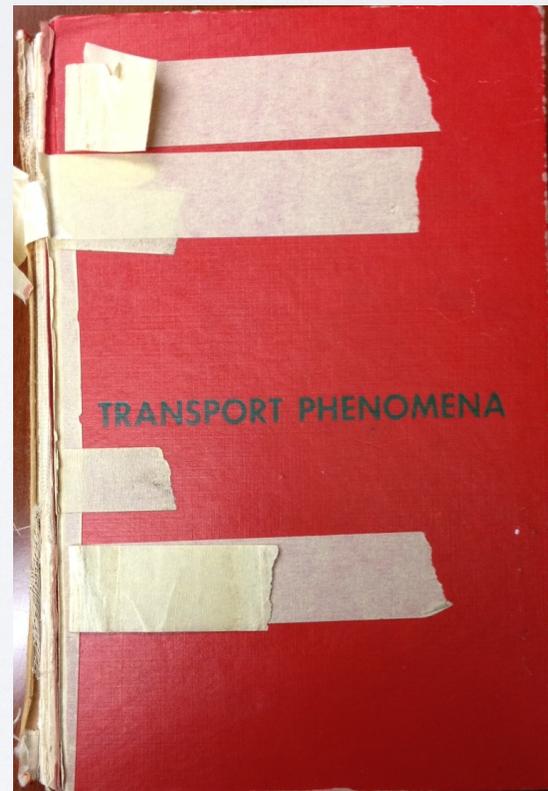


INTRODUCTION LECTURE  
CBE 60544  
TRANSPORT PHENOMENA

January 15, 2014

# TRANSPORT PHENOMENA

- “name is from the book from 1960 by Robert Bird, Warren Stewart and Ed Lightfoot.

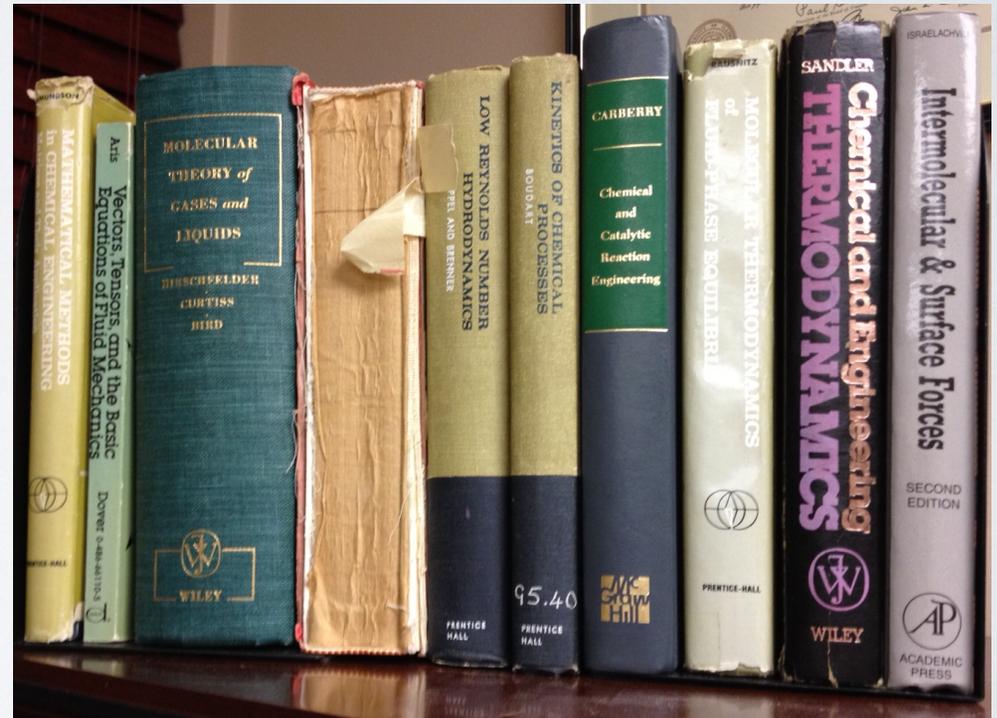
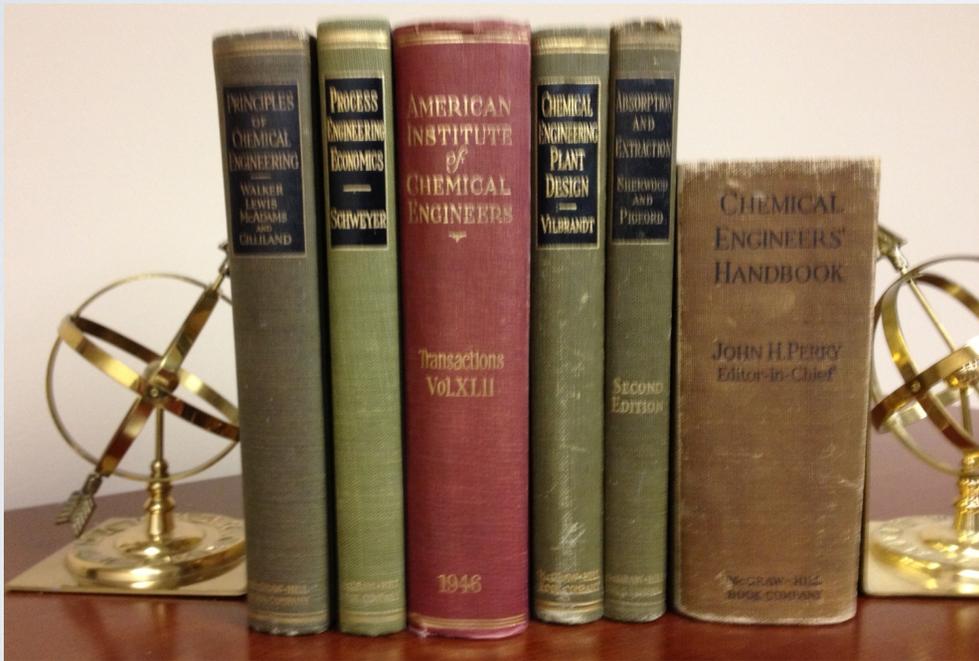


# ONE NOVELTY

TABLE I. SCHEMATIC DIAGRAM OF THE ORGANIZATION OF TRANSPORT PHENOMENA

Entity Being Transported Type of Transport	Momentum	Energy	Mass
TRANSPORT BY MOLECULAR MOTION	1 VISCOSITY $\mu$ Newton's law of viscosity Temperature, pressure, and composition dependence of $\mu$ Kinetic theory of $\mu$	8 THERMAL CONDUCTIVITY $k$ Fourier's law of heat conduction Temperature, pressure, and composition dependence of $k$ Kinetic theory of $k$	16 DIFFUSIVITY $D, D_B$ Fick's law of diffusion Temperature, pressure, and composition dependence of $D, D_B$ Kinetic theory of $D, D_B$
TRANSPORT IN LAMINAR FLOW OR IN SOLIDS, IN ONE DIMENSION	2 SHELL MOMENTUM BALANCES Velocity profiles Average velocity Momentum flux at surfaces	9 SHELL ENERGY BALANCES Temperature profiles Average temperature Energy flux at surfaces	17 SHELL MASS BALANCES Concentration profiles Average concentration Mass flux at surfaces
TRANSPORT IN AN ARBITRARY CONTINUUM	3 EQUATIONS OF CHANGE (ISOTHERMAL) Equation of continuity Equation of motion Equation of energy (isothermal)	10 EQUATIONS OF CHANGE (NONISOTHERMAL) Equation of continuity Equation of motion for forced and free convection Equation of energy (nonisothermal)	18 EQUATIONS OF CHANGE (MULTICOMPONENT) Equations of continuity for each species Equation of motion for forced and free convection Equation of energy (multicomponent)
TRANSPORT IN LAMINAR FLOW OR IN SOLIDS, WITH TWO INDEPENDENT VARIABLES	4 MOMENTUM TRANSPORT WITH TWO INDEPENDENT VARIABLES Unsteady viscous flow Two-dimensional viscous flow Ideal two-dimensional flow Boundary-layer momentum transport	11 ENERGY TRANSPORT WITH TWO INDEPENDENT VARIABLES Unsteady heat conduction Heat conduction in viscous flow Two-dimensional heat conduction in solids Boundary-layer energy transport	19 MASS TRANSPORT WITH TWO INDEPENDENT VARIABLES Unsteady diffusion Diffusion in viscous flow Two-dimensional diffusion in solids Boundary-layer mass transport
TRANSPORT IN TURBULENT FLOW	5 TURBULENT MOMENTUM TRANSPORT Time-smoothing of equations of change Eddy viscosity Turbulent velocity profiles	12 TURBULENT ENERGY TRANSPORT Time-smoothing of equations of change Eddy thermal conductivity Turbulent temperature profiles	20 TURBULENT MASS TRANSPORT Time-smoothing of equations of change Eddy diffusivity Turbulent concentration profiles
TRANSPORT BETWEEN TWO PHASES	6 INTERPHASE MOMENTUM TRANSPORT Friction factor $f$ Dimensionless correlations	13 INTERPHASE ENERGY TRANSPORT Heat-transfer coefficient $h$ Dimensionless correlations (forced and free convection)	21 INTERPHASE MASS TRANSPORT Mass-transfer coefficient $k_c$ Dimensionless correlations (forced and free convection)
TRANSPORT BY RADIATION	Numbers refer to the chapters in this book	14 RADIANT ENERGY TRANSPORT Planck's radiation law Stefan-Boltzmann law Geometrical problems Radiation through absorbing media	This book may be studied either as "optional" or as "core"
TRANSPORT IN LARGE FLOW SYSTEMS	7 MACROSCOPIC BALANCES (ISOTHERMAL) Mass balance Momentum balance Mechanical energy balance (Bernoulli equation)	15 MACROSCOPIC BALANCES (NONISOTHERMAL) Mass balance Momentum balance Mechanical and total energy balance	22 MACROSCOPIC BALANCES (MULTICOMPONENT) Mass balances for each species Momentum balance Mechanical and total energy balance

# EVOLUTION OF CHEMICAL ENGINEERING AS AN ACADEMIC DISCIPLINE



# CHEMICAL ENGINEERING CORE TODAY



# HANS HAUG REACTOR SPECIALIST AT DUPONT



**The more you  
know, the better  
engineer you will  
be!**

# RANDOM PAPER

Journal of Surgical Research 103, 55–60 (2002)

doi:10.1006/jsre.2001.6340, available online at <http://www.idealibrary.com> on



## Local Pharmaceutical Release from a New Hydrogel Implant

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**Background.** Solid hydrogel polymers can act as reservoirs for controlled drug release. The object of this study was to quantify release kinetics for a single example of a class of uniquely structured hydrogels. The polymer of this study belongs to a class of permanent implants that release pharmaceuticals by diffusion from an entangled cross-linked matrix rather than by absorption of the implant by the body. The cross-linked matrix (CLM) of this study is biocompatible and polymerized *in situ*, forming a solid that is mechanically bonded to the implant site. It can seal tissue as well as deliver drugs at predetermined rates. We evaluated dye and antibiotic egress and assessed release kinetics and retention of antibiotic activity following

tent with a diffusion release mechanism. Antibiotic released from the tissue sealant was shown to be potent by consistent inhibition of *E. coli*.

**Conclusion.** Pharmaceutical release by a representative CLM was found to be controllable by varying the concentration of the pharmaceutical in the activating aqueous solution. The polymerization and release mechanisms did not degrade antibiotic biologic activity. CLMs may be a general class of biocompatible polymers that can locally deliver clinically useful biologics, the release kinetics of which are unaffected by the variability of implant absorption/inflammation mechanisms. © 2002 Elsevier Science (USA)

**Key Words:** cross-linked matrix; antibiotics; controlled release; drug delivery.

# SOME DATA ANALYSIS?

Fit with Log?  
At long times  
curves should  
converge

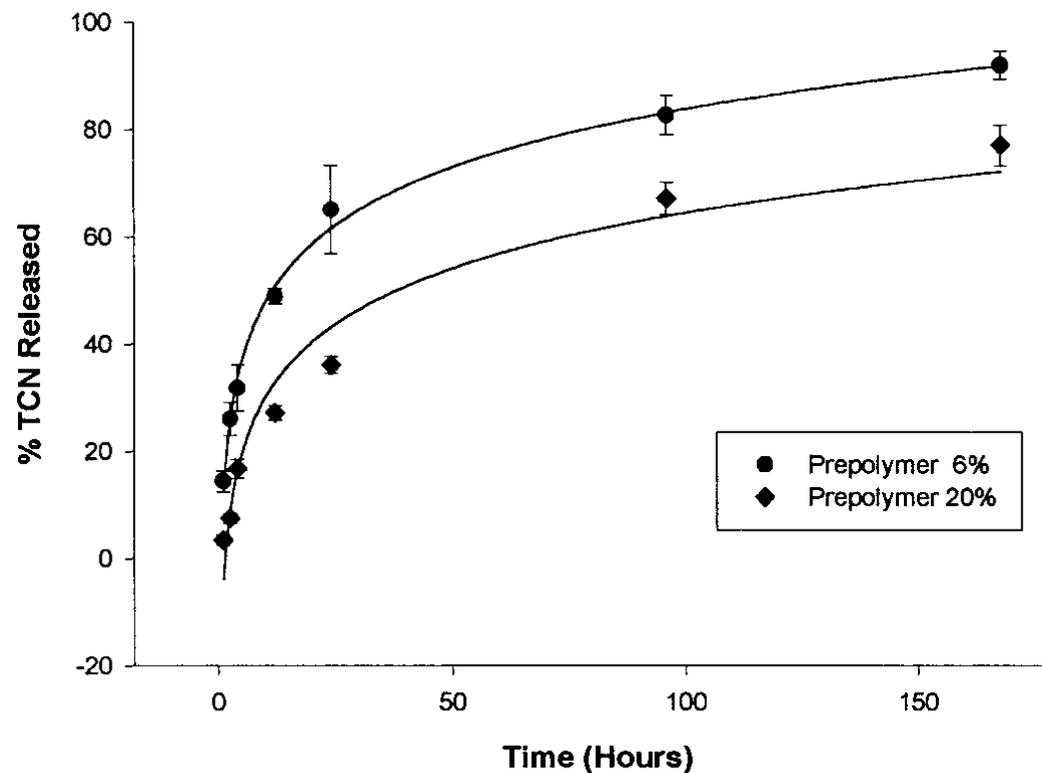
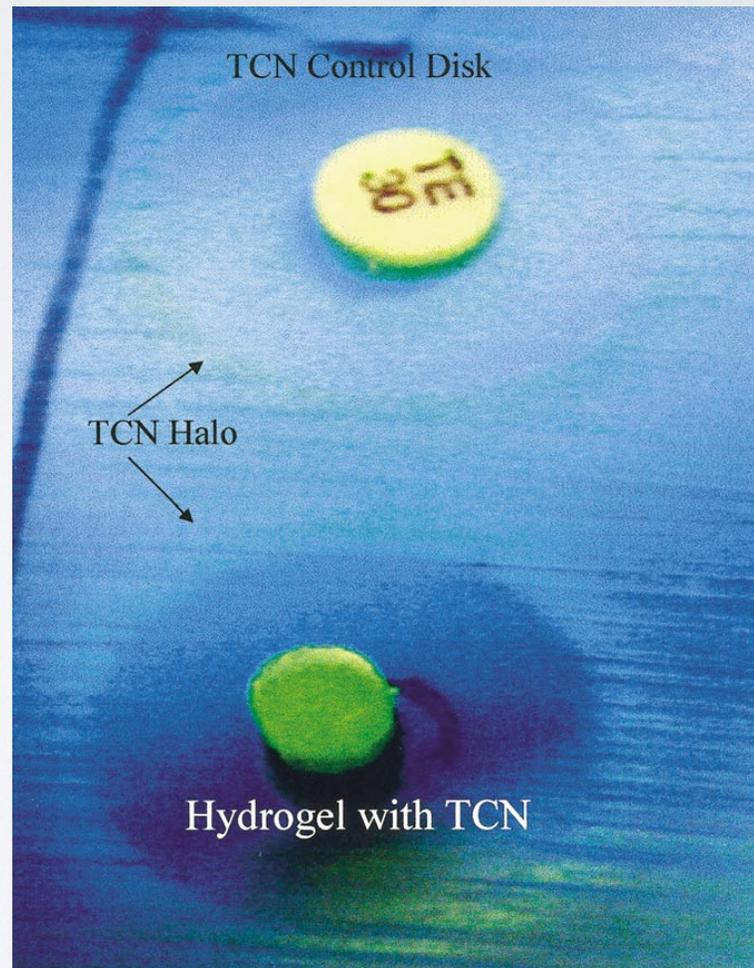


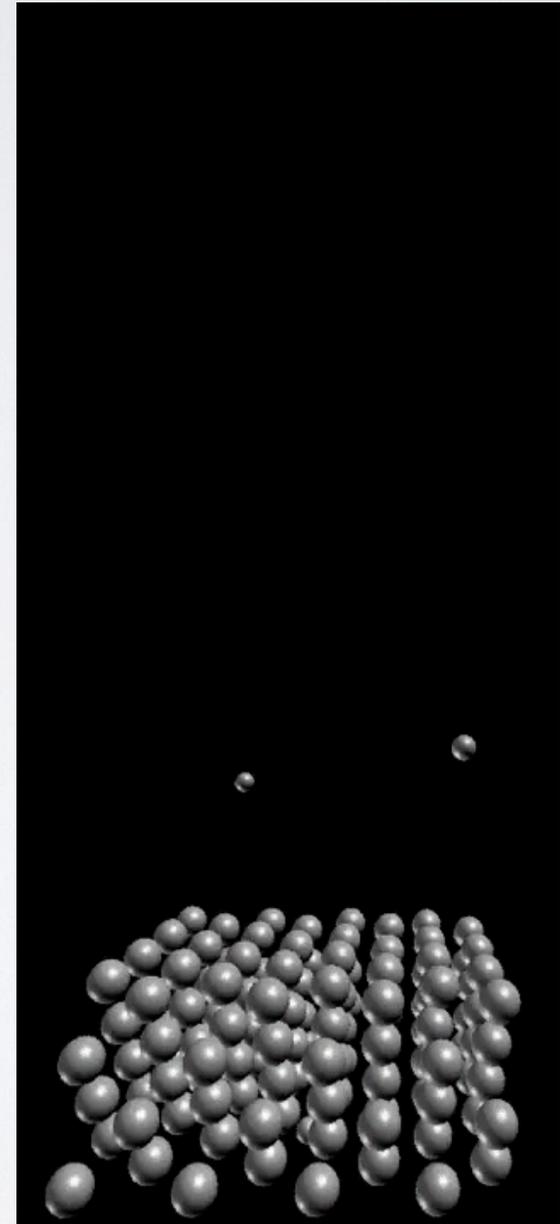
FIG. 2. Release curves for tetracycline from 6 and 20% prepolymer solutions over time. Values at each time point represent percent tetracycline release (mean  $\pm$  SEM).

# WOULD LOVE TO HAVE MORE DATA, $R(T)$

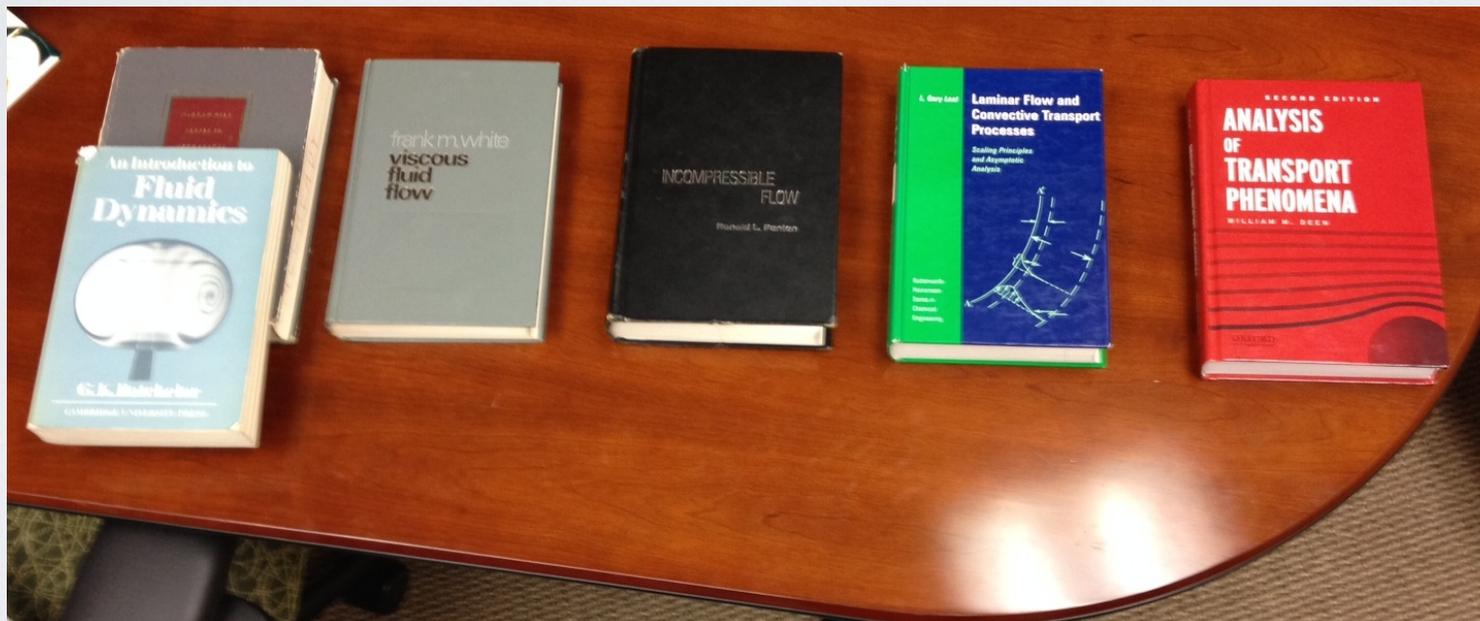
- Should be Bessel function solutions



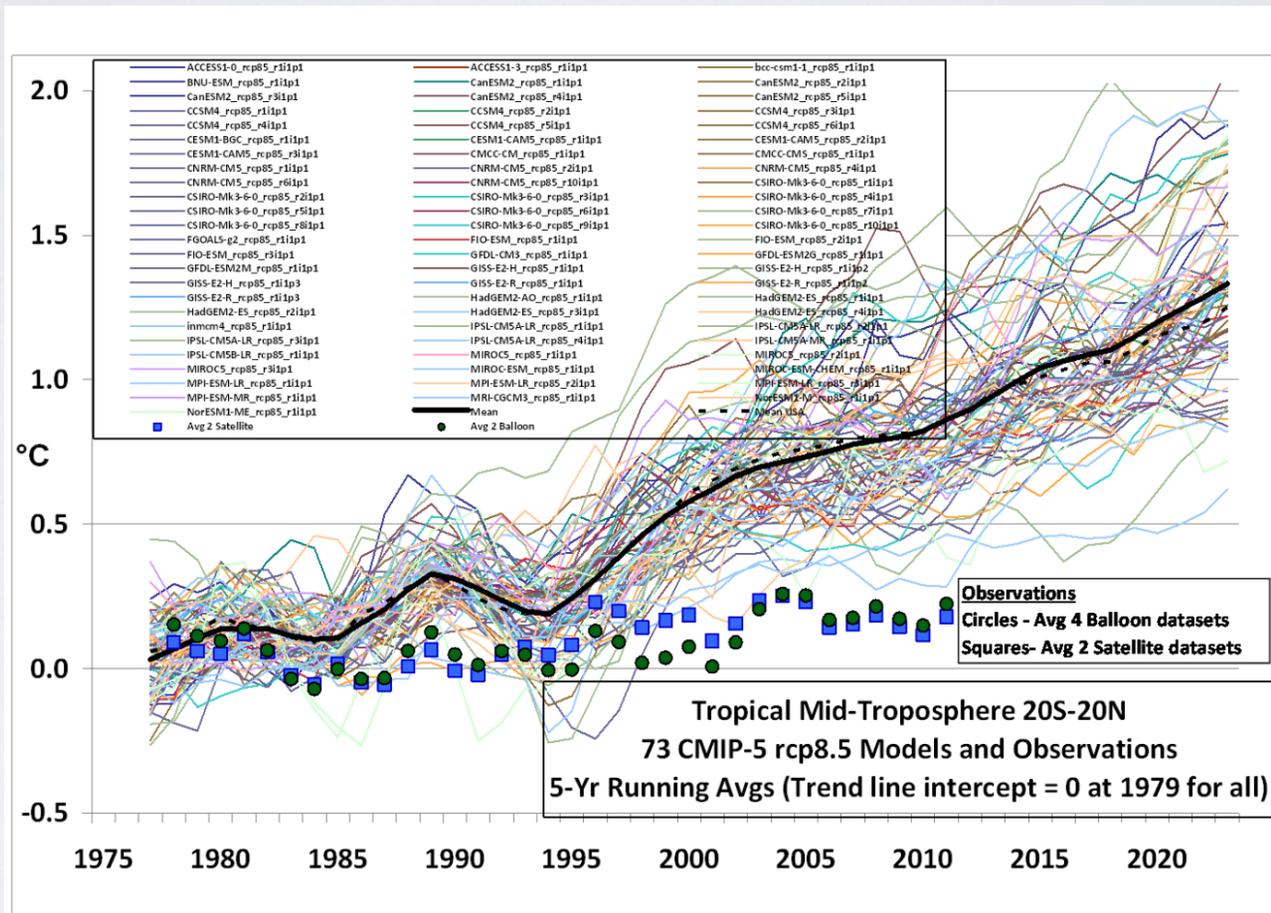
# MOLECULAR SIMULATION



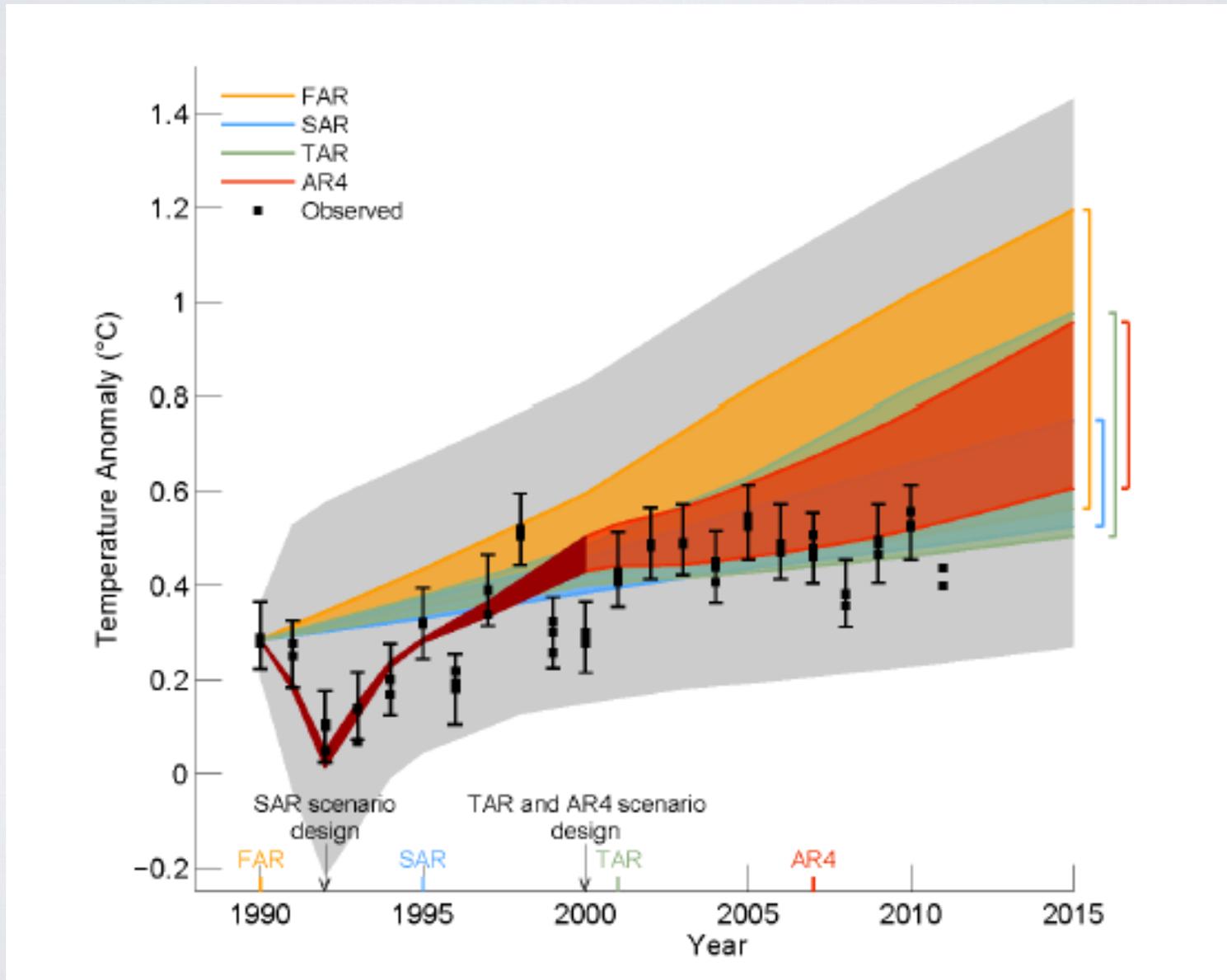
# CBE 60544 EVOLUTION



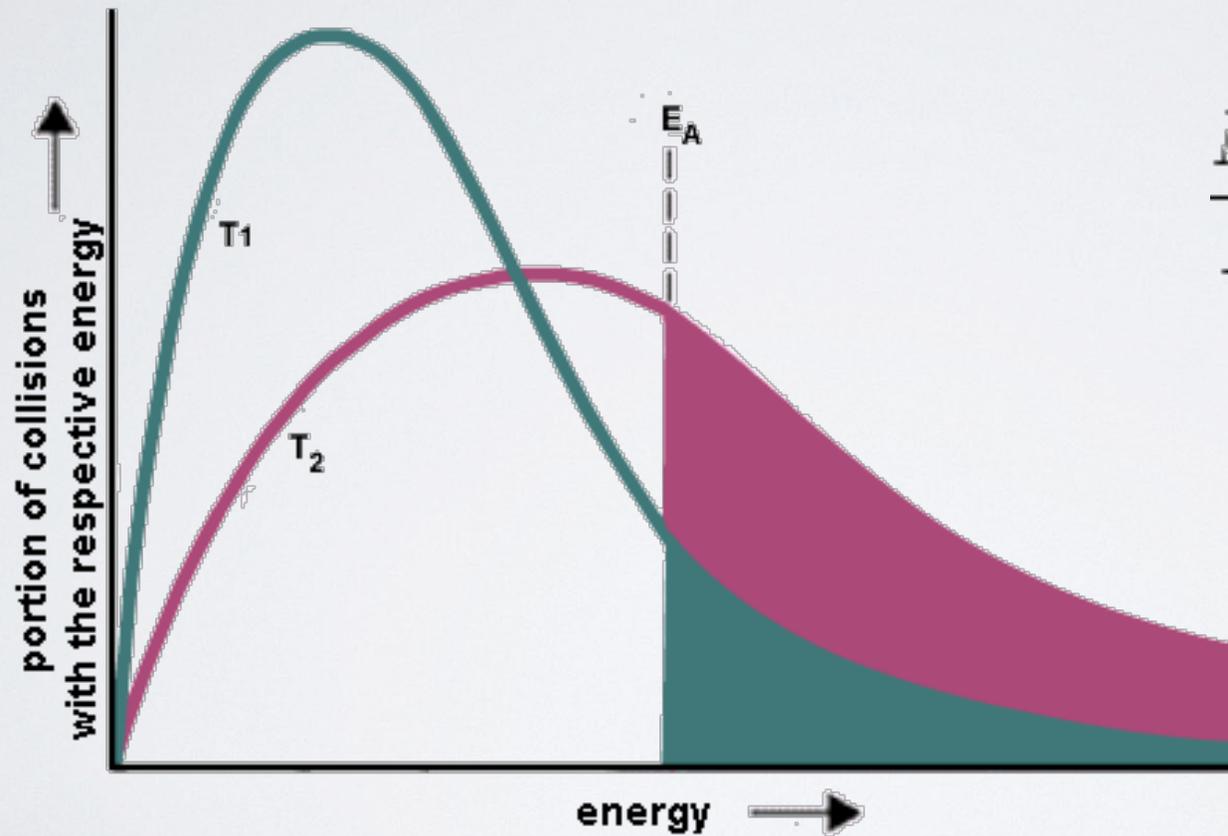
# “WE KNOW THE EQUATIONS”



# “WE KNOW THE EQUATIONS”



# BOLTZMANN DISTRIBUTION



$$\frac{N_i}{N} = \frac{g_i e^{-E_i/(k_B T)}}{Z(T)}$$

# ARRHENIUS KINETICS

- Most (elementary) reactions follow a temperature dependence that is called Arrhenius kinetics:

$$k = A_0 e^{-\frac{E_a}{RT}}$$

- In this equation,  $k$  is the reaction rate constant,  $R$  is the gas constant,  $T$  is absolute temperature,  $E_a$  is the activation energy and  $A_0$  is the “pre-exponential” factor
- The exponential term tells the fraction of molecules that have enough kinetic energy to get over the reaction threshold

$A_0$  is related to the rate at which molecules can rearrange internally and the number of collisions between molecules for unitary values of concentrations. It is a weak function of temperature.

# REACTION RATE W/ TEMP

- You may recall the generalization that reaction rates typically double for a change in temperature of 10K
- While this is a generalization, it is amazingly useful. We will explore why this is the case.

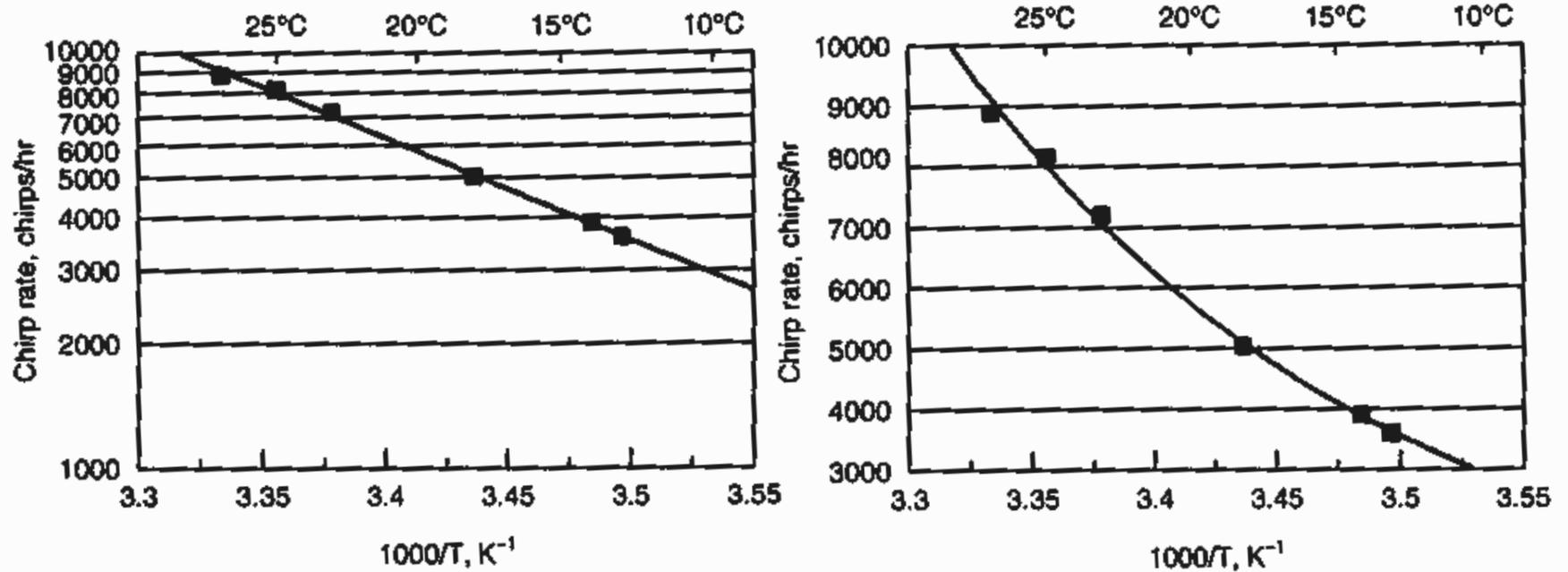
# PROBABLE ORIGIN OF STATEMENT

**Table 2.6 The variation in rate of a series of reactions with a 10-K change in temperature**

Reaction	Temperature range, °C	Rate Change with a 10-K Temperature Change
$\text{CH}_3\text{COOCH}_2\text{CH}_3 + \text{H}_2\text{O} \xrightleftharpoons{\text{H}^+} \text{CH}_3\text{COOH} + \text{CH}_3\text{CH}_2\text{OH}$	3.6–30.4	2.03
$\text{CH}_3\text{CH}_2\text{Cl} + \text{NaOH} \rightleftharpoons \text{H}_2\text{C}=\text{CH}_2 + \text{NaCl} + \text{H}_2\text{O}$	23.5–43.6	2.87
$\text{CH}_3\text{CH}_2\text{CH}_2\text{Cl} + \text{NaOH} \rightleftharpoons \text{CH}_3\text{CH}=\text{CH}_2 + \text{NaCl}$	24.5–43.6	2.68
$\text{HPO}_3 + \text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{PO}_4$	0–61	3.0

*Source:* Data from Van't Hoff (1884).

# CRICKET CHIRP RATES



**Figure 2.11** The rate that crickets chirp as a function of temperature. Data for field crickets (*Gryllus pennsylvanicus*). From Heinrich (1993).

# E-COLI GROWTH RATE

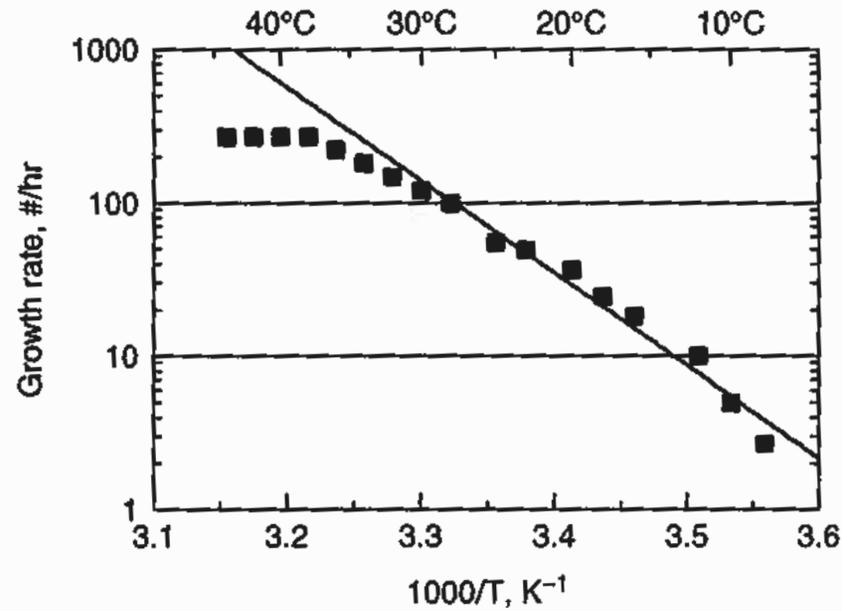


Figure 2.10 The rate of *E. coli* growth as a function of temperature. [Adapted from Bailey and Ollis (1977).]

# PLANT GROWTH

**Table 2.7 The variation in the respiration rate of plants with a 10° change in temperature**

---

Wheat	2.47
Lilac	2.48
Lupine	2.46

---

*Source:* Data from Clausen (1890).

# GEOCHEMICAL REACTIONS

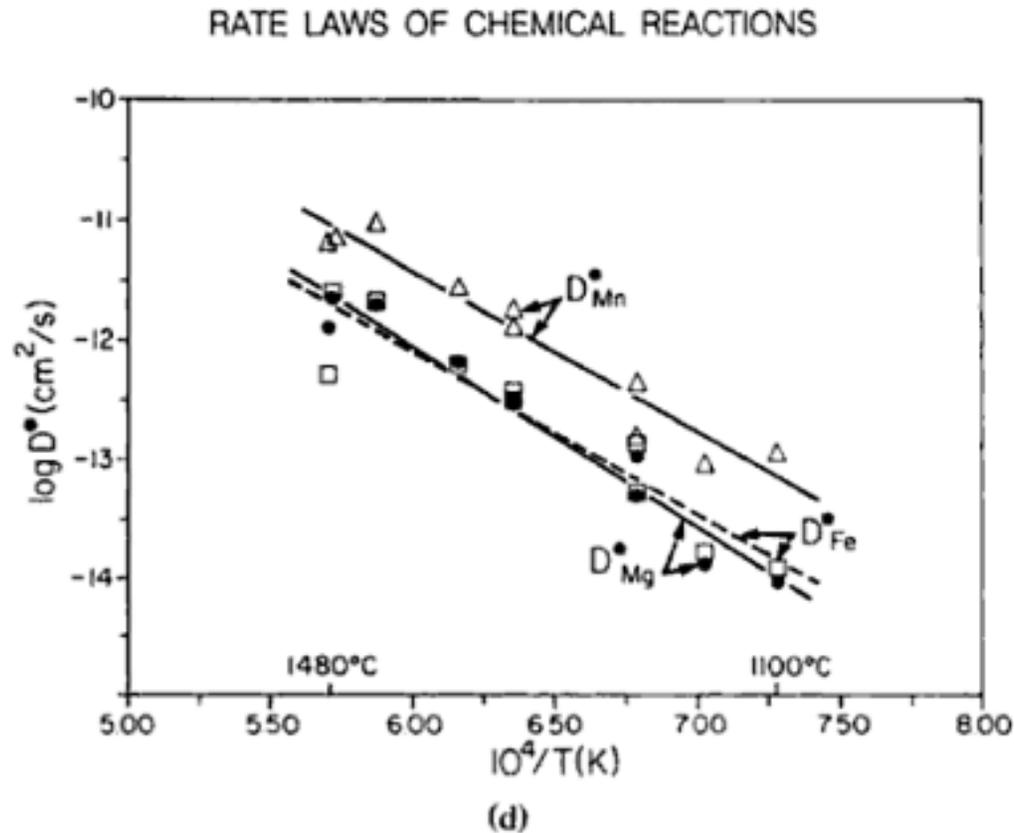


FIGURE 1.24. Some typical Arrhenius plots for geochemical reactions. (d) Mg tracer diffusion data for garnets normalized to 10 kbar and  $f_{\text{O}_2}$  conditions determined by the graphite- $\text{O}_2$  buffer. (Figure and data from Chakraborty and Ganguly 1991 and Chakraborty et al. 1992.)

# REACTION TIME SCALES FOR DIFFERING ACTIVATION ENERGY

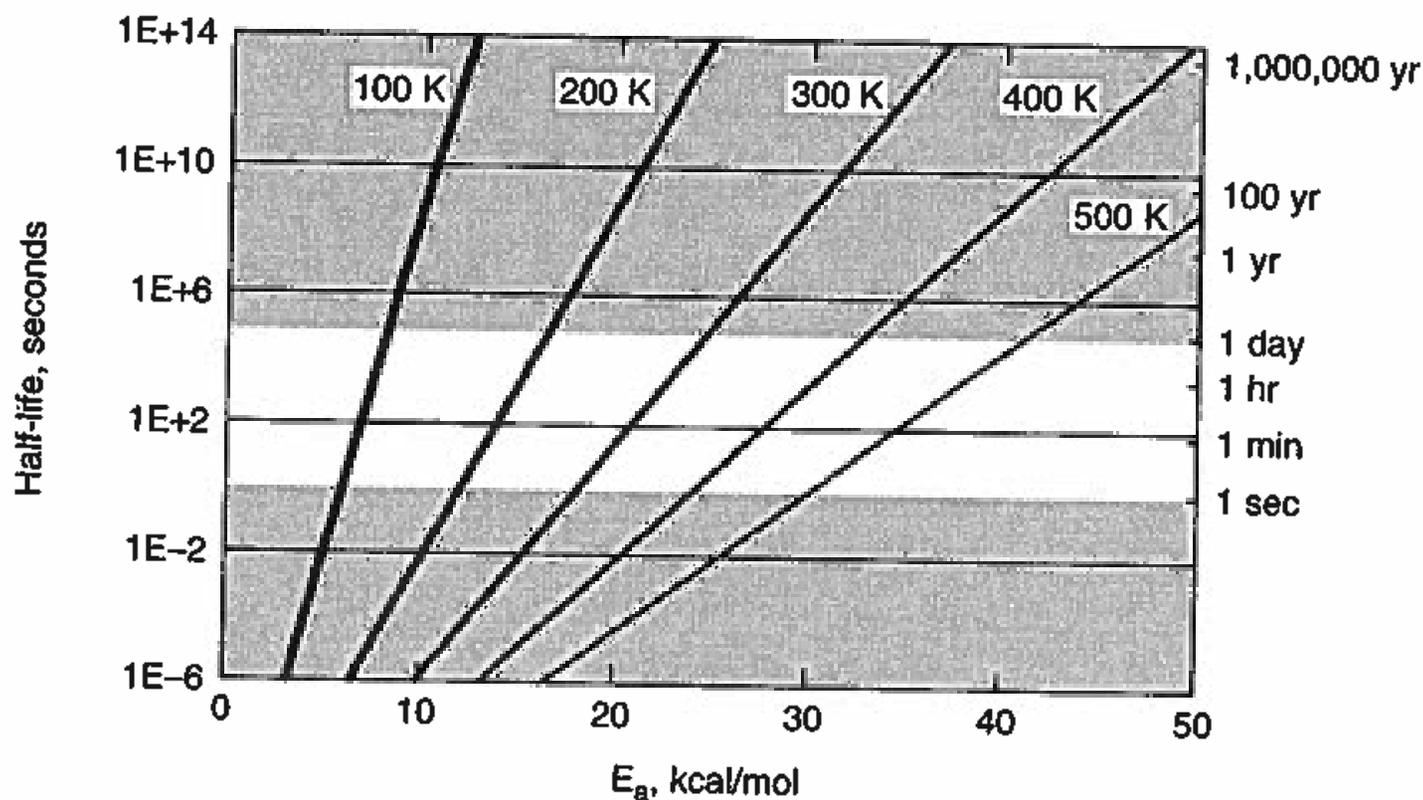
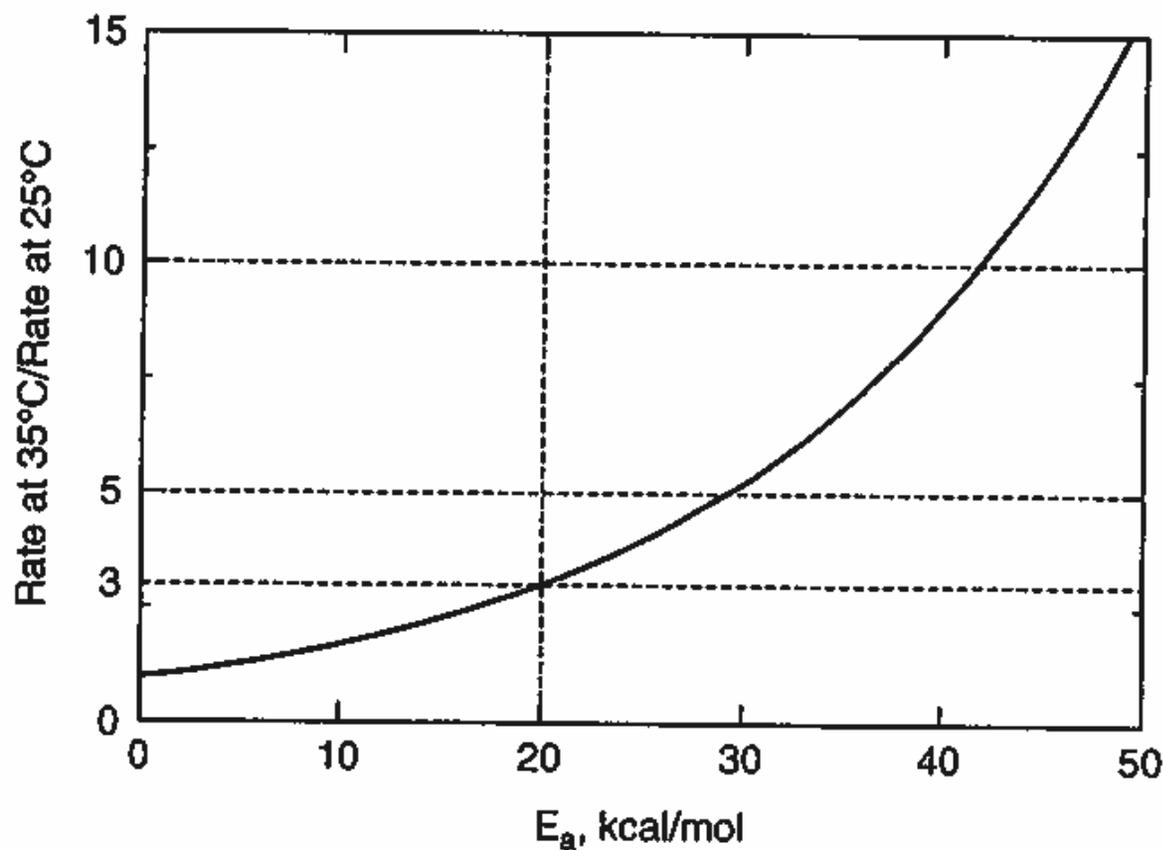


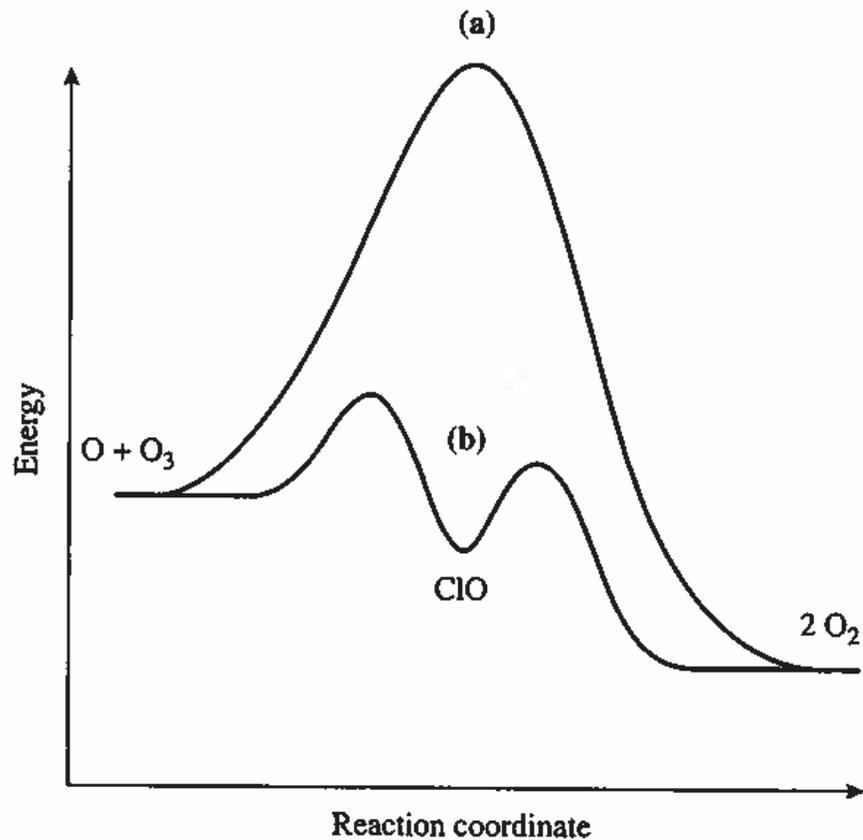
Figure 2.8 A plot of  $\tau_{1/2}$  versus  $E_a$  at 100, 200, 300, 400, and 500 K.

# REACTION RATE CHANGE WITH TEMPERATURE



**Figure 2.9** The fractional change in the rate of an  $n$ th-order reaction when the temperature is changed from 25 to 35°C.

# CATALYZED REACTION PATHWAY



**Figure 4.1.2 |**  
Energy versus reaction coordinate for ozone decomposition.  
(a) direct reaction, (b) Cl catalyzed reaction.

# INDUSTRIAL CATALYSTS

Industrial catalysts operate in the same nominal rate range

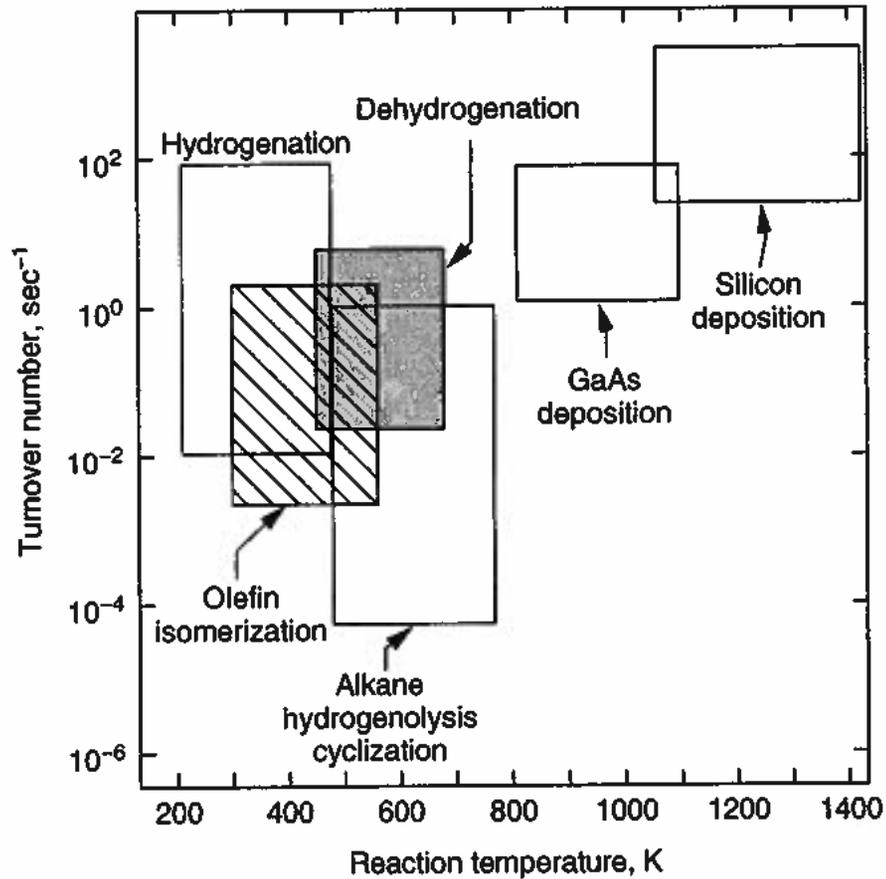


Figure 2.21 Turnover numbers for some typical reactions. [From Masel (1996).]

# REACTING SYSTEMS



- rate of accumulation of moles of “A” =
- rate that moles of A flow into the system -
- rate that moles of A flow out of the system
- - rate at which moles of A are consumed by reaction

$$\frac{d n_A}{dt} = \dot{n}_{A,in} - \dot{n}_{A,out} - \dot{\psi}_{A, reaction}$$

$$V \frac{d C_A}{dt} = q_{in} C_{A,in} - q_{out} C_{A,out} - r_A V$$

$V$  --- Volume of system

$q$  --- volumetric flow rate

$C$  --- concentration moles/volume

$r$  --- reaction rate

# IF NO INFLOW OR OUTFLOW

$$V \frac{d C_A}{dt} = -r_A V$$

$$\frac{d C_A}{dt} = -r_A$$

$$\frac{d C_A}{dt} = -k C_A$$

- Or a more complicated reaction term

# RATE EQUATIONS

$$r_A = k \quad \text{"0 order"}$$

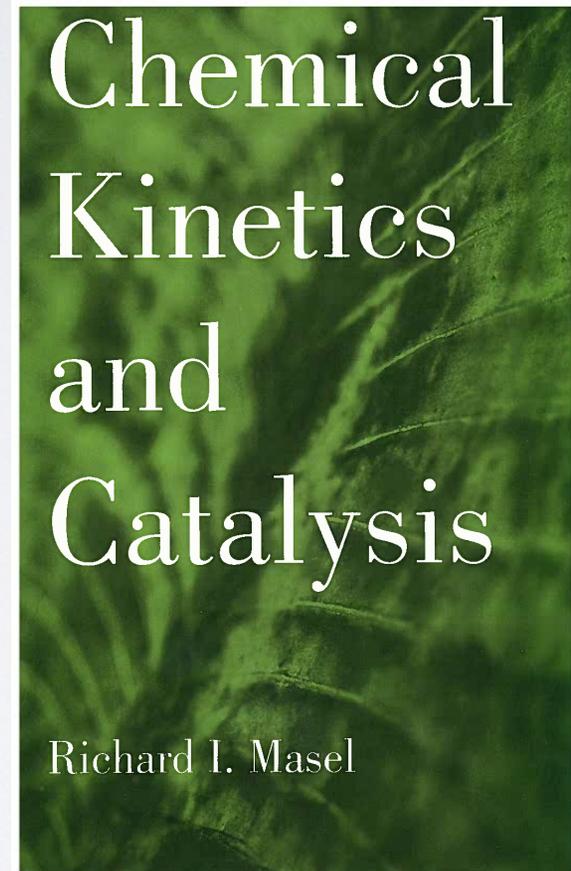
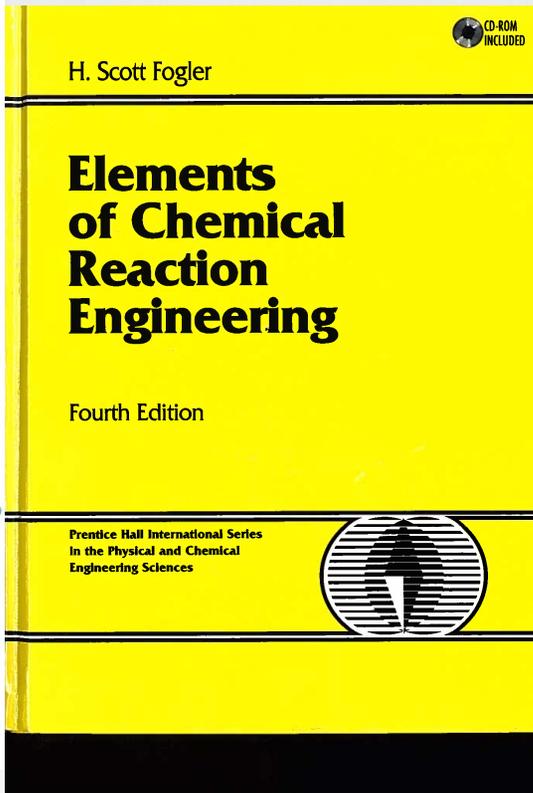
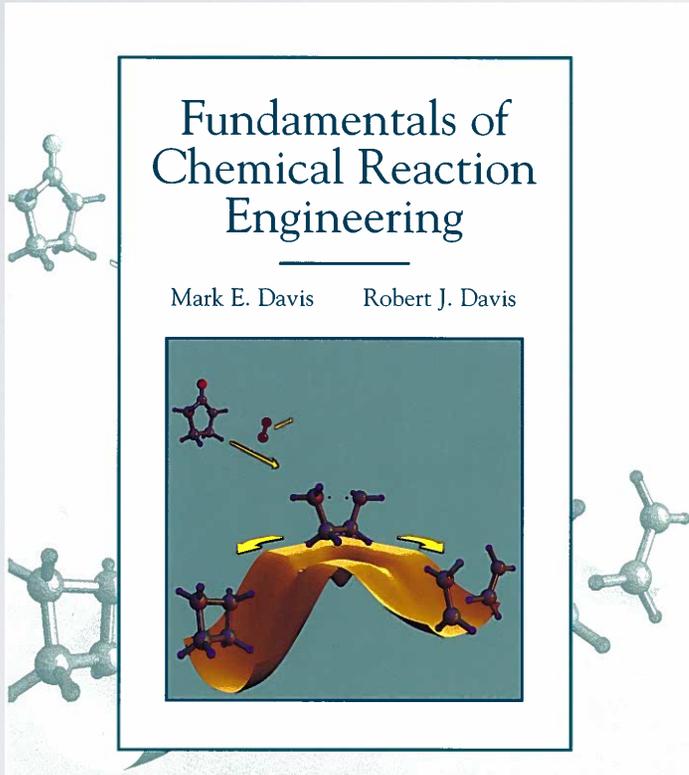
$$r_A = kC_A \quad \text{"1st order"}$$

$$r_A = kC_A C_B \quad \text{"2nd order"}$$

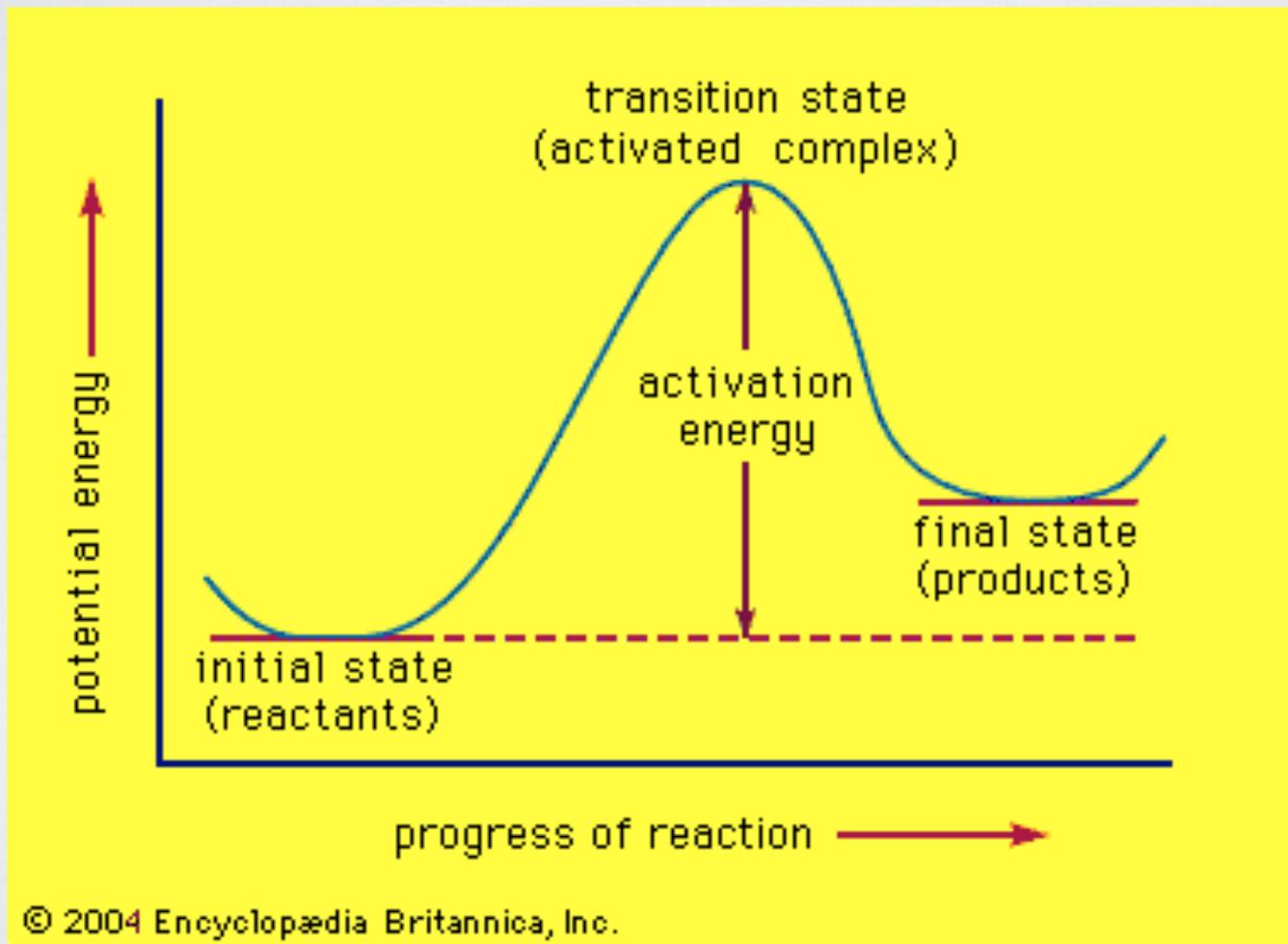
$$r_A = kC_A^n C_B^m \quad \text{"n + m order"}$$

$$r_S = \frac{kC_s C_{Ez0}}{K_m + C_s} \quad \text{(Michaelis-Menton)}$$

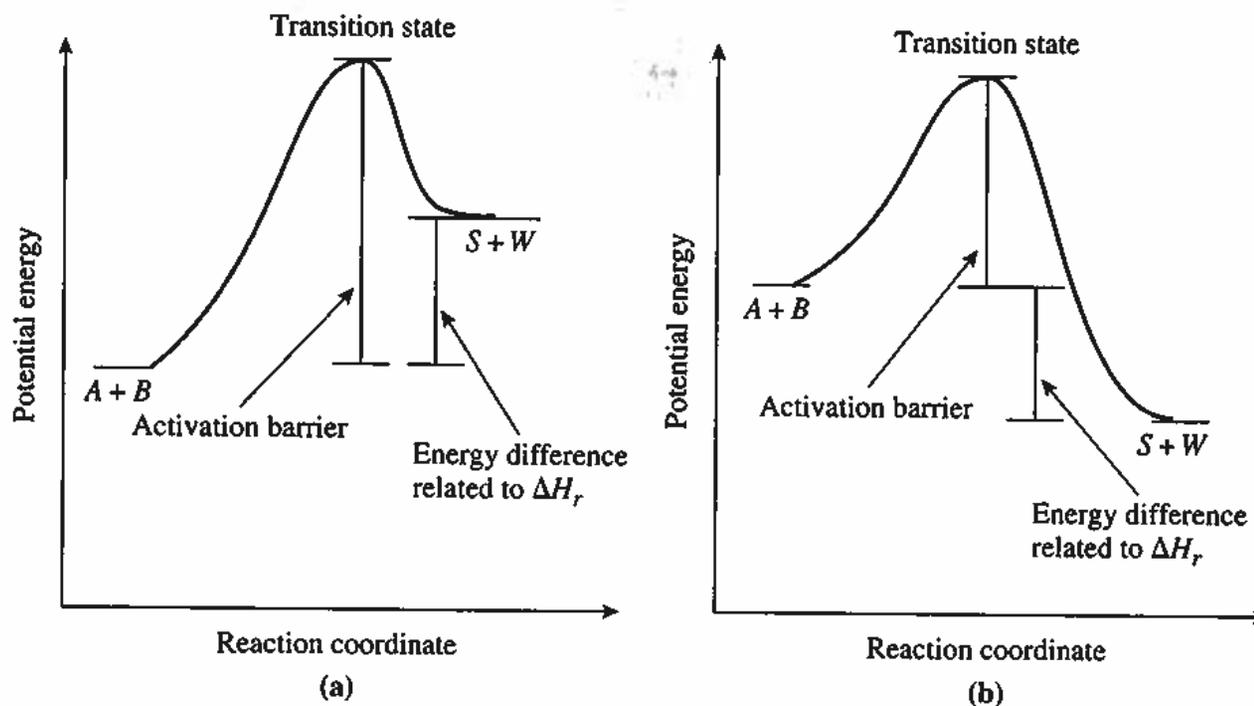
# REFERENCES FOR TODAY



# REACTION PROGRESS



# EXO/ENDOTHERMIC REACTIONS



**Figure 2.3.1 |** Potential energy profiles for the elementary reaction  $A + B \rightarrow S + W$  for (a) an endothermic reaction and (b) an exothermic reaction.

# RATE EQUATIONS

$$r_A = k \quad \text{"0 order"}$$

$$r_A = kC_A \quad \text{"1st order"}$$

$$r_A = kC_A C_B \quad \text{"2nd order"}$$

$$r_A = kC_A^n C_B^m \quad \text{"n + m order"}$$

$$r_S = \frac{kC_s C_{Ez0}}{K_m + C_s} \quad \text{(Michaelis-Menton)}$$

# RATE EQUATIONS FOR CHEMICAL REACTIONS

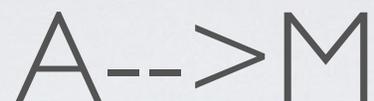
**Table 1.4.3** | Molecularity and rates of elementary steps.

Molecularity	Number of reactant molecules	General description	Example (1)	Rate constant (1)
Unimolecular	1	$A \rightarrow \text{products}$	$\text{N}_2\text{O}_5 \rightarrow \text{NO}_2 + \text{NO}_3$	$1.96 \times 10^{14} \exp[-10660/T], \text{s}^{-1}$
Bimolecular	2	$2A \rightarrow \text{products}$ $A + B \rightarrow \text{products}$	— $\text{NO} + \text{NO}_3 \rightarrow 2\text{NO}_2$	— $2.0 \times 10^{11}, \text{cm}^3/\text{s}/\text{molecule} \text{ (2)}$
Trimolecular (rare)	3	$3A \rightarrow \text{products}$ $2A + B \rightarrow \text{products}$ $A + B + C \rightarrow \text{products}$	— $2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2$ $\text{NO} + \text{NO}_2 + \text{H}_2\text{O} \rightarrow 2\text{HNO}_2$	— $3.3 \times 10^{-39} \exp(530/T), \text{cm}^6/\text{s}/\text{molecule}^2 \text{ (2)}$ $\leq 4.4 \times 10^{-40}, \text{cm}^6/\text{s}/\text{molecule}^2 \text{ (2)}$

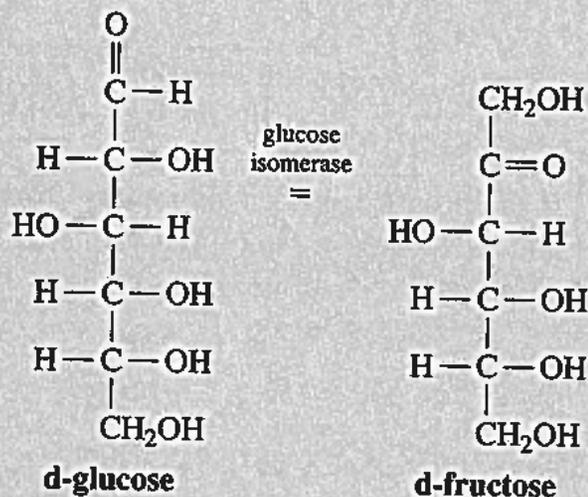
(1) From J. H. Seinfeld, *Atmospheric Chemistry and Physics of Air Pollution*, Wiley, 1986, p. 175.

(2) Concentrations are in molecules/cm<sup>3</sup>.

# UNIMOLECULAR ISOMERIZATION



Glucose isomerase is an enzyme that converts d-glucose into d-fructose:



Although glucose, fructose, and sucrose are all sugars, they are not equally sweet. If sucrose would be ranked as 100 on an arbitrary sweetness scale, then fructose would be 173 and glucose only 74. Therefore, products like Coke and Pepsi now use fructose in their formulations. This fructose is produced from corn. Raw corn starch is "depolymerized" and treated to yield an aqueous solution of glucose that is then converted to fructose by the enzyme glucose isomerase. The enzyme is immobilized on a ceramic support and this heterogeneous catalyst can provide greater than 18 tons of fructose per ton of catalyst.

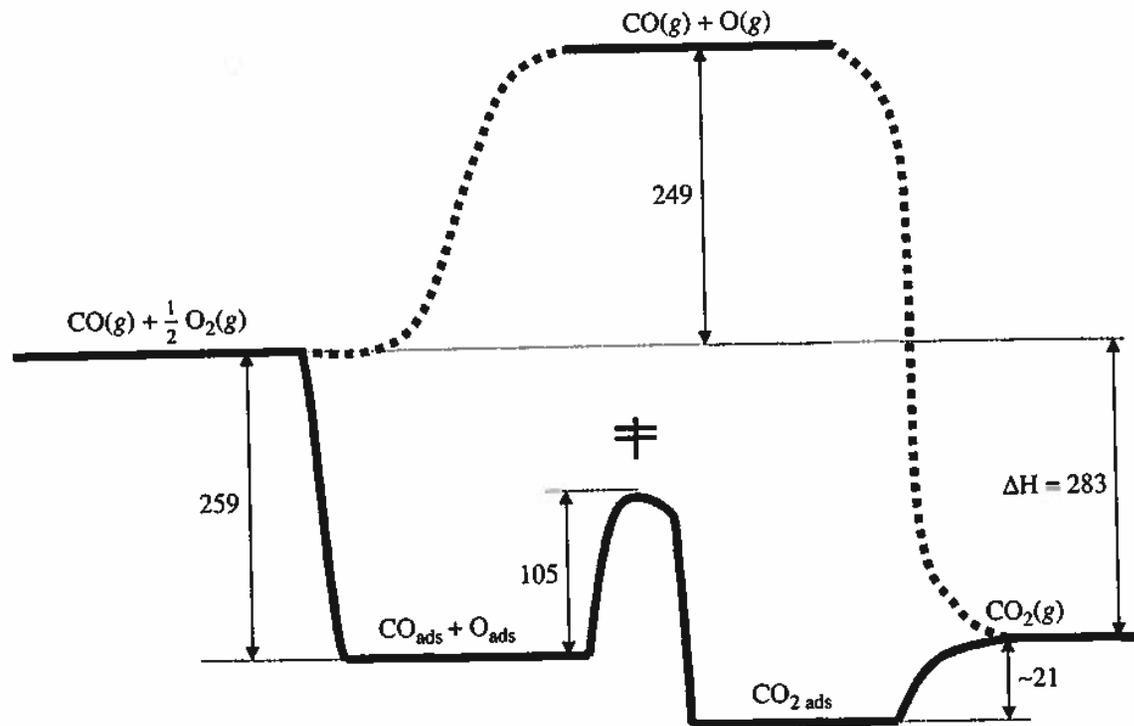
# EFFECT OF CATALYSTS

**Table 2.10** The change in rate of some typical reactions seen when a catalyst is added to the reaction mixture

Reaction	Catalyst	$E_a$ Uncatalyzed, kcal/mol	$E_a$ , Catalyzed, kcal/mol	Rate of Enhancement Calculated at 500 K
$\text{H}_2 + \text{I}_2 \rightarrow 2\text{HI}$	Pt	44	14	$10^{13}$
$2\text{N}_2\text{O} \rightarrow 2\text{N}_2 + \text{O}_2$	Au	58	29	$10^{13}$
$(\text{C}_2\text{H}_5)_2\text{O} \rightarrow 2\text{C}_2\text{H}_4 + \text{H}_2\text{O}$	$\text{I}_2$	53	34	$10^8$

Source: Table adapted from data in Bond (1987).

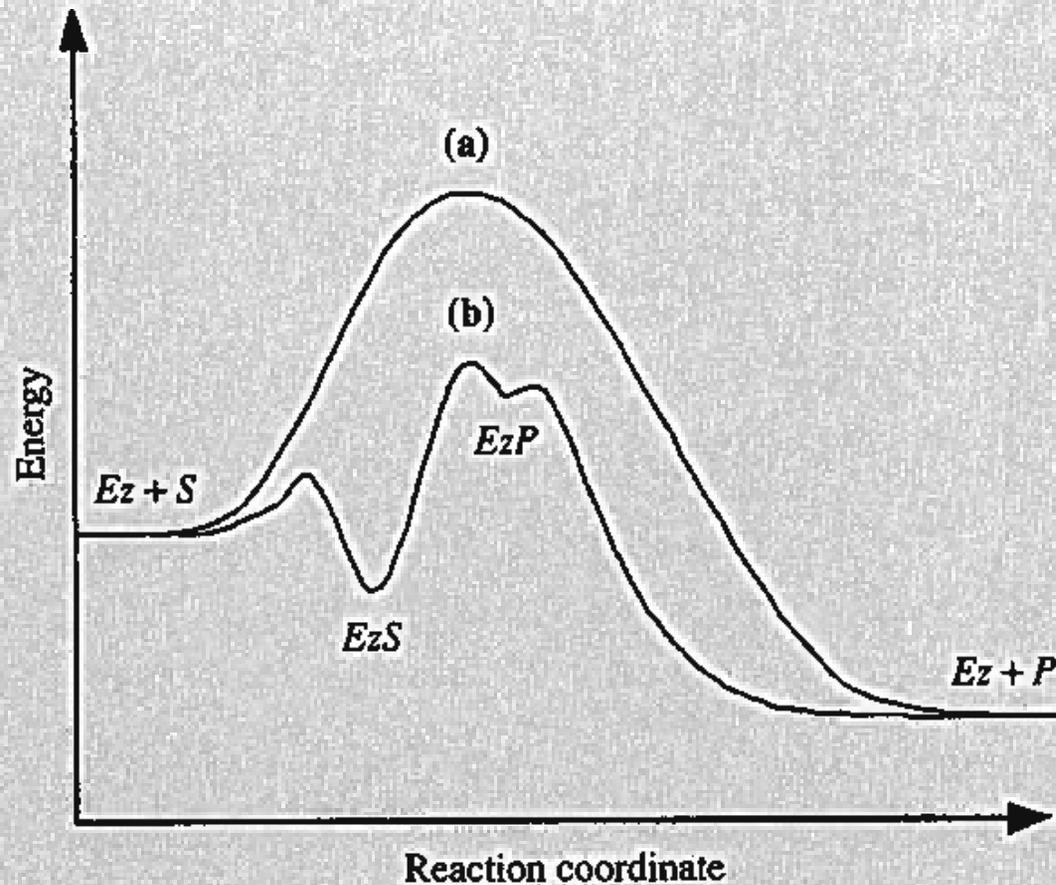
# EFFECT OF CATALYST ON ENERGY PATHWAY



**Figure 5.1.1 |**

Schematic energy diagram for the oxidation of CO and a Pt catalyst. (From data presented by G. Ertl in *Catalysis: Science and Technology*, J. R. Anderson and M. Boudart, Eds., vol. 4, Springer-Verlag, Berlin, 1983, p. 245.) All energies are given in  $\text{kJ mol}^{-1}$ . For comparison, the heavy dashed lines show a noncatalytic route.

# ENZYME CATALYSTS



**Figure 4.2.4** | Energy versus reaction coordinate.  
(a) Direct reaction, (b) enzyme catalyzed reaction.

# INDUSTRIAL CATALYSTS

**Table 2.9 Common Heterogeneous Catalysts**

Catalyst	Reaction
Platinum on alumina, nickel on alumina	Hydrogenation/dehydrogenation
Platinum/tin on acidic alumina	Reforming
Solid acids (zeolites)	Hydrocarbon isomerization, cracking
Silver	$C_2H_4 + \frac{1}{2}O_2 \rightarrow$ ethylene oxide
$(B_2O_3)_x(MO_3)_y$	$CH_2=CHCH_3 + \frac{3}{2}O_2 + NH_3 \rightarrow CH_2CH-CHO + H_2O$
$V_2O_5$	$SO_2 + \frac{1}{2}O_2 \rightarrow SO_3$
Platinum gauze	$2NH_3 + 4O_2 \rightarrow N_2O_5 + 3H_2O$

# “REAL” (APPARENT) KINETICS CAN BE COMPLEX

**Table 2.11** A selection of some of the rate equations for some common catalytic reactions extracted from the compilation of Mezaki and Inoue (1991)

Reaction	Catalyst	Rate Equation
$\text{SO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{SO}_3$	$\text{V}_2\text{O}_5$	$\frac{k_1 K_3 K_4 P_{\text{SO}_2} P_{\text{O}_2}^{1/2} - k_2 K_5 P_{\text{SO}_3}}{1 + K_3 P_{\text{O}_2}^{1/2} + K_4 P_{\text{SO}_2} + K_5 P_{\text{SO}_3}}$
$\text{N}_2 + \frac{3}{2}\text{H}_2 \rightarrow \text{NH}_3$	$\text{Fe}/\text{Al}_2\text{O}_3$	$k_1 P_{\text{N}_2} \left( \frac{P_{\text{H}_2}^3}{P_{\text{NH}_3}^2} \right)^a - k_2 \left( \frac{P_{\text{NH}_3}^2}{P_{\text{H}_2}^3} \right)^{1-a}$
$\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH}$	$\text{CuO}/\text{ZnO}/\text{Al}_2\text{O}_3$	$\frac{k_1 P_{\text{CO}} P_{\text{H}_2}^2 - k_2 P_{\text{CH}_3\text{OH}}}{1 + k_3 P_{\text{H}_2} + k_4 P_{\text{CO}} + k_5 P_{\text{CO}} P_{\text{H}_2}^{3/2}}$
$\text{C}_2\text{H}_4 + \text{H}_2 \rightarrow \text{C}_2\text{H}_6$	$\text{Ni}/\text{Al}_2\text{O}_3$	$\frac{k_1 K_2 K_3 P_{\text{H}_2} P_{\text{C}_2\text{H}_4}}{(1 + K_2 P_{\text{H}_2} + K_3 P_{\text{C}_2\text{H}_4})^2}$
$\text{C}_2\text{H}_4 + \frac{1}{2}\text{O}_2 \rightarrow \text{C}_2\text{H}_4\text{O}$	$\text{Ag}/\text{Al}_2\text{O}_3$	$\frac{k_1 K_2 P_{\text{O}_2} P_{\text{C}_2\text{H}_4}}{1 + K_2 P_{\text{O}_2} P_{\text{C}_2\text{H}_4}}$
$\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2$	$\text{Fe}_2\text{O}_3/\text{Cr}_2\text{O}_3$	$\frac{k_1 K_3 K_4 P_{\text{CO}} P_{\text{H}_2\text{O}} - k_2 K_5 K_6 P_{\text{H}_2} P_{\text{CO}_2}}{(1 + K_3 P_{\text{CO}} + K_4 P_{\text{H}_2\text{O}} + K_5 P_{\text{CO}_2} + K_6 P_{\text{H}_2})^2}$
$4\text{NH}_3 + 6\text{NO} \rightarrow 5\text{N}_2 + 6\text{H}_2\text{O}$	$\text{Pt}$	$\frac{k_1 K_2 K_3 P_{\text{NO}} P_{\text{NH}_3}^{1/2}}{(1 + K_2 P_{\text{NO}} + K_3 P_{\text{NH}_3}^{1/2})^2}$

# OTHER RATE EXPRESSIONS

**Table 1.4.2<sup>1</sup>** | Examples of rate functions of the type:  $r = k \prod_i C_i^{\alpha_i}$ .

Reaction	Rate function
$\text{CH}_3\text{CHO} \Rightarrow \text{CH}_4 + \text{CO}$	$k(\text{CH}_3\text{CHO})^{1.5}$
$\text{C}_2\text{H}_6 + \text{H}_2 \Rightarrow 2\text{CH}_4$ (catalytic)	$k(\text{C}_2\text{H}_6)^{0.9}(\text{H}_2)^{-0.7}$
$\text{SbH}_3 \Rightarrow \text{Sb} + \frac{3}{2} \text{H}_2$	$k(\text{SbH}_3)^{0.6}$
$\text{N}_2 + 3\text{H}_2 \Rightarrow 2\text{NH}_3$ (catalytic)	$k(\text{N}_2)(\text{H}_2)^{2.25}(\text{NH}_3)^{-1.5}$

<sup>1</sup>From M. Boudart, *Kinetics of Chemical Processes*, Butterworth-Heinemann, 1991, p. 17.

# DIFFERENT REACTOR TYPES

TABLE 2-4 TYPICAL SPACE TIME FOR INDUSTRIAL REACTORS<sup>2</sup>

<i>Reactor Type</i>	<i>Mean Residence Time Range</i>	<i>Production Capacity</i>
Batch	15 min to 20 h	Few kg/day to 100,000 tons/year
CSTR	10 min to 4 h	10 to 3,000,000 tons/year
Tubular	0.5 s to 1 h	50 to 5,000,000 tons/year

# TIME SCALES FOR REACTIONS

Table 2-5 shows space times for six industrial reactions and reactors.

TABLE 2-5 SAMPLE INDUSTRIAL SPACE TIMES<sup>3</sup>

	<i>Reaction</i>	<i>Reactor</i>	<i>Temperature</i>	<i>Pressure</i> <i>atm</i>	<i>Space Time</i>
(1)	$C_2H_6 \rightarrow C_2H_4 + H_2$	PFR <sup>†</sup>	860°C	2	1 s
(2)	$CH_3CH_2OH + HCH_3COOH \rightarrow$ $CH_3CH_2COOCH_3 + H_2O$	CSTR	100°C	1	2 h
(3)	Catalytic cracking	PBR	490°C	20	1 s < $\tau$ < 400 s
(4)	$C_6H_5CH_2CH_3 \rightarrow C_6H_5CH=CH_2 + H_2$	PBR	600°C	1	0.2 s
(5)	$CO + H_2O \rightarrow CO_2 + H_2$	PBR	300°C	26	4.5 s
(6)	$C_6H_6 + HNO_3 \rightarrow$ $C_6H_5NO_2 + H_2O$	CSTR	50°C	1	20 min

<sup>†</sup>The reactor is tubular but the flow may or may not be ideal plug flow.

Typical  
industrial  
reaction space  
times

# SIMPLEST PROCESS ECONOMICS

- We might start with a need or desire to produce a certain mass of product per year.
- Immediately we would do a calculation on the expected revenue from such production, \$/year
- The next calculation would be cost to produce

$$\frac{\$}{yr} = \frac{\$}{kg} \frac{kg}{yr} = \frac{\$}{kg} \rho V k$$

- in this equation  $\rho$  is density,  $V$  is reactor volume and  $k$  is the first order reaction constant, “space-time”  $\sim k$
- If  $k$  is too small, then  $V$  will be too big for the process to be economical this is (at least at the moment) a problem with cellulosic ethanol.
- Note that you can increase “ $k$ ” by increasing temperature, there is a limit because this can cost more (unless the reaction is very exothermic) or because the molecules decompose.

# SUMMARY

- Reaction kinetics for a very wide range of reactions follow (or roughly follow) Arrhenius kinetics
- Most important biological reactions need to occur on time scales of seconds and hence have activation energies of approximately 20 kcal/mole.
  - This leads to a doubling of reaction rate in approximately 10 degrees of temperature increase
- While in general, reactions of common components can have arbitrary rates, industrial processes need to be profitable, this requires reaction rates on the order of fractions of a sec or at least not longer than minutes.
  - Thus most industrially significant reactions use a catalyst which reduces the nominal activation energy to be lower than 35-40 kcal/mole. Many typical reactions occur with an activation energy of about 25 kcal/mole. Again, in the range of typical reaction conditions, a 10C increase in temperature causes something close to a doubling of reaction rate.
- Simple process economics can be determined from just knowing the reaction rate (expressed as a first order rate constant.) If the rate is too slow, the reactor volume will be too large for the process to be profitable.