ISOC 2017

Catalytic Mechanisms and High Pressure, Operando Kinetic Studies of Homogeneous Catalysts

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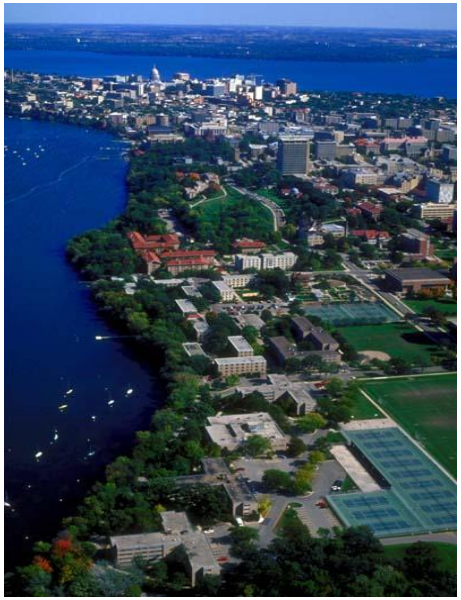


Common Reactions with Gaseous Reagents that Are Catalyzed by Homogeneous Organometallics

Hydrogenation

Hydroformylation

Hydroesterification/Hydrocarboxylation

Ethylene/Propene Polymerization, Oligomerization

Ethylene/Alkene Metathesis

CO_2 Reduction

Oxidation

Heck Reaction

Hydrocyanation

Alcohol Carbonylation

>50 Billion Pounds product per year for homogeneous processes using gases

Regarding Catalysis and Mechanisms

Understanding reaction mechanisms

1. has practical value
2. creates knowledge

AT BEST, mechanistic studies are a process of attrition...

- We can NEVER know a mechanism because

Nature uses Avogadro's number of molecules sampling many pathways on fast time scales

Our brains are too small

- but we CAN eliminate mechanisms that are inconsistent with mechanistic models

Regarding Catalysis and Mechanisms (cont.)

- Catalysts Make Reactions Proceed Faster

  Kinetic studies are intrinsic to understanding catalytic phenomena

- Good Catalysts yield Fast Reactions

- Fundamental Questions in Catalysis:

  How much of the catalyst is active?

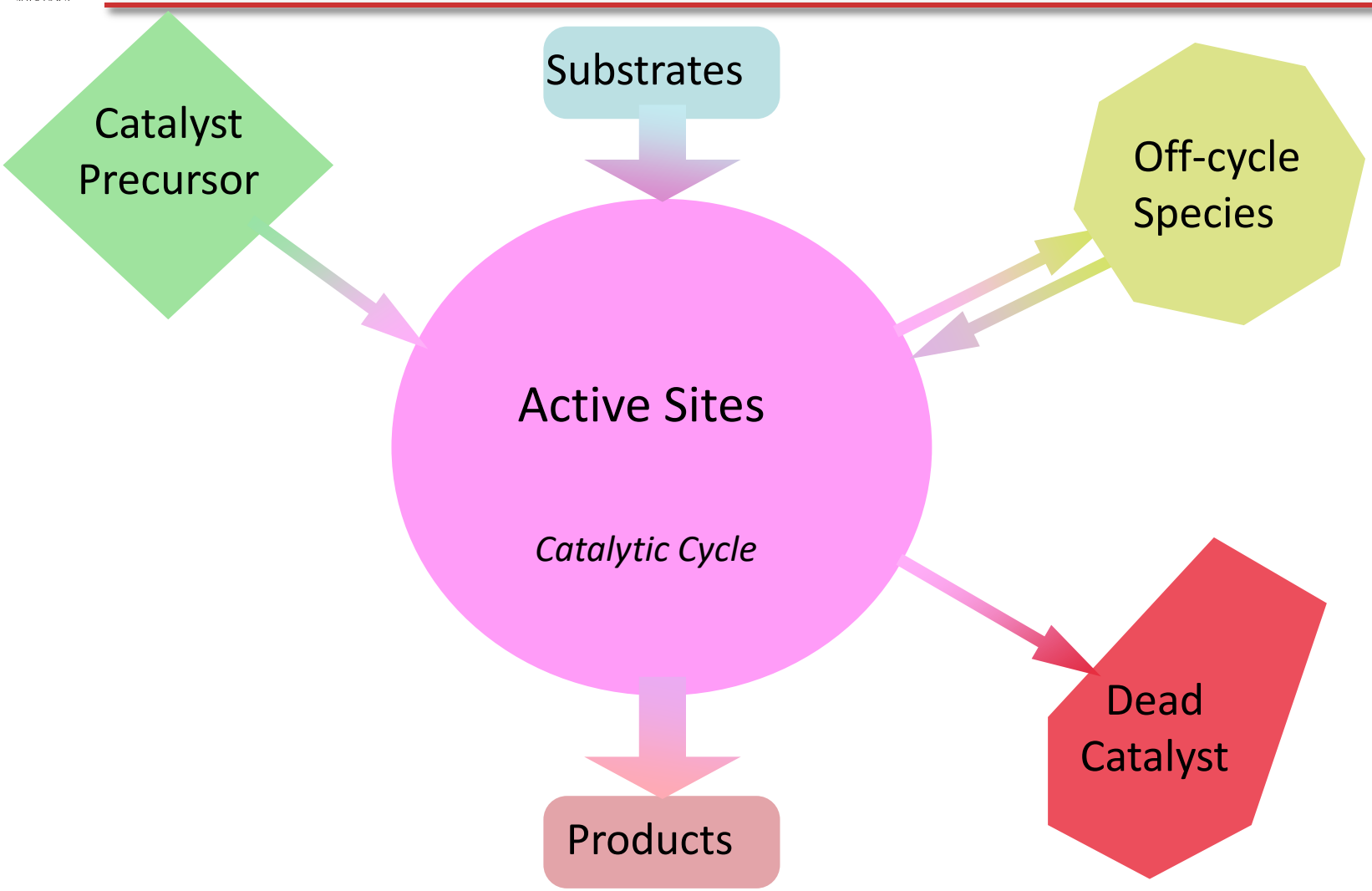
  What is the reaction mechanism?

  What are the rate laws for important steps in the reaction?

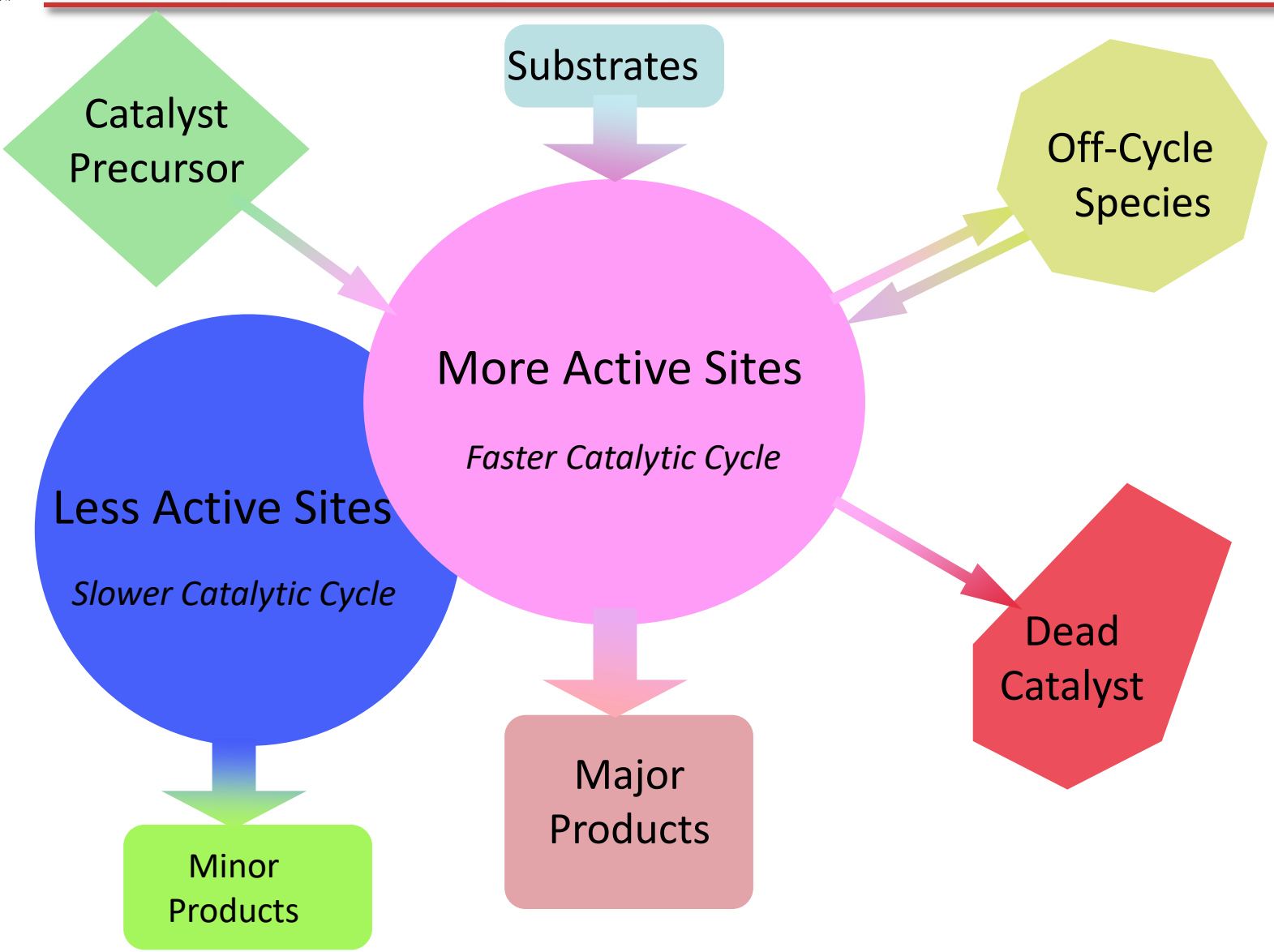
- Fundamental Problems in Catalysis:

  Limited methods for simultaneously monitoring reaction rates and catalyst speciation of good catalysts under realistic conditions

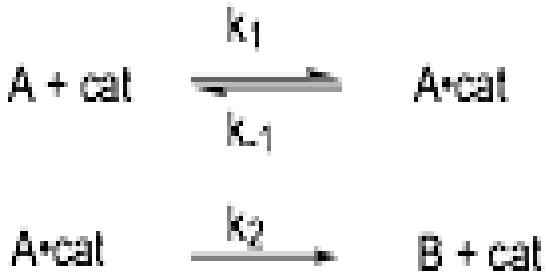
Catalyst Speciation and Terminolgy

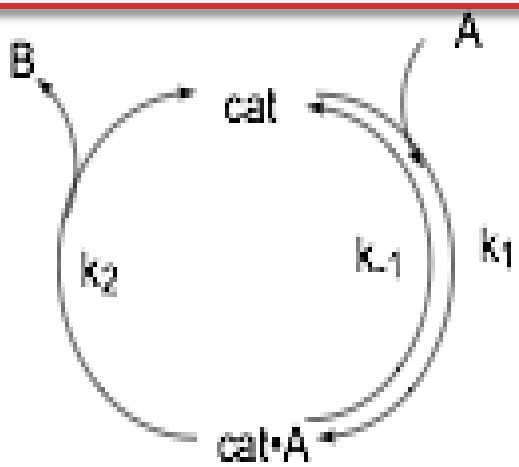


Multiple Catalytic Cycles



Two Step Catalytic Cycle





Consider the following conditions:

[A] is constant, $k_1[A] = 10\ s^{-1}$, $k_{-1} = 1\ s^{-1}$, $k_2 = 0.1\ s^{-1}$

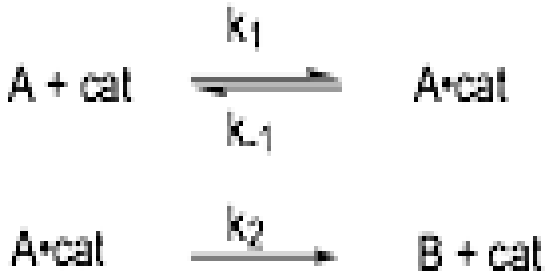
Which one of the following statements is true for the reaction in the steady state?

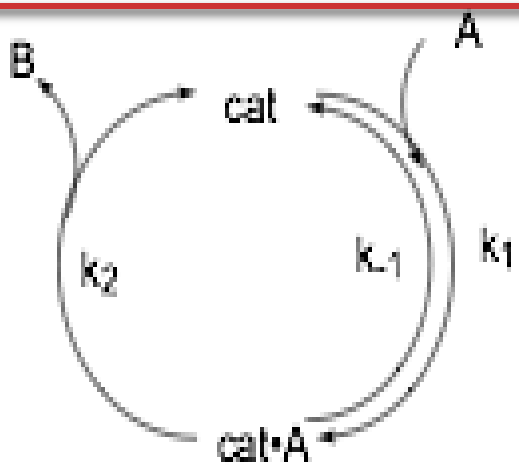
1. The net rates of step 1 and step 2 are the same

2. The concentration of cat > cat•A

3. The resting state is cat

Two Step Catalytic Cycle





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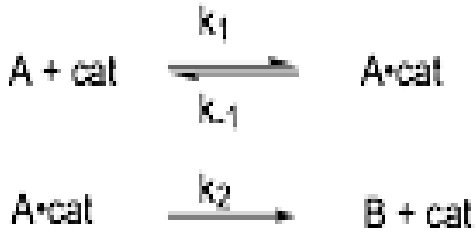
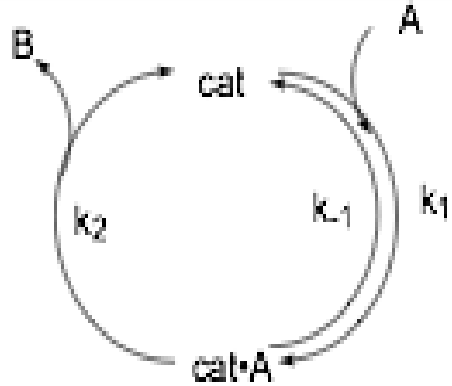
Two Step Catalytic Cycle - Rates, etc





Consider the following conditions:

[A] is constant, $k_1[A] = 10\ s^{-1}$, $k_{-1} = 1\ s^{-1}$, $k_2 = 0.1\ s^{-1}$

- The net rates of step 1 and step 2 are *equivalent – in the steady-state the net rates of all steps are identical*
- Step 1 is a pre-equilibrium, with both forward and reverse fluxes (k_1[cat][A] & k_{-1}[cat•A]) greater than step 2 (k_2[cat•A])
- The ratio of [cat•A]/[cat]=10 is *thermodynamically controlled* and cat•A is the *resting state*
- Step 2 is appropriately termed the *Turnover-Limiting* step.

Simple Catalytic Kinetics - Pre-equilibrium Approximation

$$\text{Rate} = \frac{\partial[B]}{\partial t} = k_2[\text{cat} \bullet A]$$

$$A + \text{cat} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} A\bullet\text{cat}$$

$$A\bullet\text{cat} \xrightarrow{k_2} B + \text{cat}$$

In general, we only know how much catalyst put into the reaction, not its steady-state form

$$[\text{cat}]_{tot} = [\text{cat}] + [\text{cat} \bullet A]$$

In this simple example we assume that the first step is fast.

<u>Pre-equilibrium Assumption</u>:

$k_2 << k_{-1}$, ratio of [cat]/[cat•A] is **thermodynamically** controlled

$$K_1 = \frac{[\text{cat} \bullet A]}{[A][\text{cat}]}$$

$$[\text{cat}] = \frac{[\text{cat} \bullet A]}{K_1[A]} \Rightarrow [\text{cat}]_{tot} = [\text{cat} \bullet A] + \frac{[\text{cat} \bullet A]}{K_1[A]}$$

$$[\text{cat} \bullet A] = \frac{K_1[A][\text{cat}]_{tot}}{1 + K_1[A]} \quad \therefore \quad \text{Rate} = \frac{k_2 K_1[A][\text{cat}]_{tot}}{1 + K_1[A]}$$

Simple Catalytic Kinetics & Steady-State

$$A + cat \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} A{\bullet}cat$$

$$A{\bullet}cat \xrightarrow{k_2} B + cat$$

$$\text{Rate} = \frac{\partial[B]}{\partial t} = k_2[cat \bullet A]$$

In general, we only know how much catalyst we put into the reaction, not its steady-state form

$$[cat]_{tot} = [cat] + [cat \bullet A]$$

Another, more general treatment is the Steady-State Approximation

<u>Steady-state</u>: $k_2 >> k_{-1}$, ratio of [cat]/[cat•A] **kinetically** controlled

$$\frac{\partial[cat \bullet A]}{\partial t} = 0 = k_1[cat][A] - (k_{-1} + k_2)[cat \bullet A]$$

$$[cat \bullet A] = \frac{k_1[cat][A]}{k_{-1} + k_2}$$ but we still need to express rate in terms of $[cat]_{tot}$

mass balance: $[cat]_{tot} = [cat] + \frac{k_1[cat][A]}{k_{-1} + k_2}$

$$[cat] = \frac{[cat]_{tot}}{1 + \frac{k_1[A]}{k_{-1} + k_2}}$$

$$\text{Rate} = k_2[cat \bullet A] = \frac{k_2 k_1[cat][A]}{k_{-1} + k_2}$$

substitute for [cat]

$$\text{Rate} = \frac{k_2 k_1[A]}{k_{-1} + k_2}\left(\frac{[cat]_{tot}}{1 + \frac{k_1[A]}{k_{-1} + k_2}}\right)$$

$$\text{Rate} = \frac{k_1 k_2}{k_{-1} + k_2 + k_1[A]}[A][cat]_{tot}$$

Wilkinson's Catalyst

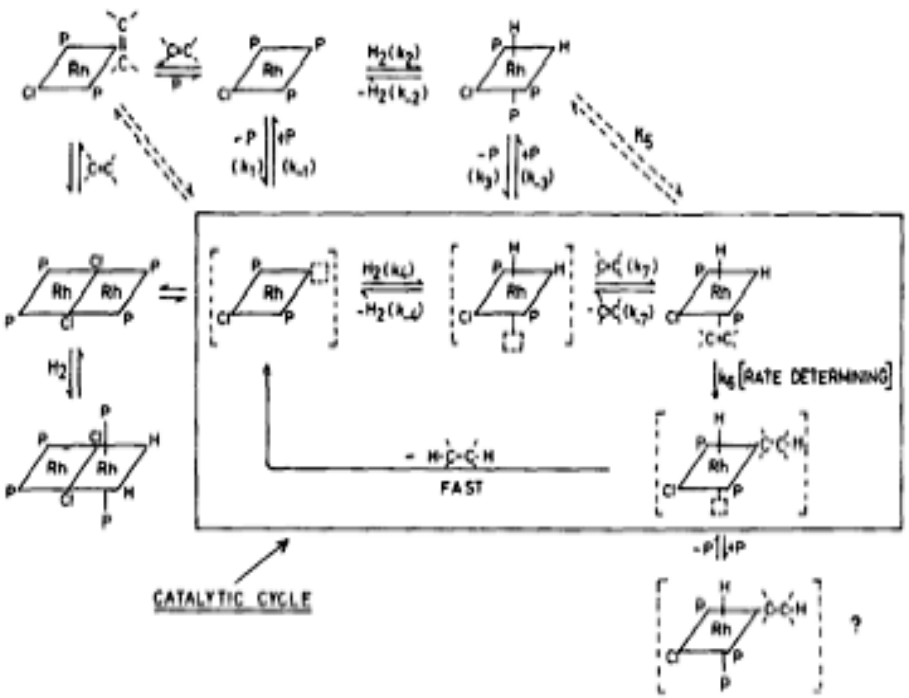


Fig. 1. Mechanism of the 'Rh(PPh$_3$)$_3$Cl'-catalyzed hydrogenation of cyclohexene.

Halpern, J. *Inorganica Chimica Acta* **1981**,*50, 11-19.*

- Virtually all of the species observed *in situ* lie OUTSIDE the catalytic cycle are ***spectator sites***

- Observation of overall catalytic rate laws led to several wrong mechanisms - ***kinetics of catalytic process are necessary but not sufficient to determine the mechanism***.

- Coordinatively unsaturated species play important roles even thought their absolute concentrations are very low.

Methods for Measuring Catalytic Rates

- Quench
- Gas Uptake
- Calorimetry
- Operando IR
- Mass Spectrometry
- NMR

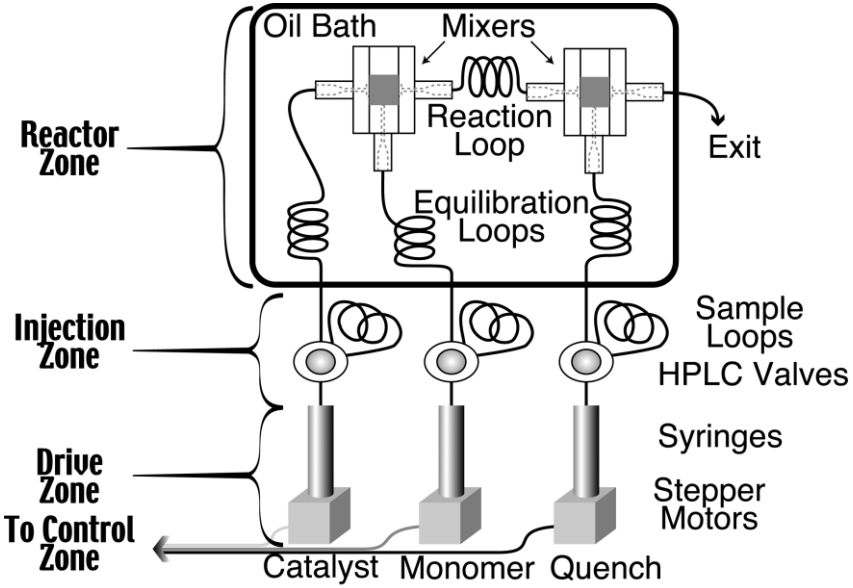
Measuring Catalytic Rates- Quench

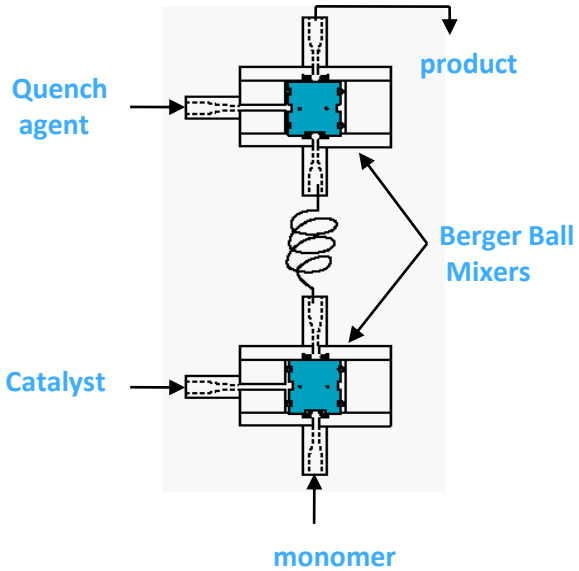
- *Perform reaction in suitable vessel, remove aliquots, stop reaction, measure reaction progress.*
- Common time scales: tens of seconds between time points
- Suitable vessels: simple flask (atmospheric), pressure bottle fitted with GC septum (150 psig), high pressure autoclave reactor (>150 psig)
- Aliquot withdrawal: syringe (atmospheric), gas-tight syringe (150 psig at low volume), dip-tube
- Reaction quench: remove from gaseous reactants, add poison, cool, dilution, etc.
- Measurement: mass, GC, LC, NMR, IR, UV-Vis, MS, whatever
- Pros: Simple Cons: Slow, tedious

Measuring Catalytic Rates– Quench Flow

A.2. *Rapid* Quench Methods

Automated equipment suitable for very fast time scales





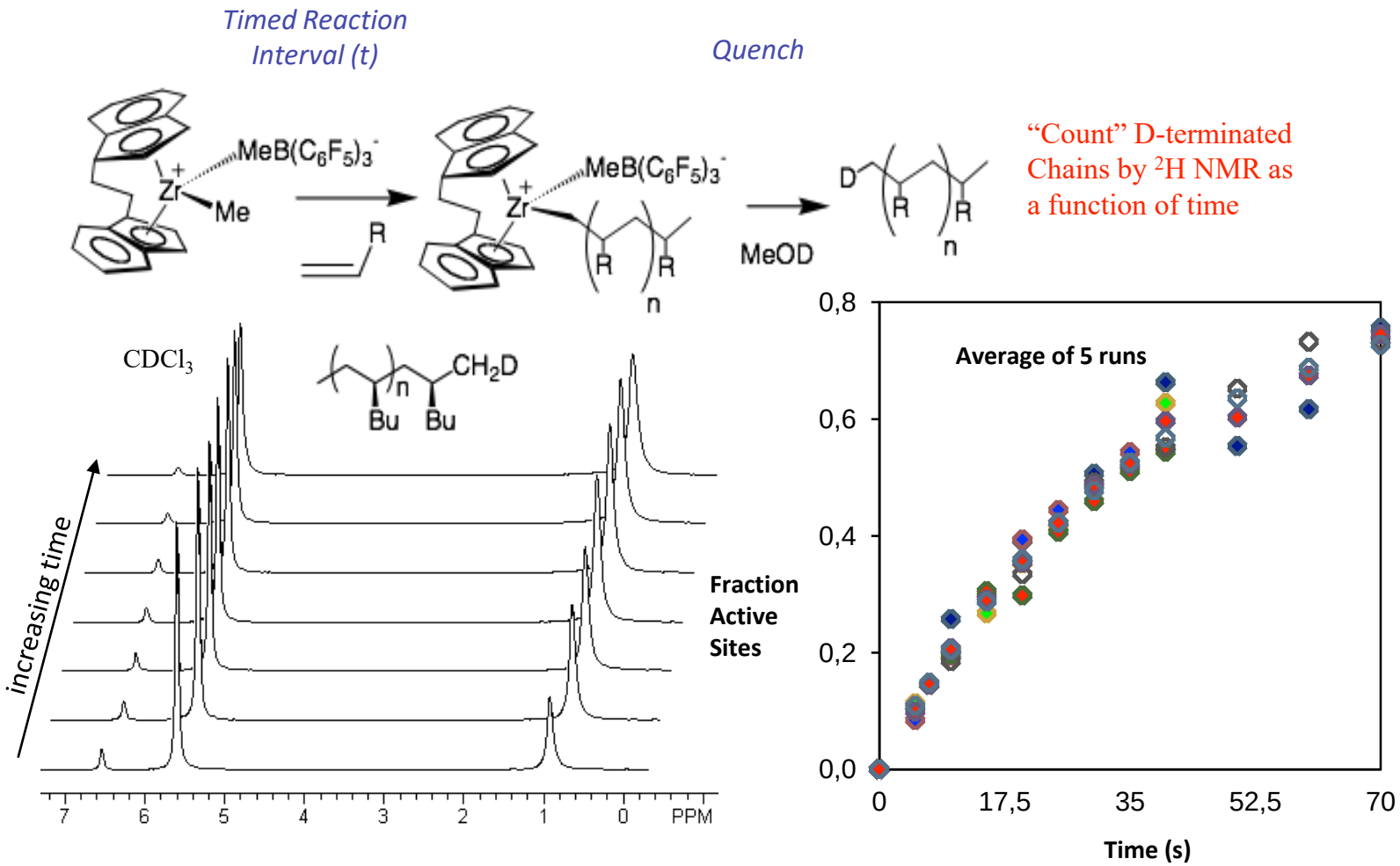
Time scales: 8 msec - hours
Automated with LabView Software
Can handle dissolved gases upto 2000 psig

Commercial Vendors:
Hi-Tech (www.hi-techsci.com)
Biologic (www.bio-logic.info)
Update (www.updateinstrument.com)

A Rapid Quenched-Flow Device for the Study of Homogeneous Polymerization Kinetics', White, C. B.; Rosaaen, K. A.; Landis, C. R. *Rev. of Sci. Instr.*, **2002**, *73*, 411-415.

Quench-Flow Example

Active Site Count, Initiation & Propagation Kinetics for Catalytic Alkene Polymerization

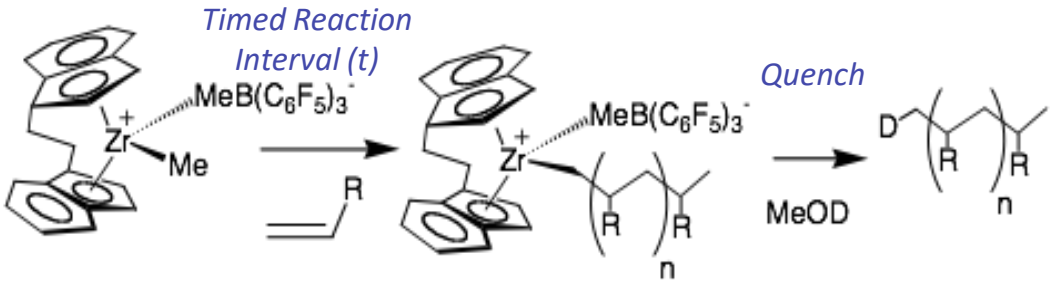


'A ^{2}H-Labeling Scheme for Active-Site Counts in Metallocene-Catalyzed Alkene Polymerization.' Liu, Zhixian; Somsook, Ekasith; Landis, Clark R. *J. Am. Chem. Soc.* **2001**, *123(12)*, 2915-2916.

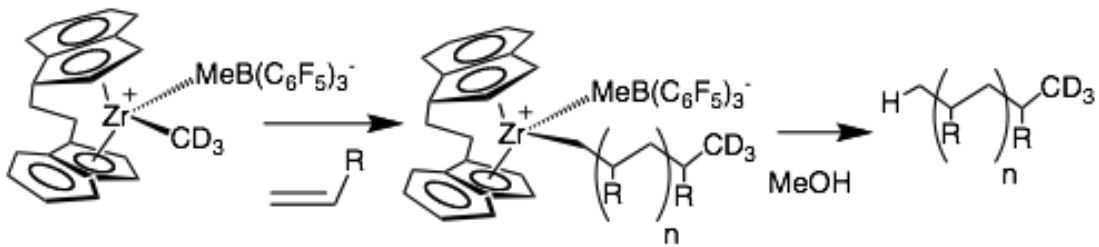
Quench Label and Active Site Counts

Active Site Count, Initiation & Propagation Kinetics for Catalytic Alkene Polymerization

1.



2.



Match the correct statement with the experiment

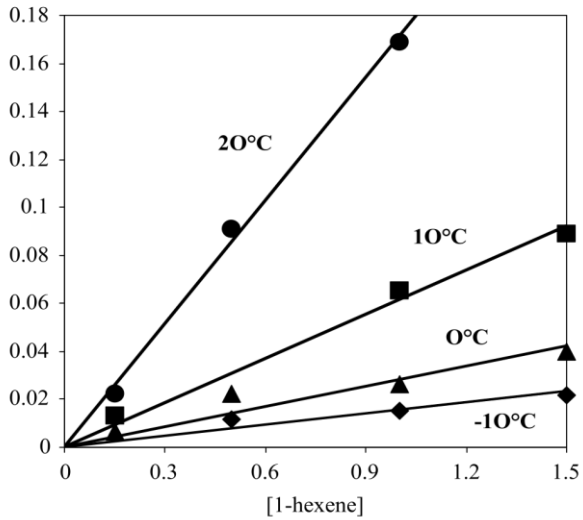
a. Measures the number of catalyst precursors that started to grow polymer chains

b. Measures the number of catalysts that had chains at the time of quench

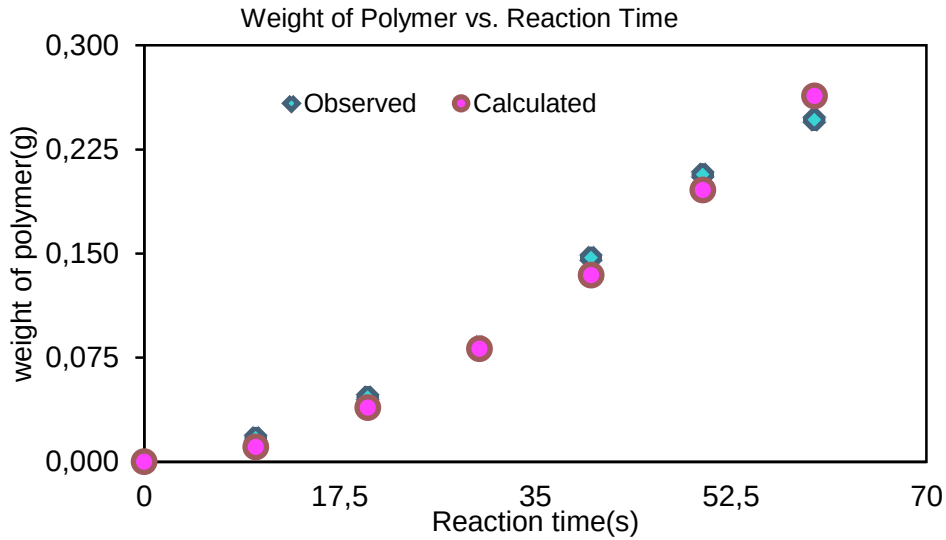
'A ^{2}H-Labeling Scheme for Active-Site Counts in Metallocene-Catalyzed Alkene Polymerization.' Liu, Zhixian; Somsook, Ekasith; Landis, Clark R. *J. Am. Chem. Soc.* **2001**, *123(12)*, 2915-2916.

1.A. Modern Methods - QF Propagation

Initiation



Propagation



Rate = k_i [Zr][1-hexene]

k_i = 0.25 $M^{-1}s^{-1}$ at 24°C

$\Delta H^{\ddagger}$= 11.5(1.5) kcal/mol

$\Delta S^{\ddagger}$= -24(6) cal/mol-K

Prop. Rate = k_p[Zr][1-hexene]

k_p = 8.1 $M^{-1}s^{-1}$ at 25°C

$\Delta H^{\ddagger}$= 6.4(1.5) kcal/mol

$\Delta S^{\ddagger}$=-33(5) cal/mol-K

Mass of polymer accelerates with time. This means

a. Propagation is slower than initiation

b. Propagation is faster than initiation

Liu, Z., et al. *J. Am. Chem. Soc.* **2001**, *123*(45), 11193-11207

Measuring Catalytic Rates - Gas Uptake Kinetics

Symyx PPR (www.symyx.com)
ChemSpeed (www.chemspeed.com)
Endeavor (www.biotage.com)

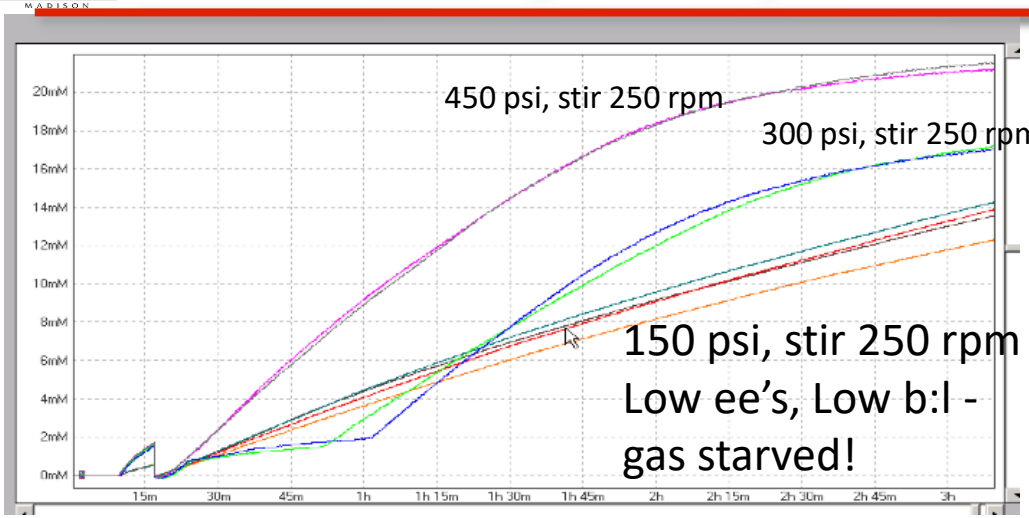
Gas-Uptake Kinetics Attributes

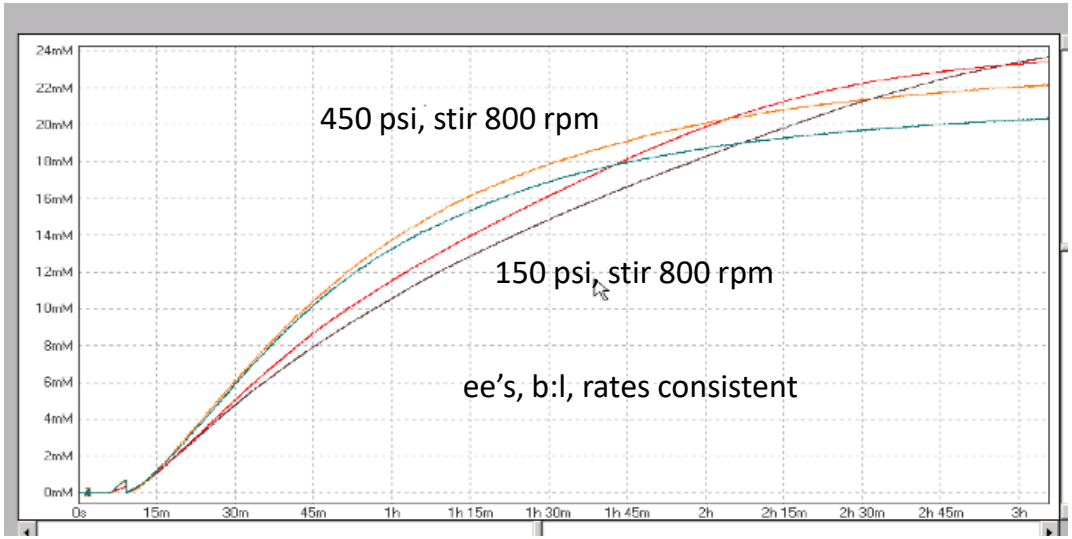
1. Commonly constant pressure, constant temperature
2. Gas introduced in small aliquots to maintain constant P
3. Rates depend on mass transport - *gas-liquid mixing is commonly problematic, especially for low solubility gases such as* H_2 - must test by examining stirring speed effects
4. Maximize mass transport by fast stirring, high gas-liquid surface area.

Pros: Simple, sensitive, high P and high T compatible

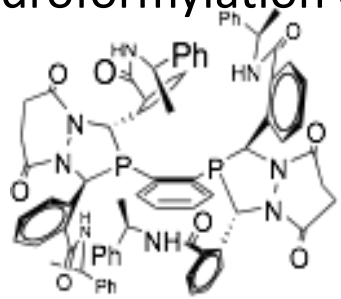
Cons: Mass transport can cause problems, low information content

Measuring Catalytic Rates - Gas Uptake Example



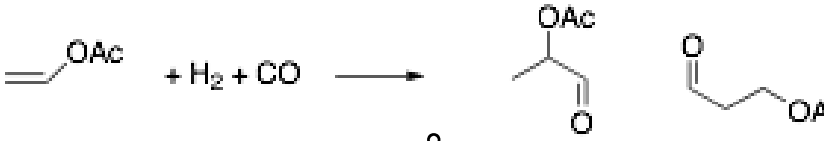


Enantioselective
Hydroformylation of Vinyl Acetate



Ligand

catalyst precursor = $Rh(acac)(CO)_2$



Temperature = 80° C
1:1 H_2:CO
$[\text{vinyl acetate}]_0$ = 1.89 M
[catalyst] = 4.6×10^{-5} M
Biotage Endeavor Instrument

Measuring Catalytic Rates - Gas Uptake Kinetics

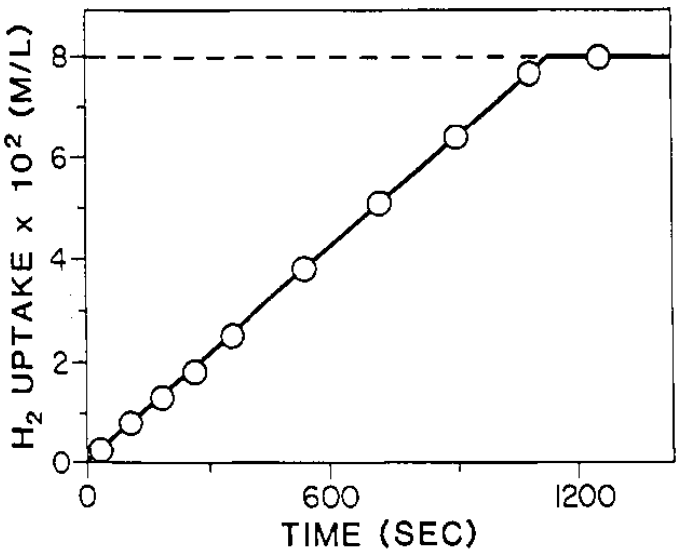


Figure 5. Plot of H_2 uptake vs. time for the $[Rh(dipamp)]^+$-catalyzed hydrogenation of mac at 25.0 °C: $[Rh]_{tot} = 5.1 \times 10^{-4}$ M; initial [mac] = 0.080 M; H_2 pressure = 1.1 atm.

Constant pressure gas uptake plot for the enantioselective hydrogenation of methyl acetamidocinnamate (MAC) as catalyzed by $[Rh(DIPAMP)(NBD)]^+$

Which one of the following statements most likely is true?

a. The rate law is zero-order in $[H_2]$
a. The rate law is first-order in $[H_2]$
a. The rate law is zero-order in [MAC]
a. The rate law is first-order in [MAC]

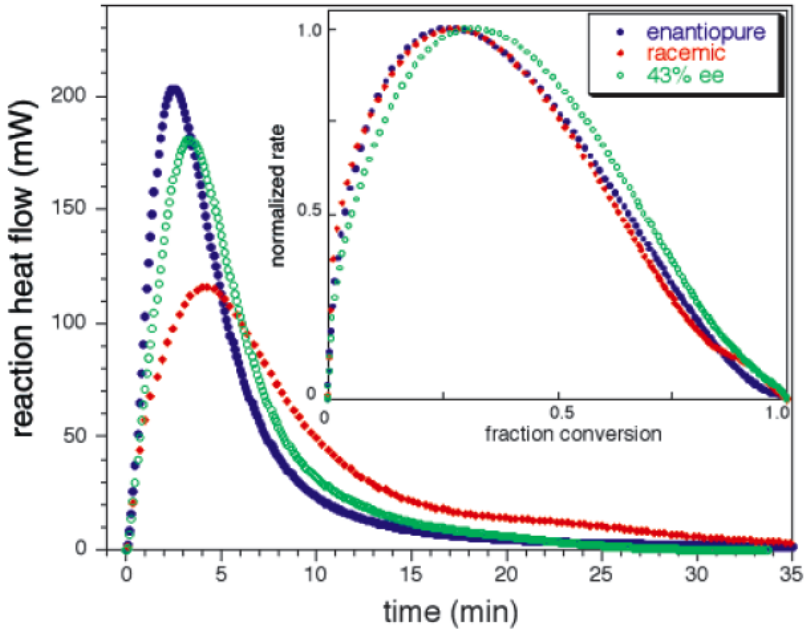
Measuring Catalytic Rates - Calorimetry

Example: Omnical Calorimeter

Calorimeter measures the *heat flow rate, q*, in a reactor relative to a control.

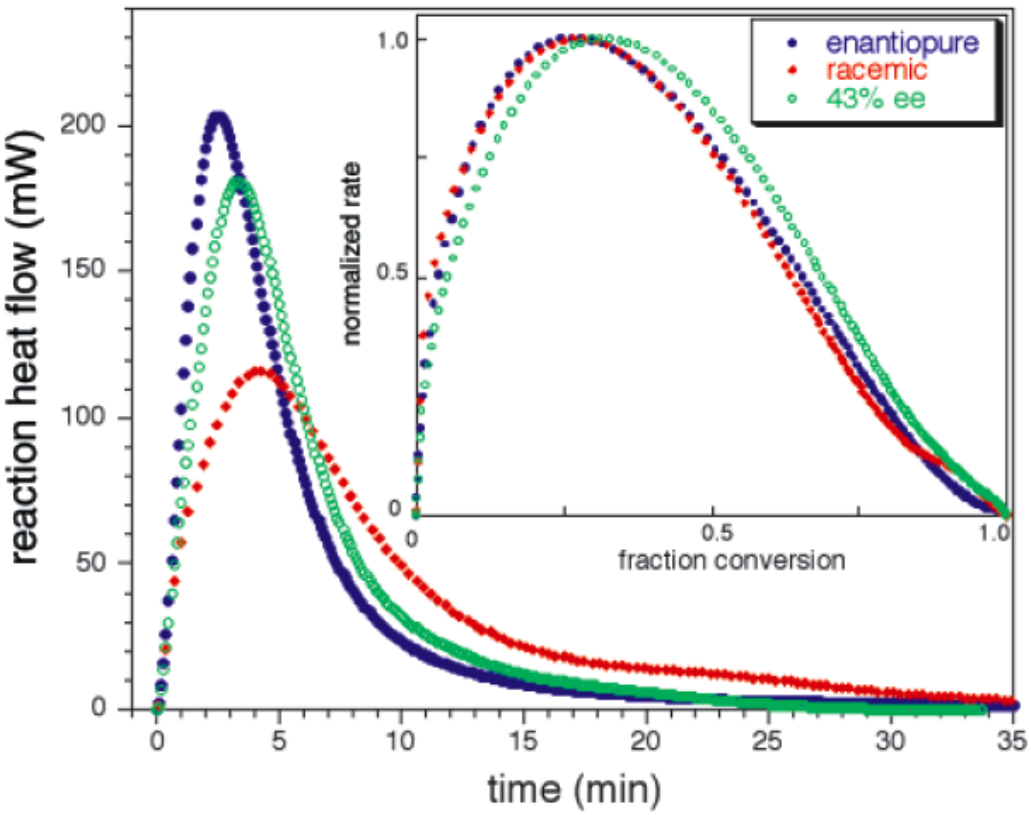
The reaction rate, *R*, is proportional to the heat flow rate as follows:

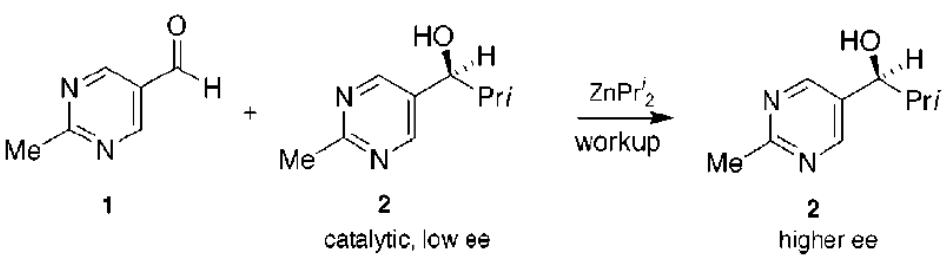
$q = R \bullet \text{Reaction volume} \bullet \Delta H_{rxn}$



- Calorimetry can be very sensitive
- Relatively slow (ca. 30 second half-lives)
- Intrinsically a derivative technique (measures rates) rather than concentrations (which are obtained by integration)

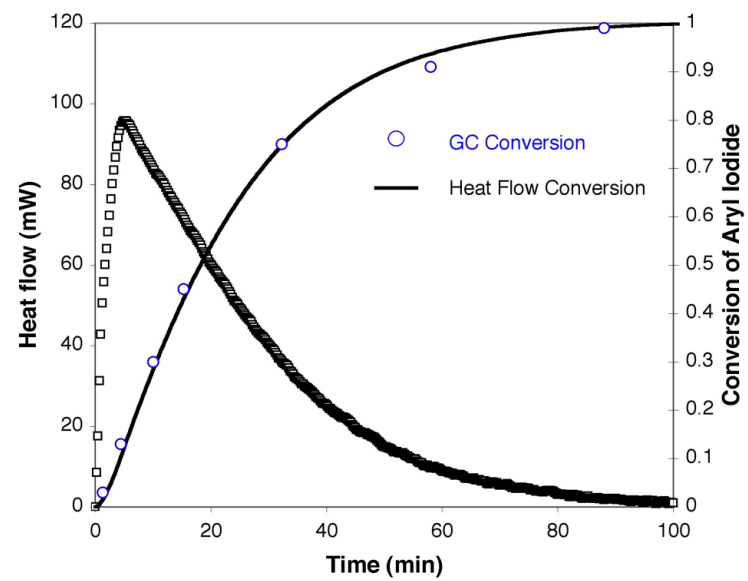
Measuring Catalytic Rates - Calorimetry





Fraction conversion obtained by integrating the heat flow over time:

$$fractional\ conversion = \frac{\int_0^t q \cdot dt}{\int_0^{t_f} q \cdot dt}$$

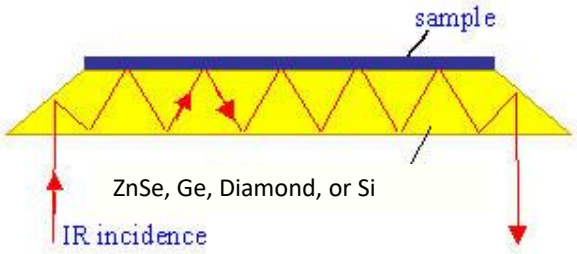


Origins of Asymmetric Amplification in Autocatalytic Alkylzinc Additions
Blackmond, D. G.; McMillan, C. R.; Ramdeehul, S.; Schorm, A.; Brown, J. M.
J. Am. Chem. Soc.; **(Communication); 2001**; 123(41); 10103-10104.

Measuring Catalytic Rates - IR Spectroscopy

IR spectroscopy of reaction mixtures, although complex, have high information density and can be adapted to many different environments, including high temperature and pressures. Virtually all reactions yield useful changes in IR spectra.

Attenuated Total Reflectance



- Path length depends on number of reflections - usually a shorter path length than transmission cell
- Shorter path length means lower sensitivity
- Chemical inertness of diamond and silicon enable direct contact with solution
- Probes may be attached to autoclave, arranged as dip probes, etc. - popularized as ReactIR

Transmission Cell

- Longer path length
- Greater sensitivity
- Not commercially available in high pressure cell
- Difficult to engineer into reactors

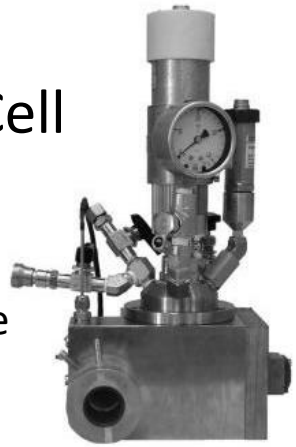


Figure 7.4 High pressure IR cell connected to an autoclave (constructed at ICCOM-CNR, 2003).

Analysis Software

- Major developments in principle component analysis simplify the analysis of complex spectra (e.g. ConcIRT software).

Measuring Catalytic Rates- IR Analysis

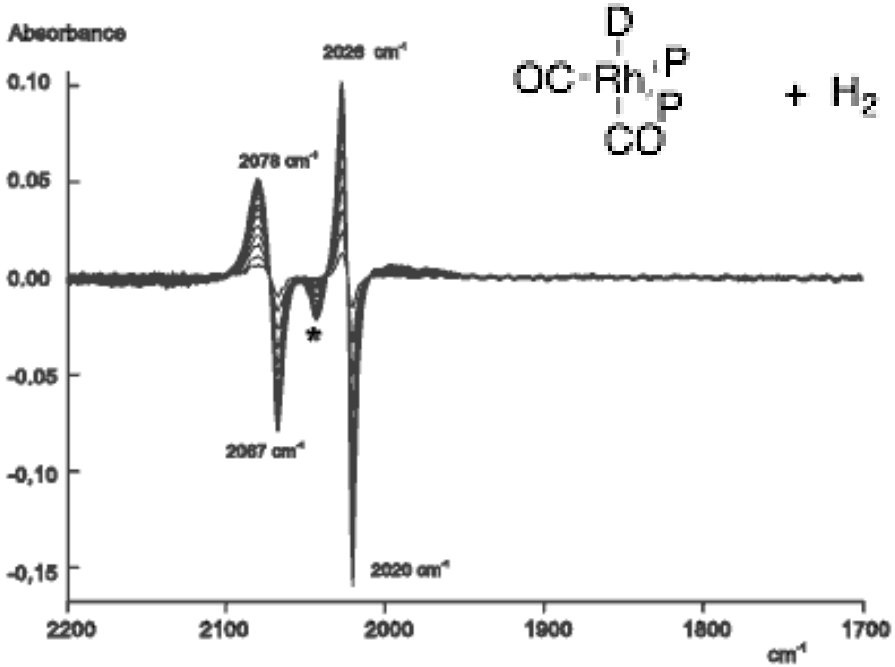


Figure 6.15 Difference IR spectrum obtained after addition of H_2 to a solution of DRh(**38**)(CO)$_2$ and DRh(**38**)$_2$(CO) (indicated by *) under carbon monoxide pressure at 80 °C. Reproduced from Ref. [55] with permission.

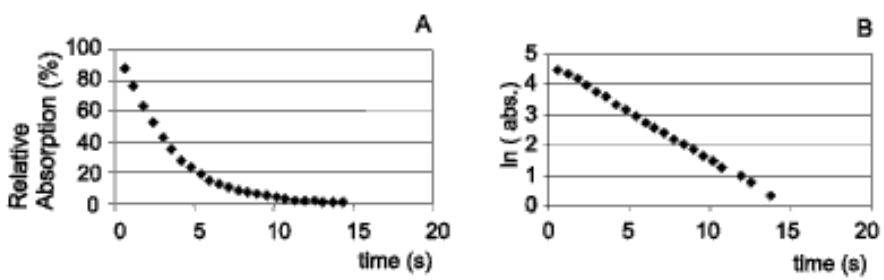


Figure 6.16 Kinetic data of the H/D exchange. A. Exponential decay of ν_{CO} at 2020 cm^{-1} vs. time. B. Logarithmic plot of the decay of the relative absorption at 2020 cm^{-1} vs. time. Reproduced from Ref. [55] with permission.

Figure 7.4 High pressure IR cell connected to an autoclave (constructed at ICCOM-CNR, 2003).