrium

First, we have to compare K and Q in order to know the direction of the reaction:

$$K_c = \frac{[\text{I}]^2}{[\text{I}_2]} = 3.76 \cdot 10^{-5} \quad Q = \frac{[\text{I}]^2}{[\text{I}_2]} = \frac{(2.5 \cdot 10^{-3} \text{ M})^2}{0.5 \text{ M}} = 1.25 \cdot 10^{-5} \quad Q < K_c$$

Therefore, the reaction goes to the right

The value of "x" is:

$$K_c = \frac{[\text{I}]^2}{[\text{I}_2]} = 3.76 \cdot 10^{-5} = \frac{(0.005 + 2x)^2}{2(1-x)}$$

$$7.52 \cdot 10^{-5} - 7.52 \cdot 10^{-5} x = 4x^2 + 0.02x + 2.5 \cdot 10^{-5}$$

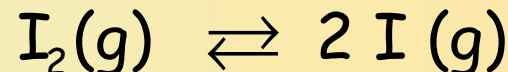
Approximation:  $0.02x + 7.52 \cdot 10^{-5} x \approx 0.02x$

$$4x^2 + 0.02x - 5.02 \cdot 10^{-5} = 0$$

$$x = \frac{-0.02 \pm \sqrt{(0.02)^2 + 8.032 \cdot 10^{-4}}}{8} \rightarrow x = 1.84 \cdot 10^{-3}$$

The concentrations at equilibrium are:

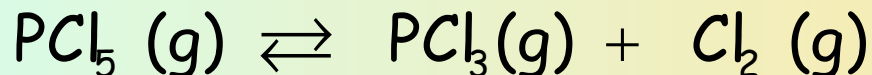
$$[\text{I}] = \frac{0.005 + 2x}{2} = 4.34 \cdot 10^{-3} \text{ M}; [\text{I}_2] = \frac{1-x}{2} = 0.499 \text{ M}$$



n initial	1	0.005
n change	-x	2x
n equil.	1-x	0.005+2x
[ ] equil.	(1-x)/2	(0.005+2x)/2

## Chemical Equilibrium: Exercises

3. A 5 L-container is charged with 2 moles of  $\text{PCl}_5$  (g) and 1 mole of  $\text{PCl}_3$  (g). The mixture is heated at  $250^\circ\text{C}$  and this equilibrium is reached:



The equilibrium constant at that temperature is  $K_c = 0.042$ . Determine:

- a) The concentration of  $\text{Cl}_2$  at equilibrium. b) The value of  $K_p$  at that temperature  
c) The dissociation percent of  $\text{PCl}_5$

At equilibrium we have:

$$K_c = \frac{[\text{PCl}_3][\text{Cl}_2]}{[\text{PCl}_5]} = 0.042 = \frac{(1+x) \times x}{5(2-x)}$$

From this expression we can calculate x:

$$x^2 + 1.21x - 0.42 = 0$$

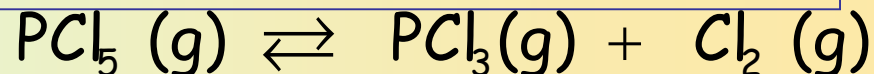
$$x = \frac{-1.21 \pm \sqrt{1.4641 + 1.68}}{2} \rightarrow x = 0.282$$

a) The concentration of  $\text{Cl}_2$  is:  $[\text{Cl}_2] = x/5 = 5.64 \cdot 10^{-2} \text{ M}$

b) The value of  $K_p$ :  $K_p = K_c (RT) = 0.042 \cdot 0.082 \cdot (250+273) = 1.80$

c) The dissociation percent:

$$\alpha = \frac{x}{2} = 0.141 = 14.1 \%$$



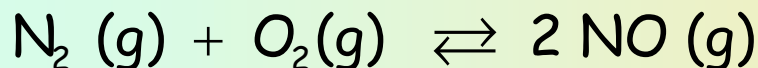
n initial	2	1	0
n change	-x	x	x
n equil	2-x	1+x	x
[ ] equil	(2-x)/5	(1+x)/5	x/5

## Chemical Equilibrium: Exercises

4. A 5 L-container is charged with 0.92 moles of  $N_2$  and 0.51 moles of  $O_2$ . The mixture is heated at 2200 K and the following equilibrium is reached:

If 1.09 % of the initial nitrogen reacts, determine:

- The concentrations of all components at equilibrium
- The values of  $K_c$  and  $K_p$



n initial	0.92	0.51	0
n change	-x	-x	2x
n equil	0.92-x	0.51- x	2x
[ ] equil	(0.92-x)/5	(0.51- x)/5	2x/5

where  $x = 0.92 \alpha = 0.92 \frac{1.09}{100} = 0.01$

a) The concentrations at equilibrium

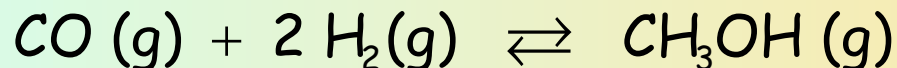
$$[NO] = \frac{2x}{5} = 0.004 \text{ M}$$
$$[N_2] = \frac{0.92 - x}{5} = 0.182 \text{ M}$$
$$[O_2] = \frac{0.51 - x}{5} = 0.10 \text{ M}$$

b) The values of  $K_c$  and  $K_p$

$$K_p = K_c = \frac{[NO]^2}{[N_2][O_2]} = \frac{(0.004)^2}{(0.182)(0.10)} = 8.79 \cdot 10^{-4}$$

# Chemical Equilibrium: Exercises

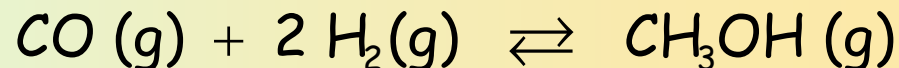
5. The synthesis of methanol is based on this equilibrium



In a 1 L-flask we have initially 2 moles of CO and 2 moles of hydrogen and the mixture is heated to 600 K. At equilibrium 0.8 moles of methanol are formed. Determine:

- a) The number of moles of each component at equilibrium  
 b) The value of  $K_p$  at 600 K  
 c) The effect produced when the equilibrium is disturbed by increasing the volume of the container

b) The value of  $K_p$



$$K_c = \frac{[\text{CH}_3\text{OH}]}{[\text{CO}][\text{H}_2]^2} = \frac{0.8}{1.2 * (0.4)^2} = 4.17$$

$$K_p = \frac{K_c}{(RT)^2} = \frac{4.17}{(0.082 * 600)^2} = 1.72 * 10^{-3}$$

n initial  
 n change  
 n equil  
 [ ] equil

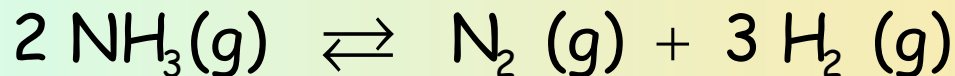
n initial	2	2	0
n change	-x	-2x	x
n equil	2-x=1.2	2-2x=0.4	x = 0.8
[ ] equil	1.2 M	0.4 M	0.8 M

c) The effect

volume  $\uparrow$   $\rightarrow$  total pressure  $\downarrow$   $\rightarrow$  system reacts increasing pressure  
 $\rightarrow$  # of moles  $\uparrow$   $\rightarrow$  to the left more reactants

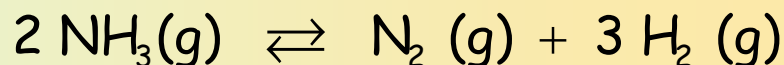
# Chemical Equilibrium: Exercises

6. At 400 °C ammonia is 40 % dissociated in nitrogen and hydrogen when the pressure of the mixture is 710 mm Hg. Determine:



- a) The partial pressures of each component when we start with 4 moles of ammonia  
b) The value of Kp

a) The partial pressures:



n initial  
n change  
n equil

n initial	4	0	0
n change	$-n\alpha = -1.6$	0.8	2.4
n equil	2.4	0.8	2.4

$$n = 2.4 \text{ mol} + 0.8 \text{ mol} + 2.4 \text{ mol} = 5.6 \text{ mol}$$

$$P_{\text{NH}_3} = P_{\text{H}_2} = \frac{2.4 \text{ mol}}{5.6 \text{ mol}} * 710 \text{ mm Hg} = 304.3 \text{ mm Hg}$$

$$P_{\text{N}_2} = \frac{0.8 \text{ mol}}{5.6 \text{ mol}} * 710 \text{ mm Hg} = 101.4 \text{ mm Hg}$$

b) Kp:

The partial pressures in atm

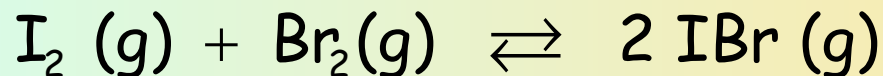
$$P_{\text{NH}_3} = P_{\text{H}_2} = 304.3 \text{ mm Hg} \frac{1 \text{ atm}}{760 \text{ mm Hg}} = 0.4 \text{ atm}$$

$$P_{\text{N}_2} = 101.4 \text{ mm Hg} \frac{1 \text{ atm}}{760 \text{ mm Hg}} = 0.133 \text{ atm}$$

$$K_p = \frac{P_{\text{N}_2} * P_{\text{H}_2}^3}{P_{\text{NH}_3}^2} = \frac{0.133 * (0.4)^3}{(0.4)^2} = 0.0532$$

# Chemical Equilibrium: Exercises

7. A 400 mL-flask is charged with 2.032 g of iodine and 1.28 g of bromine. The mixture is heated at 150 °C and the following equilibrium is reached:



Determine:

- The molar concentrations of each component and the total pressure
- The value of  $K_p$  at this temperature

$K_c$  (at 150 °C) = 280;  $R = 0.082 \text{ atm}\cdot\text{L}/\text{K}\cdot\text{mol}$ ; Atomic weights:  $\text{Br}=79.9$   $\text{I}=126.9$

The initial amounts in moles:

$$n(\text{I}_2) = 2.032 \text{ g} \frac{1 \text{ mol}}{253.8 \text{ g}} = 0.008 \text{ mol}$$

$$n(\text{Br}_2) = 1.28 \text{ g} \frac{1 \text{ mol}}{159.8 \text{ g}} = 0.008 \text{ mol}$$

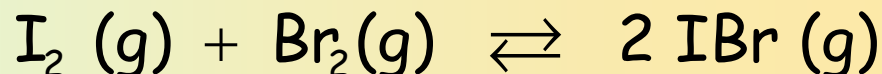
- The molar concentrations and total pressure:

$n$  initial

$n$  change

$n$  equil

[ ] equil



0.008	0.008	0
-x	-x	2x
0.008-x	0.008-x	2x
(0.008-x)/0.4	(0.008-x)/0.4	2x/0.4

$$K_c = 280 = \frac{(2x)^2}{(0.008-x)^2} \rightarrow 16.73 = \frac{2x}{0.008-x}$$

$$x = \frac{0.1338}{18.73} = 0.0071 \rightarrow [\text{I}_2] = [\text{Br}_2] = 2.25 \cdot 10^{-3} \text{ M}$$

$$[\text{IBr}] = 3.55 \cdot 10^{-2} \text{ M}$$

$$P = cRT = 0.04 \cdot 0.082 \cdot (150+273) = 1.387 \text{ atm}$$

- $K_p$

$$K_p = K_c \cdot (RT)^{\Delta n} \xrightarrow{\Delta n = 0} K_p = K_c = 280$$

# Chemical Equilibrium: Exercises

8. A 0.4 L-flask is charged with 1 mole of  $N_2$  and 3 moles of  $H_2$  at 780 K. When the following equilibrium is reached

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

the mixture has a 28 % of ammonia (in moles). Determine:

- a) The number of moles of each component in equilibrium b) The total pressure at equilibrium c) The value of  $K_p$

The value of x:

$$n_{tot} = (1-x) + (3-3x) + 2x = 4 - 2x$$

$$2x = 0.28 (4 - 2x) \rightarrow x = \frac{1.12}{2.56} = 0.4375$$

a) The number of moles of each component in equilibrium:

$$n(N_2) = 1-x = 0.5625 \text{ mol}$$

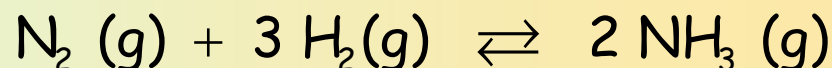
$$n(H_2) = 3-3x = 1.6875 \text{ mol}$$

$$n(NH_3) = 2x = 0.875 \text{ mol}$$

b) The total pressure at equilibrium:

$$P_{tot} = \frac{n_{tot} * R * T}{V} = \frac{3.125 \text{ mol} * 0.082 \text{ atm.L/K.mol} * 780 \text{ K}}{0.4 \text{ L}}$$

$$P_{tot} = 500 \text{ atm}$$



1	3	0
-x	-3x	2x
1-x	3-3x	2x
(1-x)/0.4	(3-3x)/0.4	2x/0.4

c) The value of  $K_p$ :

$$P(N_2) = \frac{0.5625}{3.125} * 500 \text{ atm} = 90 \text{ atm}$$

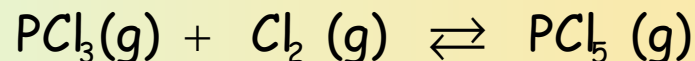
$$P(H_2) = \frac{1.6875}{3.125} * 500 \text{ atm} = 270 \text{ atm}$$

$$P(NH_3) = \frac{0.875}{3.125} * 500 \text{ atm} = 140 \text{ atm}$$

$$K_p = \frac{P(NH_3)^2}{P(N_2) * P(H_2)^3} = 1.1 * 10^{-5}$$

# Chemical Equilibrium: Exercises

9. Chlorine reacts with phosphorus trichloride to yield phosphorus pentachloride, according to this equation:



In a 2 L-vessel, at a given temperature, there is a gas mixture in equilibrium that contains 132 g of  $\text{PCl}_3$ , 56.8 g of  $\text{Cl}_2$  and 10.4 g of  $\text{PCl}_5$ .

- Determine  $K_c$  at that temperature
- Explain if  $K_p$  can be calculated with the data available in this exercise
- Determine the composition at equilibrium (concentrations) if the volume is halved.

The molar masses and moles at equilibrium:

$$M(\text{PCl}_3) = 31 + (3 \cdot 35.5) = 137.5 \text{ g/mol}$$

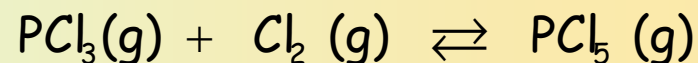
$$M(\text{Cl}_2) = 2 \cdot 35.5 = 71 \text{ g/mol}$$

$$M(\text{PCl}_5) = 31 + (5 \cdot 35.5) = 208.5 \text{ g/mol}$$

$$n(\text{PCl}_3) = \frac{132 \text{ g}}{137.5 \text{ g/mol}} = 0.96 \text{ mol}$$

$$n(\text{Cl}_2) = \frac{56.8 \text{ g}}{71 \text{ g/mol}} = 0.8 \text{ mol}$$

$$n(\text{PCl}_5) = \frac{10.4 \text{ g}}{208.5 \text{ g/mol}} = 0.05 \text{ mol}$$



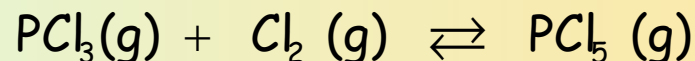
n equil	0.96	0.8	0.05
[ ] equil	0.48 M	0.4 M	0.025 M

$$\text{a) } K_c \quad K_c = \frac{[\text{PCl}_5]}{[\text{PCl}_3][\text{Cl}_2]} = \frac{0.025}{0.48 \cdot 0.4} = 0.13$$

b)  $K_p$  cannot be calculated without the value of  $T$  or the total pressure

## Chemical Equilibrium: Exercises

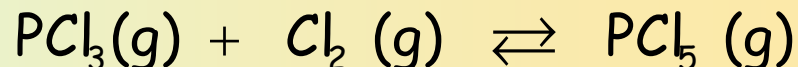
9. Chlorine reacts with phosphorus trichloride to yield phosphorus pentachloride, according to this equation:



In a 2 L-vessel, at a given temperature, there is a gas mixture in equilibrium that contains 132 g of  $\text{PCl}_3$ , 56.8 g of  $\text{Cl}_2$  and 10.4 g of  $\text{PCl}_5$ .

- Determine  $K_c$  at that temperature
- Explain if  $K_p$  can be calculated with the data available in this exercise
- Determine the composition at equilibrium (concentrations) if the volume is halved.

c) When volume is halved, the pressure increases and the reaction goes to the right (Le Châtelier)



n initial	0.96	0.8	0.05
n change	-x	-x	+x
n equil	0.96-x	0.8-x	0.05+x
[ ] equil	0.96-x	0.8-x	0.05+x

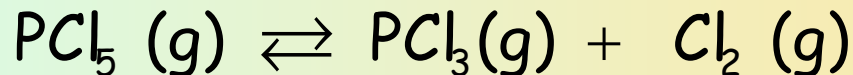
$$K_c = \frac{[\text{PCl}_5]}{[\text{PCl}_3][\text{Cl}_2]} = 0.13 = \frac{0.05 + x}{(0.96 - x) * (0.8 - x)} = \frac{0.05 + x}{x^2 - 1.76x + 0.768}$$

$$0.13x^2 - 1.229x + 0.05 = 0 \rightarrow x = \frac{1.229 \pm \sqrt{1.51 - 0.026}}{0.26} \rightarrow x = 0.042$$

$$n(\text{PCl}_3) = 0.96 - x = 0.918 \text{ mol}; n(\text{Cl}_2) = 0.758 \text{ mol}; n(\text{PCl}_5) = 0.092 \text{ mol}$$

# Chemical Equilibrium: Exercises

10. A 10 L-vessel is charged with 2 moles of  $\text{PCl}_5$  at  $162^\circ\text{C}$ . Determine  
a) The concentrations of all components when the following equilibrium is reached:



b) The total pressure at equilibrium  
 $K_c = 0.0454$  (at  $162^\circ\text{C}$ );  $R = 0.082 \text{ atm}\cdot\text{L}/\text{K}\cdot\text{mol}$

a) The concentrations at equilibrium:

$$K_c = \frac{[\text{PCl}_3][\text{Cl}_2]}{[\text{PCl}_5]} = \frac{x^2}{10(2-x)} = 0.0454$$

$$x^2 + 0.454x - 0.908 = 0$$

$$x = \frac{-0.454 \pm \sqrt{0.206 + 3.632}}{2} = 0.753$$

$$[\text{PCl}_3] = [\text{Cl}_2] = 7.53 \cdot 10^{-2} \text{ M}$$

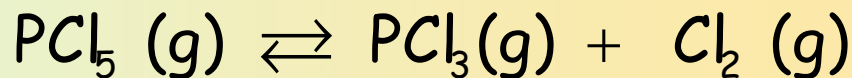
$$[\text{PCl}_5] = 0.125 \text{ M}$$

b) The total  $n_{\text{tot}} = 2 + x = 2.753 \text{ mol}$

pressure at equilibrium:

$$P_{\text{tot}} = \frac{n_{\text{tot}} * R * T}{V} = \frac{2.753 \text{ mol} * 0.082 \frac{\text{atm}\cdot\text{L}}{\text{K}\cdot\text{mol}} * (162+273) \text{ K}}{10 \text{ L}}$$

$$P_{\text{tot}} = 9.82 \text{ atm}$$



n initial	2	0	0
n change	-x	x	x
n equil	2-x	x	x
[ ] equil	(2-x)/10	x/10	x/10