

# CHAPTER → 7

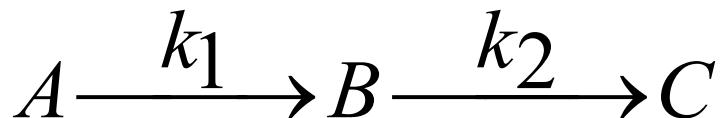
## Kinetics Of Homogeneous Complex Reactions

# Complex Reaction in Batch Reactor

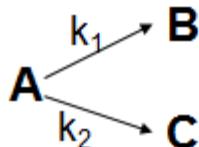
- Chemical reactions that occur with more than one reaction in a single process to produce a stable product are **called multiple reactions**.
- The majority of chemical products obtained currently involve multiple reactions.
- Multiple reactions are broadly classified into **two main category of reactions namely series** and **parallel reactions**.

## A) Simple reactions

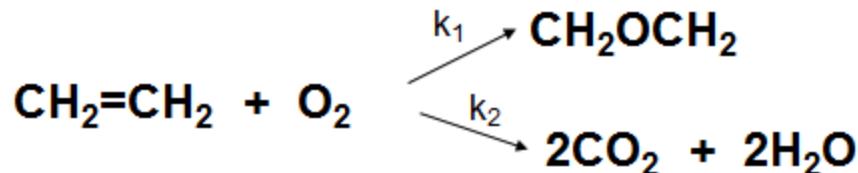
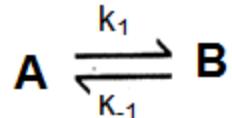
**Series (i.e., consecutive) reactions.**



▪ **Simultaneous reactions,**



▪ **Reversible reactions**

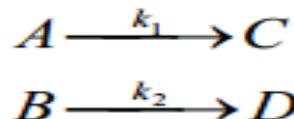


## B) Complex reactions

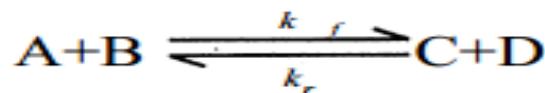
Combination of series and simultaneous in one process



- Parallel and concurrent reactions,

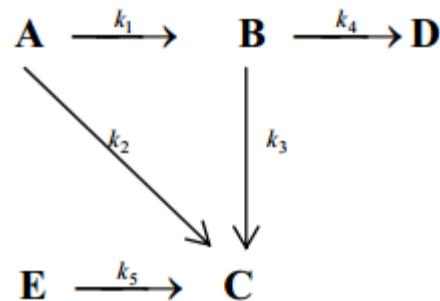


- Reversible reactions



## Example

For the following reactions, find the formation of species A,B,C,D and E for a batch reactor



## solution

$$\frac{dC_A}{dt} = -k_1 C_A - k_2 C_A = -(k_1 + k_2) C_A$$

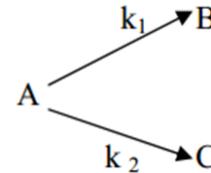
$$\frac{dC_B}{dt} = k_1 C_A - k_3 C_B - k_4 C_B = k_1 C_A - C_B (k_3 + k_4)$$

$$\frac{dC_C}{dt} = k_2 C_A + k_3 C_B + k_5 C_E$$

$$\frac{dC_D}{dt} = k_4 C_B \quad \frac{dC_E}{dt} = -k_5 C_E$$

# Simple reaction systems

- *Parallel reaction system*



- *Series reaction system*



**These** are prototype reactions for most reaction systems, and their characteristics show many of the features of any multiple reaction system. **The characteristics** of these simple reactions are

1. There is **a single reactant A**,
2. There are **two products B and C and we usually want to produce B and minimize C**,
3. **The stoichiometric coefficients of all species are unity**. These stoichiometries require that, if **we feed pure A, it must react to form either B or C. Therefore, the loss of A is**

equal to the gain in **B and C**,

$$\begin{aligned} n_{A,0} - n_A &= n_B + n_C \\ C_{A,0} - C_A &= C_B + C_C \end{aligned}$$

$$\begin{aligned} n_{A,0} &= n_A + n_B + n_C \\ C_{A,0} &= C_A + C_B + C_C \end{aligned}$$

These relations assume that there is no **B or C in the feed,  $C_{B,0} = C_{C,0} = 0$**

$$conversion = \frac{\text{loss of reactant}}{\text{feed of reactant}}$$

For reactant **A** **this can be written as**

$$X_A = \frac{n_{A,0} - n_A}{n_{A,0}} = \frac{F_{A,0} - F_A}{F_{A,0}}$$

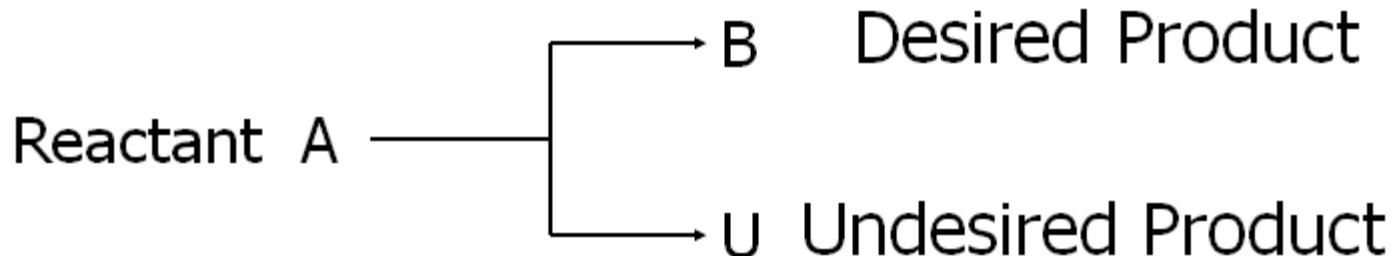
$$X_A = \frac{C_{A,0} - C_A}{C_{A,0}}$$

**For a single reaction** this was called the **fractional conversion X** (or  $X_A$ ), a number between zero and unity, because in a single reaction there is always a single variable that describes the progress of the reaction (we used  $C_A$  or  $X$ )..

# Cont....

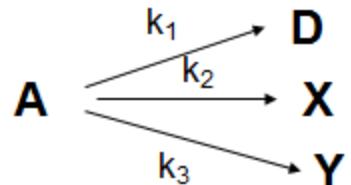
For **multiple reactants and multiple reactions** there is not always a single species common to all reactions to designate as *A*. However, there is frequently a *most valuable reactant on which to base conversion*. We emphasize that by conversion  $X_j$  we mean the fractional conversion of reactant species *j* in all reactions

## Selectivity and Yield



## Expression of rate equation for Simultaneous reactions

In Simultaneous reactions, the reacting substances, instead of proceeding in **one path** to yield a given set of products, also follow **one or more other paths** to give different products



## Simultaneous reactions in batch reactor

$$r_j = \sum_{i=1}^R v_{i,j} r_i$$

## Cont....

$$r_A = v_{A,1}r_1 + v_{A,2}r_2 + v_{A,3}r_3$$

$$\frac{dC_A}{dt} = -k_1 C^n A + -k_2 C^m A + -k_3 C^p A$$

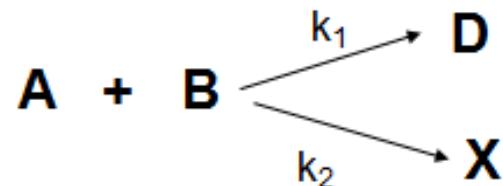
$$r_A = -k_1 C^n A + -k_2 C^m A + -k_3 C^p A$$

$$-r_A = k_1 C^n A + k_2 C^m A + k_3 C^p A$$

These reactions can be of many different types and can be distinguished with the following categories:

# Cont....

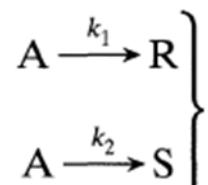
- i) Parallel reaction with a single reactant of equal reaction order, where  $n = m = p$
- ii) Parallel reaction with a single reactant but with different reaction order, where  $n \neq m \neq p$
- iii) Parallel reaction where more reactants are involved



$$-r_A = k_1 C_A^n C_B^m + k_2 C_A^p C_B^r$$

# Irreversible Reactions in Parallel.

Consider the simplest case, A decomposing by two competing paths, both elementary reactions



$$-r_A = -\frac{dC_A}{dt} = k_1 C_A + k_2 C_A = (k_1 + k_2) C_A \quad (34)$$

$$r_R = \frac{dC_R}{dt} = k_1 C_A \quad (35)$$

$$r_S = \frac{dC_S}{dt} = k_2 C_A \quad (36)$$

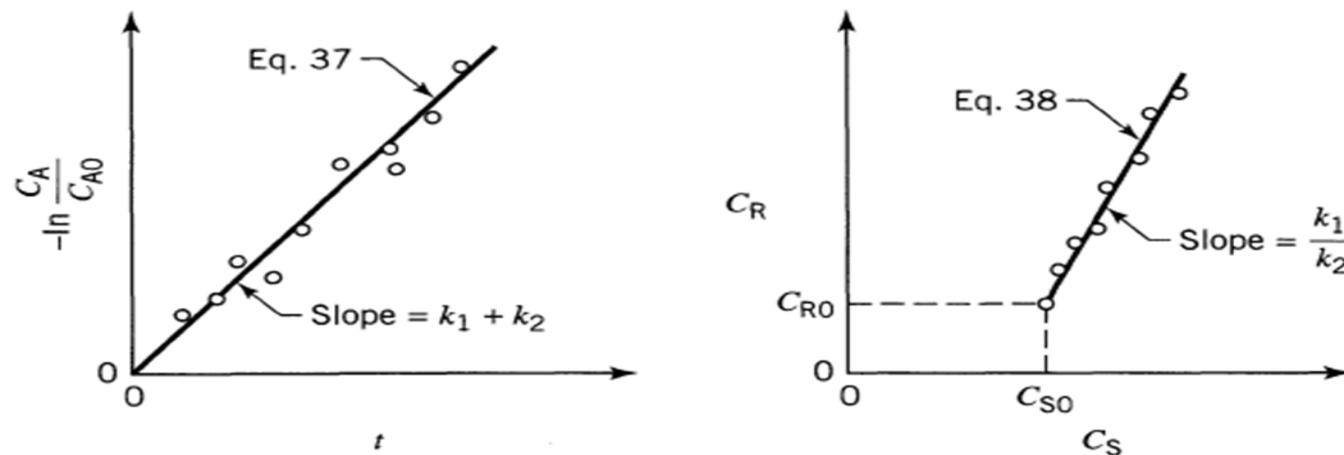
The  $k$  values are found using all three differential rate equations

$$-\ln \frac{C_A}{C_{A0}} = (k_1 + k_2)t \quad (37)$$

$$\frac{r_R}{r_S} = \frac{dC_R}{dC_S} = \frac{k_1}{k_2}$$

which when integrated gives simply

$$\frac{C_R - C_{R0}}{C_S - C_{S0}} = \frac{k_1}{k_2} \quad (38)$$

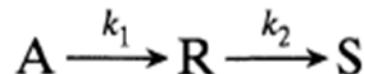


**Figure 3.6** Evaluation of the rate constants for two competing elementary

## Expression of rate equation for consecutive reactions

### Consecutive Reactions in batch reactor

#### 1. First-order consecutive reactions



The concentration of A, B, and C as a function of time are found using the following three equations

$$r_j = \sum_{i=1}^R v_{i,j} r_i$$

$$r_A = \frac{dC_A}{dt} = -k_1 C_A \quad (44)$$

$$r_R = \frac{dC_R}{dt} = k_1 C_A - k_2 C_R \quad (45)$$

$$r_S = \frac{dC_S}{dt} = k_2 C_R \quad (46)$$

## Cont..

$$-\ln \frac{C_A}{C_{A0}} = k_1 t \quad \text{or} \quad C_A = C_{A0} e^{-k_1 t} \quad (47)$$

$$\frac{dC_R}{dt} + k_2 C_R = k_1 C_{A0} e^{-k_1 t} \quad (48)$$

which is a first-order linear differential equation of the form

$$\frac{dy}{dx} + Py = Q$$

By multiplying through with the integrating factor  $e^{\int P dx}$  the solution is

$$ye^{\int P dx} = \int Qe^{\int P dx} dx + \text{constant}$$

$$C_R = C_{A0} k_1 \left( \frac{e^{-k_1 t}}{k_2 - k_1} + \frac{e^{-k_2 t}}{k_1 - k_2} \right) \quad (49)$$

- Noting that there is no change in total number of moles, the stoichiometry relates the concentrations of reacting components by

$$C_{A0} = C_A + C_R + C_S$$

which with Eqs. 47 and 49 gives

$$C_S = C_{A0} \left( 1 + \frac{k_2}{k_1 - k_2} e^{-k_1 t} + \frac{k_1}{k_2 - k_1} e^{-k_2 t} \right) \quad (50)$$

Now if  $k_2$  is much larger than  $k_1$ , Eq. 50 reduces to

$$C_S = C_{A0} (1 - e^{-k_1 t}), \quad k_2 \gg k_1$$

In other words, the rate is determined by  $k_1$  or the first step of the two-step reaction.

If  $k_1$  is much larger than  $k_2$ , then

$$C_S = C_{A0} (1 - e^{-k_2 t}), \quad k_1 \gg k_2$$

# Cont....

setting  $dC_R/dt = 0$ . The time at which the maximum concentration of R occurs is thus

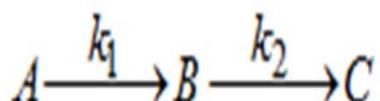
$$t_{\max} = \frac{1}{k_{\log \text{mean}}} = \frac{\ln(k_2/k_1)}{k_2 - k_1} \quad (51)$$

The maximum concentration of R is found by combining Eqs. 49 and 51 to give

$$\frac{C_{R,\max}}{C_{A0}} = \left(\frac{k_1}{k_2}\right)^{k_2/(k_2-k_1)} \quad (52)$$

# Example

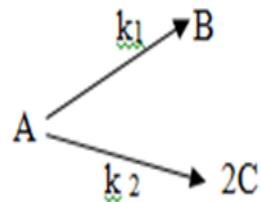
The following reaction,



is carried out in batch reactor. If  $C_B = C_{B,0} = 0$  initially and  $C_{A,0} = 100 \text{ mol/m}^3$  for a given condition a)  $k_1 = 1 \text{ s}^{-1}$ ;  $k_2 = 2 \text{ s}^{-1}$  b)  $k_1 = 1 \text{ s}^{-1}$ ;  $k_2 = 10^4 \text{ s}^{-1}$ , what is the time at which the concentration of B is maximum? What is the maximum concentration of B?

# Example 2

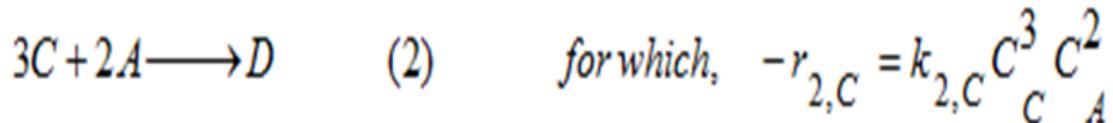
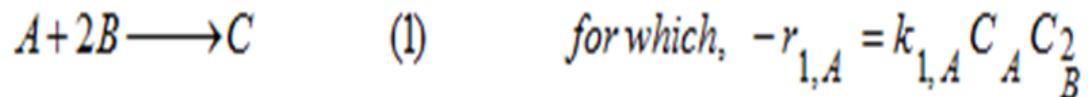
Suppose the following two first-order reaction are occurring in a constant volume and isothermal batch reactor



After a reaction time of 50 min, 90% of a reactant A has decomposed and the product is found to contain 9.1 mole of B per mole of C. Neither B nor C is present initially in the reaction vessel. Evaluate the rate constants  $k_1$  and  $k_2$ .

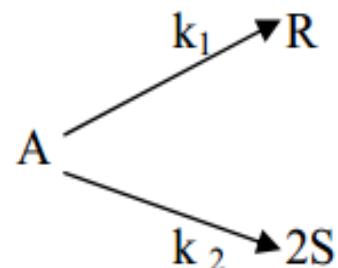
# Exercise

- Write net rates of formation of species A, B, C and D for the following combined reactions:



## 7.2 Comparison of kinetic equations for complex reactions carried out in batch plug flow and tank reactors

- in general three kinds of substances are present in complex reactions: namely **reactants**, **desired** and **undesired products**.
- The concentrations of these substances depend on the type of complex reactions where different rate constants are involved (which may mainly depend on the temperature) and on the type of reactors in which the reactions is carried out



# Batch reactor

The net rate of disappearance of A is

$$-r_A = k_1 C_A + k_2 C_A = (k_1 + k_2) C_A$$

For a batch reactor, the material balance on component A is given by,

$$-r_A = -\frac{1}{V} \frac{dn_A}{dt}$$

Combining the two equations, we get

$$-\frac{1}{V} \frac{dn_A}{dt} = (k_1 + k_2) C_A = (k_1 + k_2) \frac{n_A}{V}$$

and for the constant volume of reaction,

$$-\frac{dn_A}{dt} = (k_1 + k_2) n_A$$

By rearranging and integrating for the condition  $n_A = n_{A,0}$  at  $t = 0$ , we get

$$n_A = n_{A,0} \exp[-(k_1 + k_2)t]$$

## Cont....

Thus, taking account of material balance and the rate laws for the other components, which obeys the following

$$\frac{1}{V} \frac{dn_R}{dt} = k_1 C_A = k_1 \frac{n_A}{V}$$

Again for constant volume, we can express

$$\frac{dn_R}{dt} = k_1 n_A$$

$$\frac{dn_S}{dt} = k_2 n_A$$

In both the equations, there are three variables. In order to find a solution, it requires reduction of variables through the following methods.

# Cont....

## i) By substituting the value of $n_A$ and integrating

$$\frac{dn_R}{dt} = k_1 n_A = k_1 \{n_{A,0} \exp [-(k_1 + k_2)t]\}$$

$$\frac{dn_S}{dt} = k_2 n_A = k_2 \{n_{A,0} \exp [-(k_1 + k_2)t]\}$$

## ii) By applying material balance of the components but avoiding integration

$$n_{A,0} = n_A + n_R + n_S$$

$$n_A = n_{A,0} - n_R - n_S = n_{A,0} - n_R - \frac{k_2}{k_1} n_R$$

$$n_A = n_{A,0} - n_R \left(1 + \frac{k_2}{k_1}\right)$$

$$n_R = \frac{k_1(n_{A,0} - n_A)}{k_1 + k_2}$$

# Cont....

where,  $\frac{n_R}{n_S} = \frac{k_1}{k_2}$

Now, by substituting the value of  $n_A$ , we get

$$n_R = \frac{k_1}{k_1 + k_2} n_{A,0} \{1 - \exp[-(k_1 + k_2)t]\}$$

For constant volume, this equation becomes

$$C_R = \frac{k_1}{k_1 + k_2} C_{A,0} \{1 - \exp[-(k_1 + k_2)t]\}$$

Which is a similar equation to equation (5.7.2), for the condition  $C_{R,0} = 0$ .

In similar manner, we get

$$n_S = \frac{k_2}{k_1 + k_2} n_{A,0} \{1 - \exp[-(k_1 + k_2)t]\}$$

and for constant volume and  $C_{S,0} = 0$ ,

$$C_S = \frac{k_2}{k_1 + k_2} C_{A,0} \{1 - \exp[-(k_1 + k_2)t]\}$$

Dividing equation (5.54.2) by equation (5.55.1) we get overall selectivity of the reaction,

$$\frac{n_R}{n_S} = \frac{k_1}{k_2}$$

The selectivity can directly be calculated by applying time free basis,

$$\frac{dn_R}{dn_S} = \frac{k_1}{k_2}$$

then by integrating for  $n_R = n_S = 0$  at  $t = 0$ , we get

$$\frac{n_R}{n_S} = \frac{k_1}{k_2}$$

and for constant volume, this equation becomes,

$$\frac{C_R}{C_S} = \frac{k_1}{k_2}$$

which is a similar equation to equation (5.10.1).

# Plug flow reactors

For a plug flow reactor, the material balance on component A at steady-state is given by,

$$-r_A = - \frac{dF_A}{dV} \quad (1.7.1)$$

The net rate of disappearance of A is  $-r_A = k_1 C_A + k_2 C_A$ . Combining the material balance and the rate laws, we get

$$-\frac{dF_A}{dV} = (k_1 + k_2)C_A = (k_1 + k_2)\frac{F_A}{F_{V,T}} \quad (5.57.1)$$

By rearranging and integration for constant flow rate, we get

$$F_A = F_{A,0} \exp\left[-(k_1 + k_2)\frac{V}{F_{V,0}}\right] = F_{A,0} \exp[-(k_1 + k_2)\theta_F] \quad (5.57.2)$$

Combining the material balance and the rate laws for the other components, we get

# Cont....

$$\frac{dF_R}{dV} = k_1 C_A = k_1 \frac{F_A}{F_{V,T}}$$

$$\frac{dF_S}{dV} = k_2 C_A = k_2 \frac{F_A}{F_{V,T}}$$

In both equations, there are three variables and it is impossible to integrate as it is. Therefore, the following methods may be adopted to arrive at the solution.

- i) By substituting the value of  $F_A$  and integrating

$$\frac{dF_R}{dV} = k_1 \frac{F_A}{F_{V,T}} = \frac{k_1}{F_{V,T}} \left\{ F_{A,0} \exp \left[ - (k_1 + k_2) \frac{F_A}{F_{V,T}} \right] \right\} \quad (5.58.2)$$

$$\frac{dF_S}{dV} = k_2 \frac{F_A}{F_{V,T}} = \frac{k_2}{F_{V,T}} \left\{ F_{A,0} \exp \left[ - (k_1 + k_2) \frac{F_A}{F_{V,T}} \right] \right\} \quad (5.59.2)$$

ii) By applying material balance of the components but avoiding integration

$$F_{A,0} = F_A + F_R + F_S$$

$$F_A = F_{A,0} - F_R - F_S = F_{A,0} - F_R - \frac{k_2}{k_1} F_R$$

then

$$F_R = \frac{k_1(F_{A,0} - F_A)}{k_1 + k_2}$$

$$F_R = \frac{k_1 F_{A,0} \{1 - \exp[-(k_1 + k_2)\theta_F]\}}{k_1 + k_2}$$

By analogy to  $F_R$ , we get

$$F_S = \frac{k_2}{k_1 + k_2} F_{A,0} \{1 - \exp[-(k_1 + k_2)\theta_F]\} \quad (5.59.3)$$

and the selectivity can be obtained dividing equation (5.58.4) by (5.59.3),

$$\frac{F_R}{F_S} = \frac{k_1}{k_2}$$

or volume-free basis,

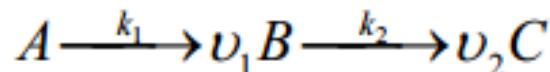
$$\frac{d F_R}{d F_S} = \frac{k_1}{k_2}$$

then, by integrating for  $F_R = F_S = 0$  at  $t = 0$ , we get,

$$\frac{F_R}{F_S} = \frac{k_1}{k_2}$$

# Example

Consider the following consecutive reaction



Reaction is carried out isothermally at 1000 K in a plug flow reactor. The rate constants for the reaction are

$$k_1 = 1.81 \times 10^4 \exp\left(\frac{-81300}{RT}\right) \text{ in } h^{-1}$$

$$k_2 = 1.16 \times 10^1 \exp\left(\frac{50000}{RT}\right) \text{ in } h^{-1}$$

where  $v_1 = 0.90$

Neglecting the change in the total number of moles,

- Calculate the conversion of A & the moles of B product per mole of A fed for space time of 2h.
- Determine the yield of B and the maximum product of B per mol of A fed.

# Solution

The rate equations are

$$r_A = \frac{dF_A}{dV} = -k_1 C_A = -k_1 \frac{F_A}{F_{V,O}}$$

$$r_B = \frac{dF_B}{dV} = r_B = v_1 k_A C_A - k_2 C_B = v_1 k_1 \frac{F_A}{F_{V,O}} - k_2 \frac{F_B}{F_{V,O}}$$

a)

$$k_1 = 1.8 \times 10^4 \exp\left(\frac{-81300}{(8.314)(1000)}\right)$$

$$= 1.0253 \text{ } h^{-1}$$

$$k_2 = 1.16 \times 10^1 \exp\left(\frac{-50000}{(8.314)(1000)}\right)$$

$$= 0.0284 \text{ } h^{-1}$$

# Cont....

By use of a method similar to equation

$$F_A = F_{A,0} e^{-k_1 \theta_F}$$

$$\frac{F_A}{F_{A,0}} = e^{-k_1 \theta_F}$$

...  
and conversion

$$X_A = \frac{F_{A,0} - F_A}{F_{A,0}} = 1 - \frac{F_A}{F_{A,0}}$$

it follows that

$$\begin{aligned} X_A &= 1 - \exp(-k_1 \theta_F) \\ &= 1 - \exp(-1.0253 \times 2) = 0.8713 \end{aligned}$$

# Cont.....

**b)**

The net rate of appearance of B

$$\frac{dF_B}{dV} = v_1 k_1 \frac{F_A}{F_{V,O}} - \frac{k_2 F_B}{F_{V,O}}$$

then

$$\frac{dF_B}{dV} + \frac{k_1 F_B}{F_{V,O}} = v_1 k_1 \frac{F_A}{F_{V,O}}$$

$$\frac{dF_B}{d\theta_F} + k_2 F_B = v_1 k_1 F_A$$

$$\frac{dF_B}{d\theta_F} + k_2 F_B = v_1 k_1 [F_{A,O} e^{-k_1 \theta_F}]$$

Differential equation for the condition  $F_{B,O} = 0$

$$\begin{aligned}\frac{F_B}{F_{A,O}} &= \frac{\nu_1 k_1}{k_2 - k_1} \left( e^{-k_1 \theta_F} - e^{-k_2 \theta_F} \right) \\ &= \frac{(0.9)(1.0253)}{(0.0284 - 1.0253)} [\exp(-1.0253x2)] \\ &= \exp(0.0284x2)\end{aligned}$$

$$\frac{F_B}{F_{A,O}} = 0.7554$$

At the maximum value of  $F_B/F_{A,O}$

$$\frac{d(F_B/F_{A,O})}{d\theta_F} = 0$$

$$\theta_F = \frac{\ln k_2 / k_1}{k_2 - k_1}$$

$$= \frac{\ln 0.0284 / 1.0253}{0.0284 - 1.0253}$$

$$\theta_F = 3.60$$

# Cont....

At this value of  $\theta_F$

$$\begin{aligned}X_A &= 1 - \exp(-1.0253 \times 3.60) = 0.7363 \\&= 0.9750\end{aligned}$$

and

$$\begin{aligned}\frac{F_B}{F_{A,O}} &= \frac{(0.9)(1.0253)}{0.0284 - 1.0253} [\exp(-1.0253 \times 3.60) - \exp(0.0284 \times 3.60)] \\&= 0.8126 \text{ mol of } B \text{ produced per } A \text{ fed}\end{aligned}$$

# Tank reactor

For a tank reactor, the material balance on component A at steady-state is given by,

$$-r_A = \frac{F_{A,0} - F_A}{V}$$

By combining the material balance and the rate laws, we get

$$\frac{F_{A,0} - F_A}{V} = \frac{F_{A,0}}{1 + a\theta_F} \quad )C_A = (k_1 + k_2) \frac{F_A}{F_{V,T}} = a \frac{F_A}{F_{V,T}}$$

where,  $a = k_1 + k_2$ , and  $\theta_F = F_{V,T}$

then the equation can be rearranged as,

$$F_A = \frac{F_{A,0}}{1 + a\theta_F}$$

By combining the material balance and the rate laws for the other components, we get

$$\frac{F_R - F_{R,0}}{V} = k_1 C_A = k_1 \frac{F_A}{F_{V,T}}$$

$$\frac{F_S - F_{S,0}}{V} = k_2 C_A = k_2 \frac{F_A}{F_{V,T}}$$

# Cont....

By rearranging for  $F_{R,0} = F_{S,0} = 0$  at  $t = 0$ , we get

$$F_R = F_{A,0} \frac{(k_1 \theta_F)}{1 + a \theta_F}$$

$$F_S = F_{A,0} \frac{(2k_2 \theta_F)}{1 + a \theta_F}$$

Division of the number of equation , gives us

$$\frac{F_R}{F_S} = \frac{k_1}{2k_2}$$

To obtain  $F_R$  and  $F_S$  as a function of space velocity we take account of the material balance and kinetic law equations and we get,

# Cont..

$$\frac{F_R - F_{R,0}}{V} = k_1 \frac{F_A}{F_{V,T}}$$

$$F_R - F_{R,0} = k_1 F_A \cdot \frac{V}{F_{V,T}} = k_1 F_A \theta_F$$

$$F_R = F_{R,0} + k_1 F_A \theta_F = F_{R,0} + k_1 \theta_F \left( \frac{F_{A,0}}{1 + a \theta_F} \right)$$

$$F_R = F_{R,0} + F_{A,0} \frac{k_1 \theta_F}{1 + a \theta_F}$$

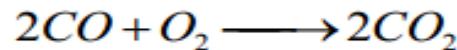
By Analogy to  $F_R$ , gives us

$$F_S = F_{S,0} + \frac{2F_{A,0}k_2\theta_F}{1 + a\theta_F}$$

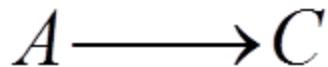
## 7.3 Chain of reactions

Chain reactions can be classified into the following types of reactions

### 1. The reactions of combustions and slow oxidation in the gas phase *example*



2. The various reactions involving hydrocarbon e.g..  
*hydrocarbon cracking in the explosive decomposition of acetylene*
3. Photo chemical reactions i.e. reactions effected by light absorptions e.g. *formations of HBr*
4. Nuclear chain reactions Ex. The decay of  $U^{235}$  in an atomic bomb



which involves the stages as given under:

Stage	Reaction	Process remarks
i. Initiation	$A + A \longrightarrow M$	Intermediate reaction
ii. Propagation	$A + M \longrightarrow B$	Intermediate reaction
iii. Termination	$A + B \longrightarrow C$	Stable reaction

where M and B are chain carriers.

The following reaction is a classic example of the chain reaction:



Initiation:	$Br_2 \longrightarrow 2 Br$
Propagation:	$Br + H_2 \longrightarrow 2 HBr + H$
	$Br_2 + H \longrightarrow HBr + Br$
	$H + HBr \longrightarrow H_2 + Br$
Termination:	$2 Br \longrightarrow Br_2$

where Br and H are chain carriers.

# Autocatalytic Reactions

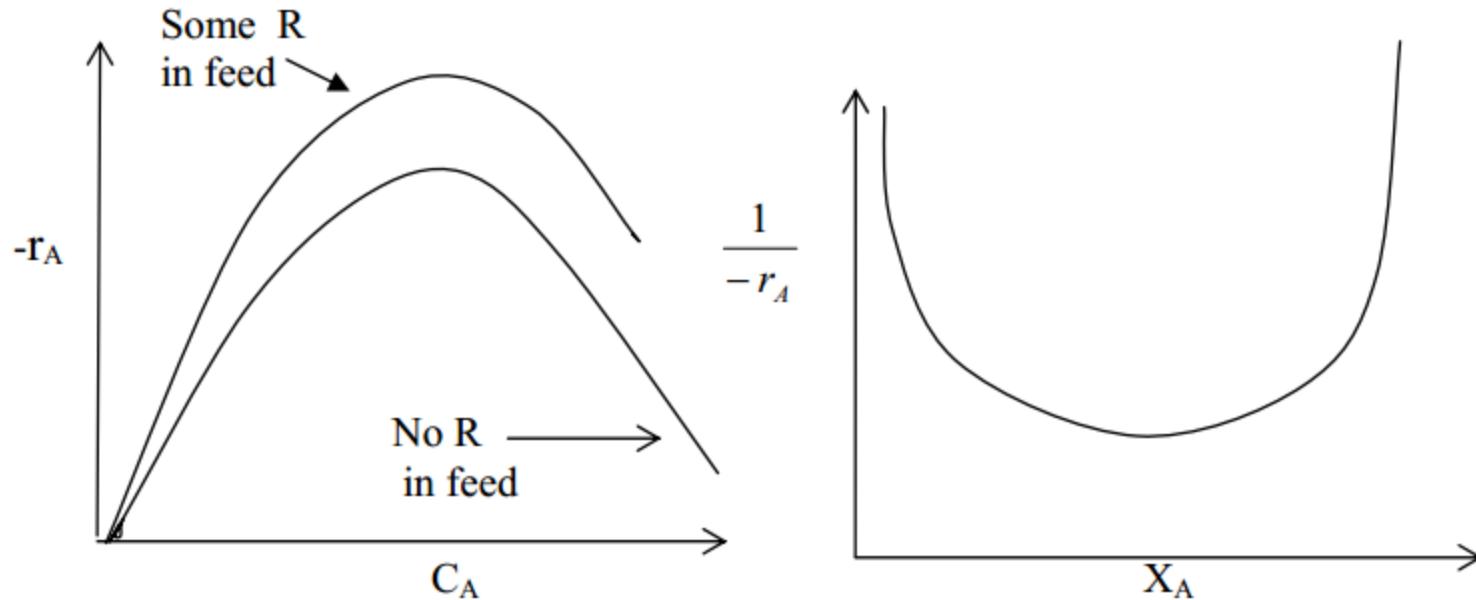
- A reaction in which one of the products of reaction acts as a catalyst is called an autocatalytic reaction. The simplest such reaction is



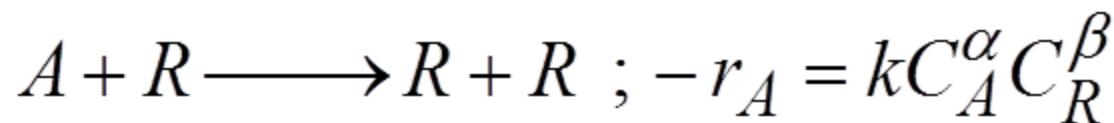
for which the rate equation is

$$-r_A = -\frac{dC_A}{dt} = kC_A C_R \quad (41b)$$

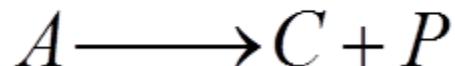
- Because the total number of moles of A and R remain unchanged as A is consumed, we may write that at any time



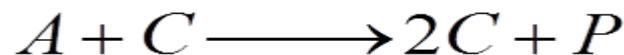
**Figure 7.4** Typical rate-concentration curve for autocatalytic reactions,



Let us consider, an autocatalytic reaction



With an assumed mechanism of



$$-\frac{dC_A}{dt} = kC_A C_C$$

$$\frac{C_A - C_{A,0}}{-1} = \frac{C_C - C_{C,0}}{1}$$

$$\begin{aligned} C_C &= C_{A,0} + C_{C,0} - C_A \\ &= M_0 - C_A \end{aligned}$$

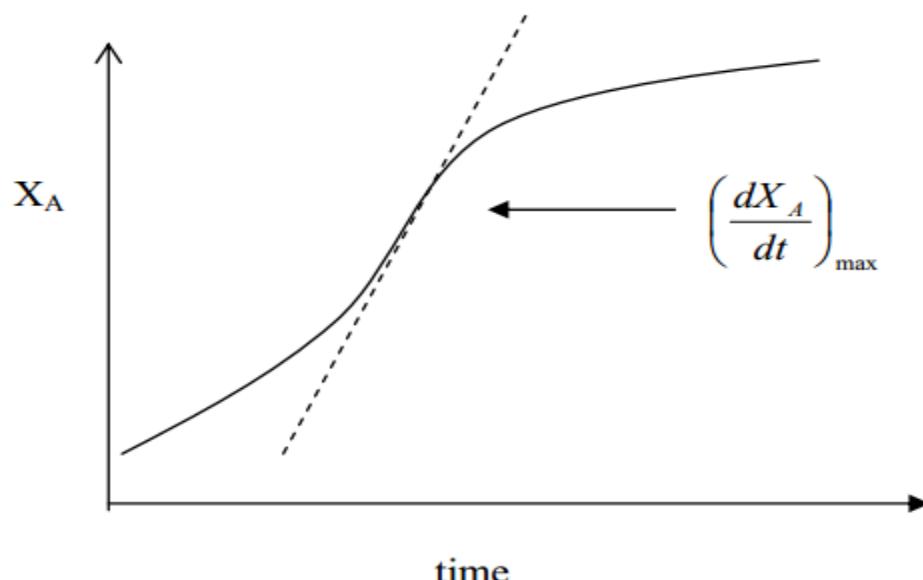
where  $M_0 = C_{A,0} + C_{C,0} = \text{Constant}$

# Cont..

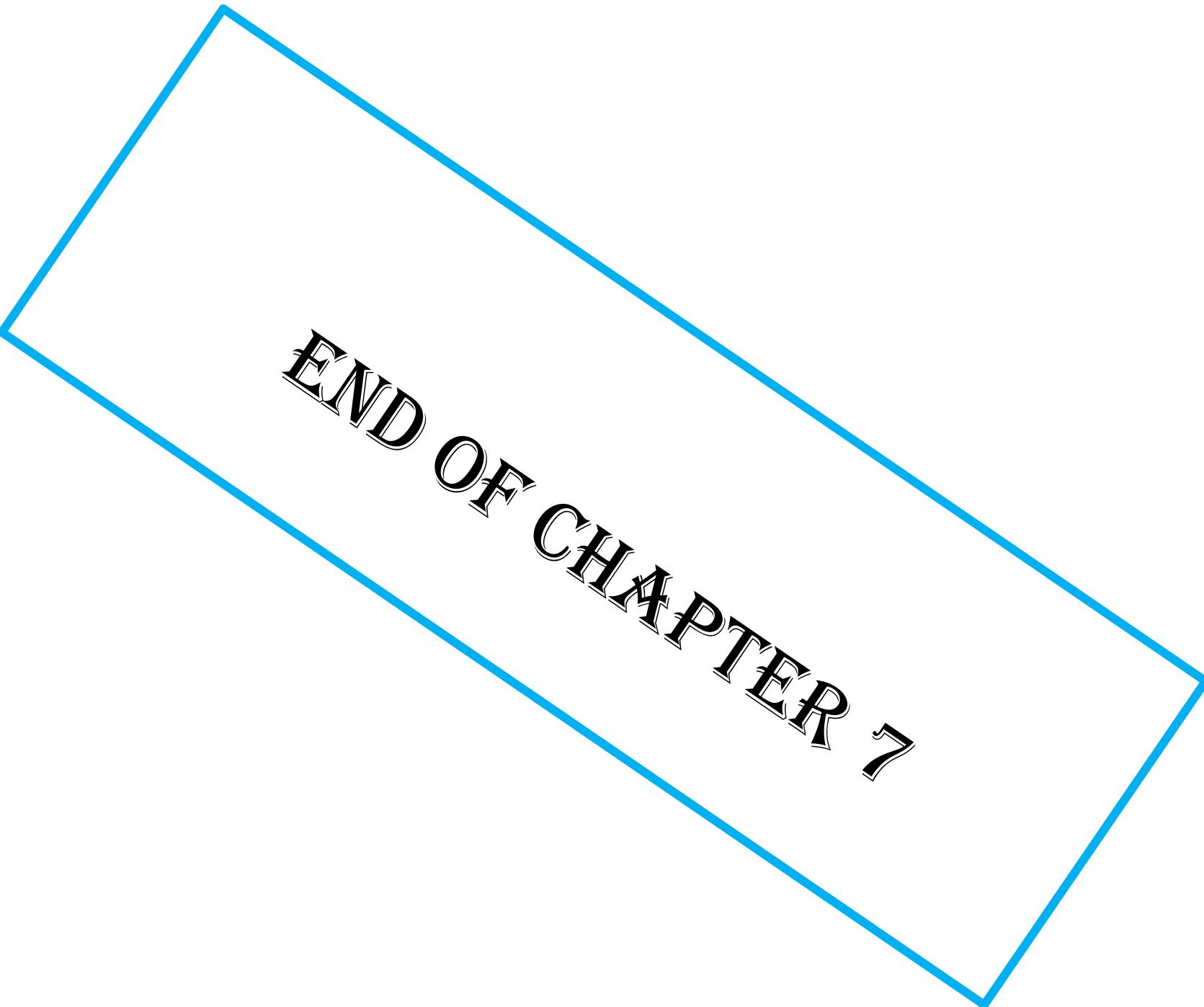
$$-\frac{dC_A}{dt} = kC_A(M_0 - C_A)$$

$$\frac{C_A}{C_{A,0}} = \frac{(M_0 / C_{C,0}) \exp(-M_0 kt)}{1 + (C_{A,0} / C_{C,0}) \exp(-M_0 kt)}$$

$$X_A = \frac{1 - \exp(-M_0 kt)}{1 + (C_{A,0} / C_{C,0}) \exp(-M_0 kt)}$$



**Figure 7.5** Characteristic of an autocatalytic reaction



**END OF CHAPTER 7**