Catalyst Synthesis

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„It is in the preparation of catalysts that the chemist is most likely to revert to type and to employ alchemical methods. From all evidence, it seems that the work should be approached with humility and supplication, and the production of a good catalyst received with rejoicing and thanksgiving.“

Murray Raney, Ind. Eng. Chem. 1940, 32, 1199.

Types of Catalysts

Terminology: J. Haber, Pure&Appl.Che. 63, 1227 (1991)

Bulk Catalysts

Metal oxides
Metals (skeletal catalysts)
Noble metal gauze

Supported Catalysts

Often noble metals
Systems which cannot be dispersed by other methods

$$\text{Dispersion} = \frac{\text{number of surface atoms}}{\text{total number of atoms}}$$

Rule of thumb for specific surface area with respect to particle size:

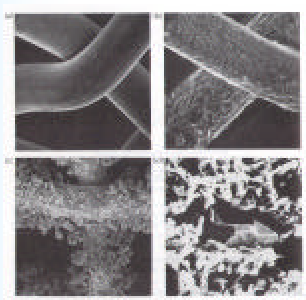
- 1 µm ˜ 1 m^2/g $A = 6/(\rho \cdot d)$
- one magnitude higher/lower particle size corresponds to one magnitude lower/higher specific surface area

Targets for Catalyst Preparation

- Activity
- Selectivity
- Stability
  - coking
  - poisoning by reactands
  - sintering
  - poisoning by impurities
- Morphology
- Mechanical strength/resistance
- Thermal properties
- Regeneration
- Reproducibility
- No patent / patentable
- Costs

Bulk Catalysts: Fused Catalysts

- Important for preparation of metal alloys for gauzes
- High dispersion of elements (in melt)
- Ostwald process (Pt/Rh)
- Andrussov process (Pt or Pt/Rh)
- Sulfuric acid catalyst ($V_2O_5/M_2S_2O_7$)
- Typically high costs of energy, process control difficult



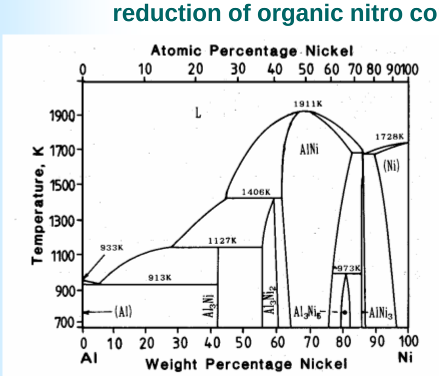
Pt/Rh gauze unactived , partially activated, well-activated, and with Rh_2O_3 crystals on surface

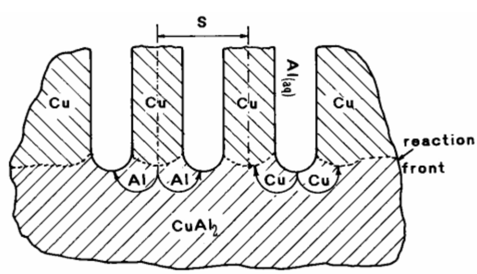
Installation gauze pad

from Catalyst Handbook, 2nd Ed., M.V. Twygg (ed), Wolfe Publishing Ltd., 1989

Bulk Catalysts: Raney Catalysts

- Principle: Formation of alloy in a melt, then extraction of one component
- usually: Ni/Al alloy, extraction of Al with alkali hydroxide solution
- Other systems known, technically Raney-Cu is used for the reduction of organic nitro compounds and nitriles

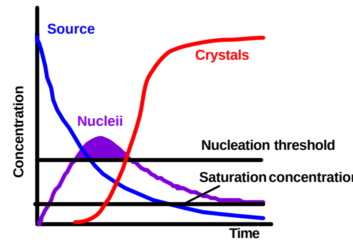




Bulk Catalysts: Precipitated Catalysts

- Precipitated Catalysts

  Nucleation is decisive



(simplified!)

- Problems:
  - Quality varies because of changing concentrations
    ➡ **continuous precipitation**
  - Inclusion of ions
    ➡ **decomposable couter ions, NO_3^-, NH_4^+, oxalate, citrate...**
  - Local supersaturation
    ➡ **homogeneous precipitation, e.g. with urea**
  - component with low K_{sp} precipitates first in co-precipitation
    ➡ **Precipitation at high supersaturation or continiuously**

Bulk Catalysts: Precipitated Catalysts

» Nowadays increasing use of organic solvents, e.g. in production of VPO ($(VO)_2P_2O_7$) catalysts or Ziegler (zirconocene/MAO/SiO_2-catalyst) catalysts

» Precipitation of defined precursor compounds followed by thermal decomposition or transformation into final catalyst

Examples:

Ni/Al_2O_3
Hydrotalcites, such as $Ni_6Al_2(OH)_{16}CO_3 \cdot 4\,H_2O$, have different calcination and reduction behavior than mixtures of components due to dispersion of elements on atomic level

Methanol catalyst (Cu/ZnO)
Depending on precipitation conditions many different phases with strongly varying catalytic properties can be obtained in dependence of conditions during transformation into catalyst

Bulk Catalysts: Sol-Gel Materials

- Sol-Gel process produces typically highly porous materials with high specific surface areas
- Precursors mostly metal alkoxides, but could as well be simply salts

Hydrolysis: M-OR + H_2O → MOH + ROH
Condensation: MOH + XO-M → M-O-M + XOH   X=H,R

- Both steps proceed simultaneously, relative reaction rate important for product properties

if hydrolysis faster than condensation ⇨ less branched material

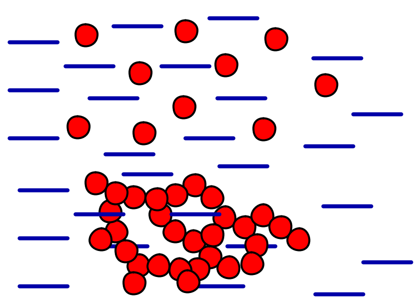
if hydrolysis slower than condensation ⇨ highly branched material

J. Brinker, W. Scherer, Sol-Gel-Science, Academic Press 1990;
J. Livage, M. Henry, C. Sanchez, Progr. Solid St. Chem. 18, 259 (1988)

Sol-Gel Formation

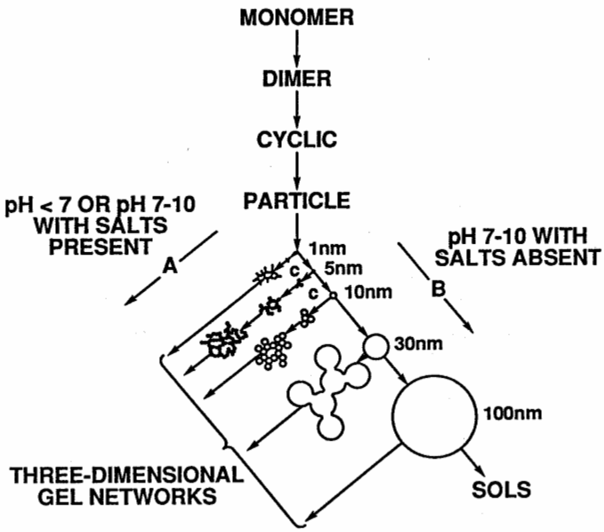
1. Sol Formation

2. Gelation

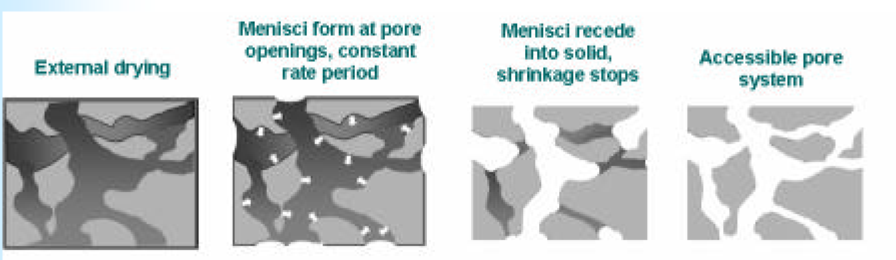


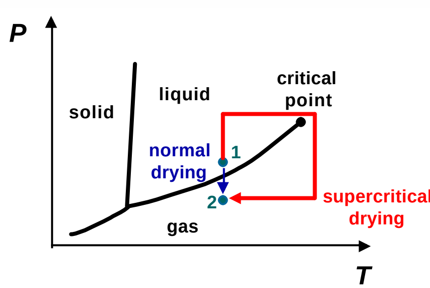
Advantage: High degree of control over product properties
easy preparation of mixed oxides with atomic dispersion of elements

Gelation of Silica



Gel Drying / Aerogels



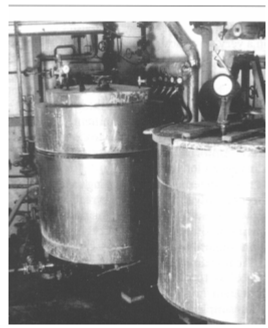


Bulk Catalysts: Hydrothermal Synthesis

- Discrimination against precipitation sometimes difficult; typically higher temperature, often pressure, longer reaction time than for precipitation
- Crucial for zeolite synthesis (crystalline, microporous aluminosilicates)

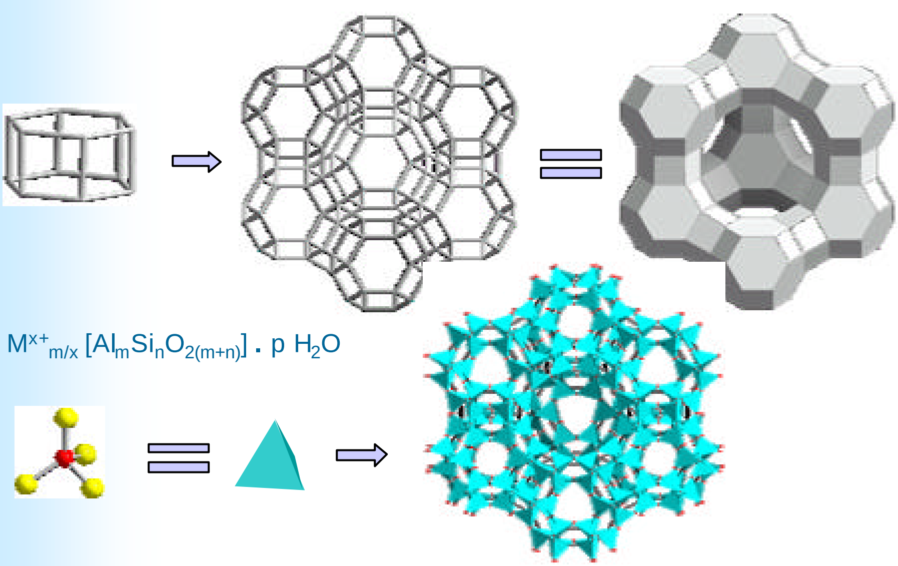
Lab autoclaves
50 - 250 ml

Stirred autoclave
1.5 - 2.5 l



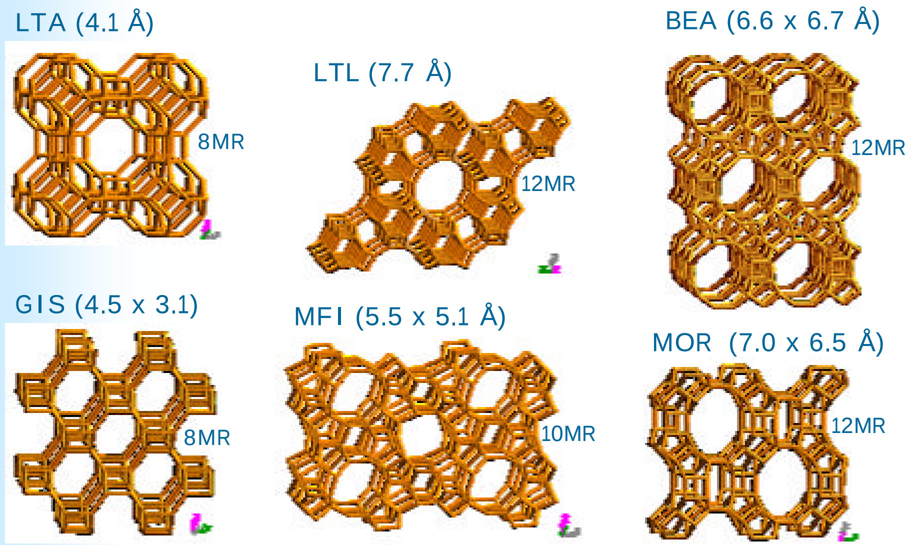
Industrial stirred reactors
50 - 5000 l

Zeolites

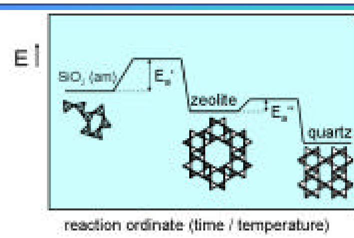


$M^{x+}_{m/x} [Al_mSi_nO_{2(m+n)}] \cdot p\ H_2O$

Zeolites



Zeolite Synthesis



Si^{4+}, Ti^{4+}, **Al^{3+}**, B^{3+}, Ga^{3+}, P^{5+} → **Oxide source** (salt, oxide, hydroxide) → **GEL**

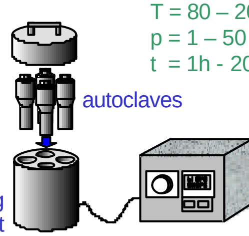
Template (amine, alkyl ammonium, alcohol) → **GEL**

H_2O → **GEL**

Mineralizer (OH^-, F^-) → **GEL**

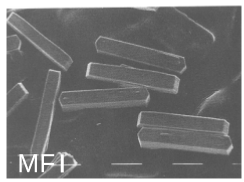
seeds (sometimes) → **GEL**

T = 80 – 200°C
p = 1 – 50 bar
t = 1h - 20 days

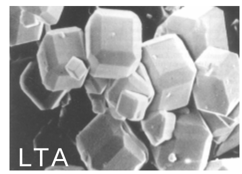


Bulk Catalysts: Hydrothermal Synthesis

- Discrimination against precipitation sometimes difficult; typically higher temperature, often pressure, longer reaction time than for precipitation
- Crucial for zeolite synthesis (crystalline, microporous aluminosilicates)
- Cristallization from silicion and aluminum containing solutions, mainly under alkaline conditions
- minimum Si/Al ratio is 1
- Often "template" required (organic additive, e.g. tetraalkylammonium ions), mainly for high silica zeolites
- Many parameters affect zeolite synthesis
  - reagents
  - pH
  - mixing sequence
  - temperature
  - heating rate
  - concentrations
  - template
  - ...



ZSM-5, Silicalite-1 (150µm)

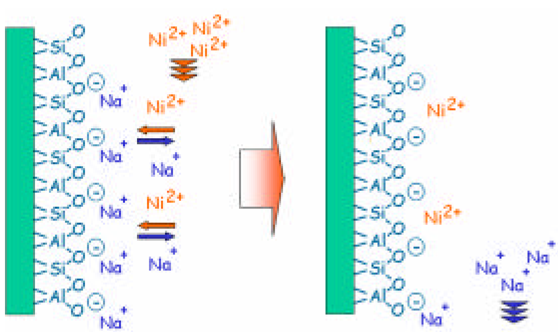


Linde Type A (0.2 - 2 µm)

Bulk Catalysts: Solid State Reactions

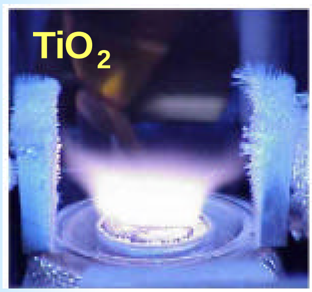
- Transformation of definied Precursors s.o.
- also reaction of mixtures of oxides obtained by milling

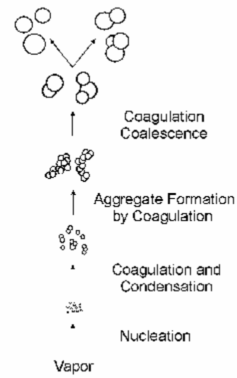
  example: Styrene catalyst
  milling of KOH + FeO_x + CrO_x, then calcination at 900 - 1300 K
- Solid state ion exchange
  example: zeolites, 600-700 K)



Bulk Catalysts: Other Methods

- Flame hydrolysis (Aerosil...)
- Sputter processes
- Spezial processes for Carbides, Nitrides
- ...





http://www.engin.umich.edu/~cre/web_mod/aerosol/frame08_pics/pict.htm

Supported Catalysts: Supports

- g-,h- or a -Al_2O_3, SiO_2, TiO_2, ZrO_2, MgO, C
- Surface functionality typically -OH for Oxides, oxo-functionality for Carbons
- Oxidic surfaces in elektrolytes generally charged

$$\text{M-OH} \longrightarrow \text{M-O}^- + \text{H}^+$$
$$\text{M-OH} + \text{H}^+ \longrightarrow \text{MOH}_2^+$$

=> decisive for loading, since no adsorption if wrongly charged!

PZC (Point of zero charge) = particle is not charged at this pH

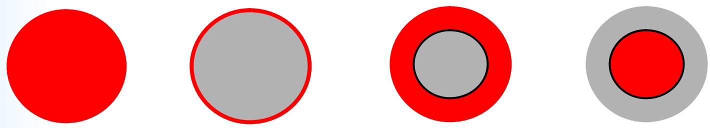
G.A. Parks, Chem. Rev. 65, 177 (1965)

Rule of thumb:

M_2O			PZC	> pH 11.5
MO	8.5	<	PZC	< 12.5
M_2O_3	6.5	<	PZC	< 10.4
MO_2	0	<	PZC	< 7.5
M_2O_5			PZC	< 0.5

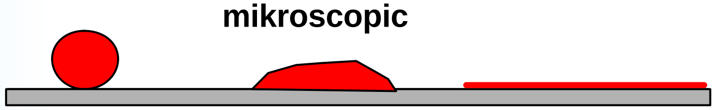
Distribution of Active Component on Support

macroskopic



homogeneous egg shell egg white egg yolk

mikroscopic



Non-wetting wetting spreading

Examples for spreading: V_2O_5 on TiO_2, MoO_3 on Al_2O_3 or on TiO_2, not on SiO_2

Supported Catalysts: Preparation

- **Wet Impregnation, Ion Exchange, Equilibrium Adsorption**
  - Often discriminated but in principle all very similar
  - Principles:

    Wet Impregnation (incipient wetness/dry impregnation)
    - Support with as much solution to just imbue support; porous material with as much solution that pores are just filled, then drying
    - Drying rate can strongly affect metal distribution

    Ion Exchange and Equibilibrium Adsorption
    - Basically the same: Ion exchange if structural charges present (zeolites)
    - Support with excess solution, wait until equilibrium reached, filtration, drying

  - But: During Wet Impregnation also always Adsorption
    During drying after Ion Exchange/Adsorption also always Wet impregnation

Supported Catalysts: Problems

Ion Exchange

» Achievable loading is limited by ion exchange capacity or saturation concentration of solution

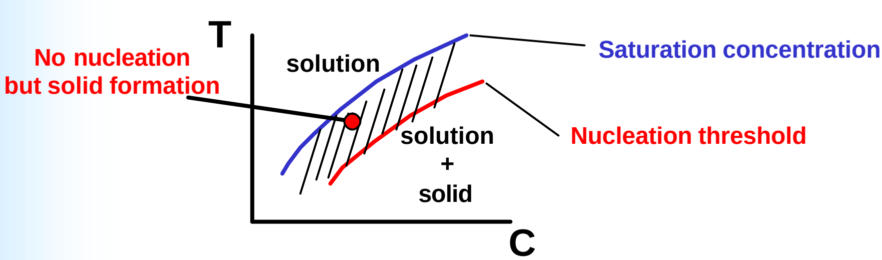
➡ Multiple exchange / loading

» Ion exchange strongly binds ions which can result in irreversible occupation of first exchange sites; might result in inhomogeneous loading

➡ Taking advantage of competetive ions, such as NH_4^+ at Ion Exchange of $[Pt(NH_3)_4]^{2+}$ in zeolites

Supported Catalysts: Precipitation-Deposition

- Support is dispersed in solution, then precipitation is started by addition of precipitation agent
- Problem can be:
  - Precipitation off support
  - Precipitation only on external surface of porous supports



Precipitation-Deposition ideally in concentration range between saturation concentration and nucleation threshold; if interaction between support and species in solution good, then only precipitation on support.

Supported Catalysts: Precipitation-Deposition

Ideal precipitation if precipitation is initiated at the same time in whole solution (homogeneous precipitation)

pH:

Urea $CO(NH_2)_2 \rightleftarrows NH_4^+ + CNO^-$

$CNO^- + 3\ H_2O \rightleftarrows NH_4^+ + 2\ OH^- + CO_2$

$NaNO_2^-$ $3\ NO_2^- + H_2O \rightleftarrows 2\ NO + NO_3^- + 2\ OH^-$ (no air!)

Oxidation state:

Fe^{2+} more soluble than Fe^{3+}, Mn^{2+} more than Mn^{3+}/Mn(IV), M^{n+} may get oxidized in solution (e.g. O_2 from air)

Removal of complexation agents:

desorption of NH_3 from ammine complexes,
oxidation of inorganic complexing agents with H_2O_2

Supported Catalysts: Grafting

- Grafting (or Anchoring): Deposition involving the formation of a strong ("covalent") bond between support and active element (J. Haber, Pure&Appl.Chem). Results in definied, good isolated species on surface
  - Typically reaction of OH-group with active species. If Silanol reacts, water usually does as well
    => exclusion of water
  - mostly metal organic reactions

    $S\text{-}OH + MX_n \longrightarrow S\text{-}O\text{-}M\text{-}X_{n-y} + y\ HX$

    $S\text{-}OH + M(CO)_n \longrightarrow S\text{-}O\text{-}MHCO_{n-2} + 2\ CO$
  - further modication by elmination or decomposition of of remaining ligands
  - Typical reactions
    - Chlorides and oxychlorides of transition metals
    - Metal alkoxides from gas phase
    - Metal allyles (Mo, Cr) or carbonyles mostly from pentane etc.

Activation / Calcination

- Irrespective of the preparation method of solid, additional steps, such as thermal treatment, are necessary after combination of components
- Easiest Case: Activation under reaction conditions. Relatively rare, in most cases customer wants equilibrated catalyst
- Calcination
  - Can be decisive for properties of catalyst
  - Many possible prozesses (decomposition of precursor, spreading, sintering, formation of new phases from active material and support, destruction)
  - Specific for each system
  - depends on gas phase; often air, but also inert gas or controlled water vapor atmosphere

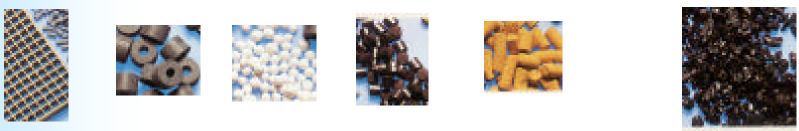
Reduction

- One of the most important steps in preparation of metal catalysts
- Starts typically from oxide (after calcination), for noble metals from chloro compounds or oxychloride
- Reduction mostly with H_2
  - often: Dispersion higher with higher reduction rate
  - However, can be inverted if nucleation is limiting factor
  - Reducibility might be different to bulk material
- SMSI (strong metal support interaction) might occur
  - Mainly for TiO_2, ZrO_2
  - H_2 sorption suppressed
  - Explanation: electronic effect, alloy, decoration of noble metal with sub-oxides (Ti_4O_7)

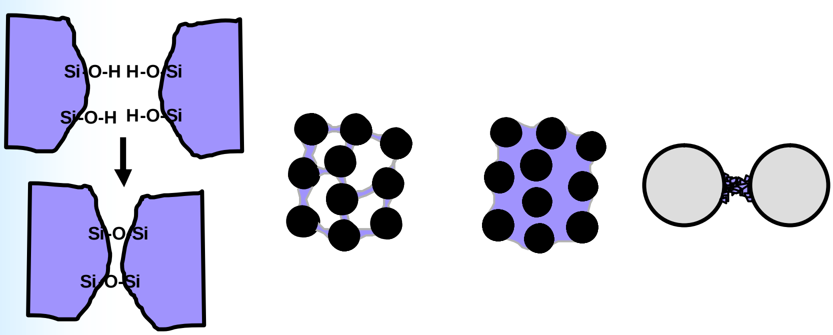
Shaping of Catalysts

- Very important, but basically empirical knowledge
- Often additives, such as oil, graphite, steatite, talc, wasser glass, starch for activated carbon (binder). (additive best protected know-how of producers)
- Shape defines pressure drop in reactor

monoliths < rings < spheres < pellets < extrudates < broken material



Forces between Particles



Chemical Bonds | Solvent Bridges | Capillarity | Solids bridges

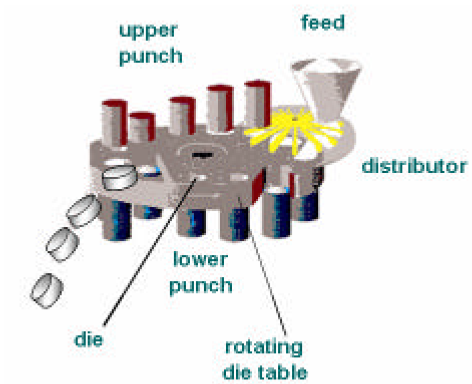
Principles of Agglomeration: S.M. Iveson et al., Powder Technology 117, 3 (2001)

Mechanism	Strength	Comment
Van der Waals forces	medium at short distances, rapid decay with distance	Magnitude depends on the interaction potentials
Electrostatic forces	Weak, but dominant for distances approaching µm	Can be repulsive, if charging of particles with same sign occurs; different for conductors and insulators
Liquid bridges	Strong	
Capillary forces	Very strong	Full saturation of granule with liquid
Solid bridges	Variable	Depends very much on conditions of solvent evaporation and crystallizing solid in bridge
Covalent bonds	Very strong	

Methods of Shaping

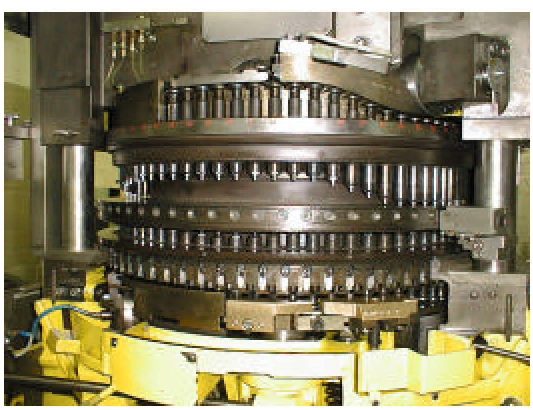
- Breaking / Milling
- Spray Drying results in small particles (7 - 700 µm)
- Tabletting: Pressing in moulds
- Extrusion: Principle of "Spätzlemaschine"
  - » press for highly viscous media
  - » screw for less viscous / thixotropic media
- Oil drop coagulation
- Pelletier pan: Snow ball principle

Rotary Tablet Press

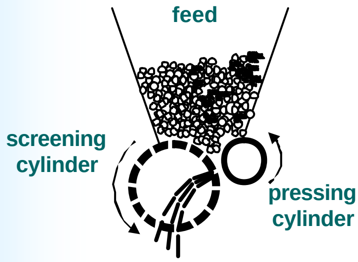


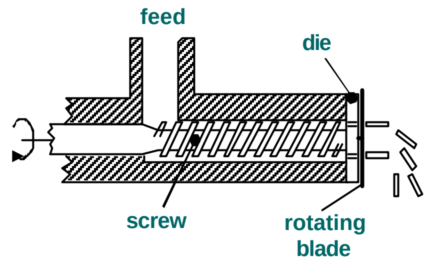
Good Review: S. Jain, Pharm. Sci. Technol. Today 2, 20 (1999)

Industrial Tableting Machine

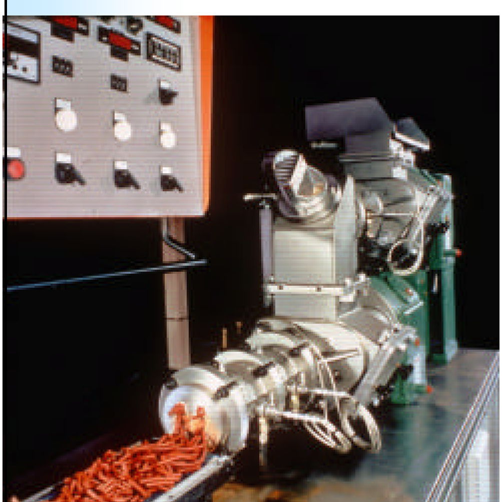


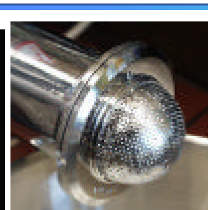
Extrusion

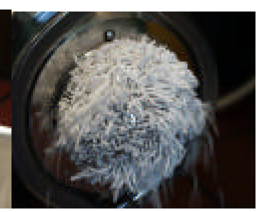


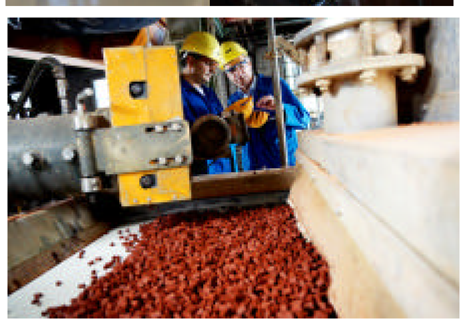


Extruders

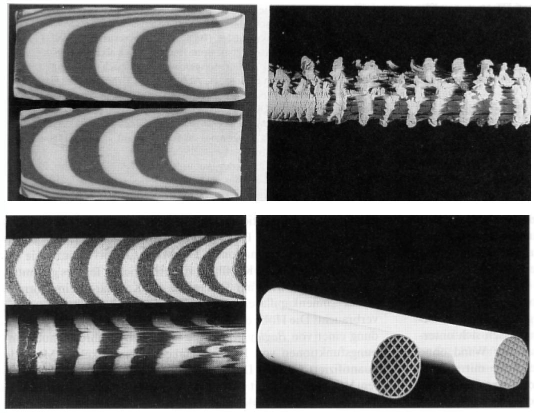








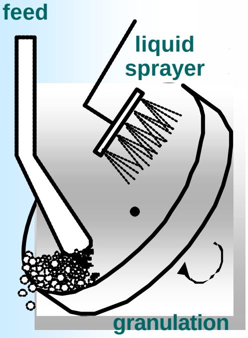
Extrudates / Monoliths



Bad extrusion characteristics

Good extrusion characteristics

Granulation / Pelletizing



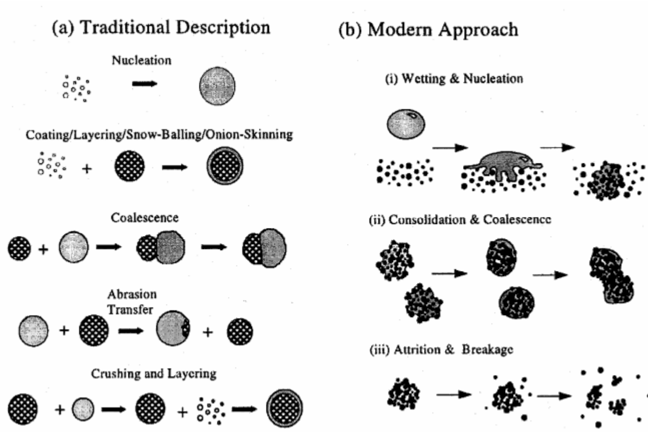
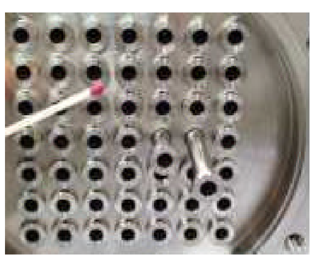


Fig. 1. Schematic of granulation processes (a) Traditional view (after Sastry and Fuerstenau [26]); (b) Modern approach [1].

Industrial Spherudizer

Novel Approaches in Catalysis

High Througput Experimentation



Catalysis research 1911
- and partly still today

Source: BASF Aktiengesellschaft

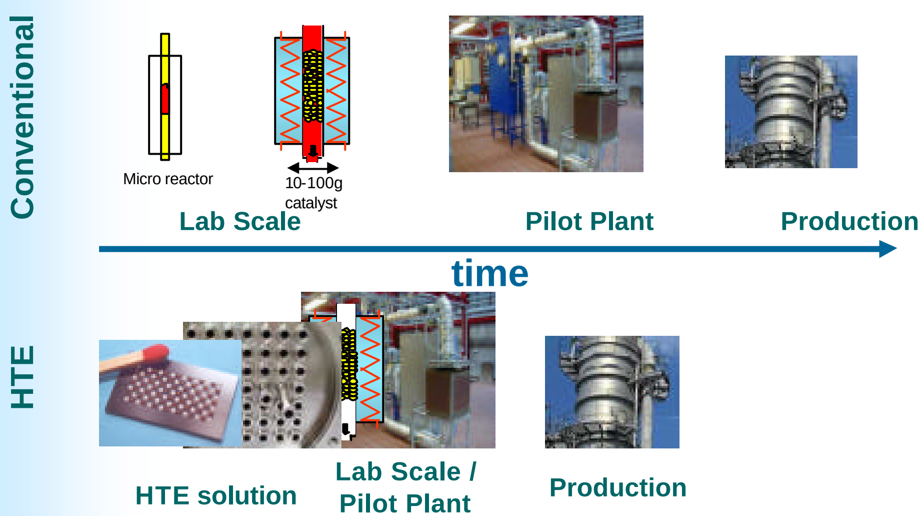
Catalyst Development

- "Rational" and "trial & error" approach
- Usually manual manufacturing
- Limited reproducibility
- Sequential testing
- Insufficient data for model development

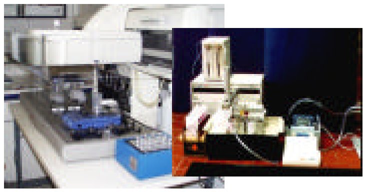
Transition technology to speed up conventional catalysis research is clearly needed

High Throughput Experimentation

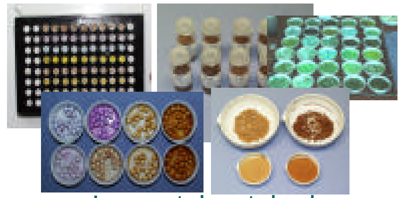
HTE Goal - Decreasing Time to Market



High Throughput Synthesis



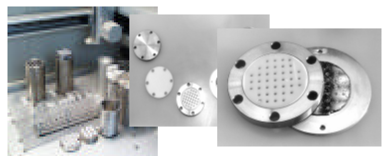
Packard and Gilson robots for impregnation/precipitation (hte and MPI)



Impregnated, coated and precipitated catalysts (hte)

Mettler and Chemspeed dispensers for precipitation (hte)

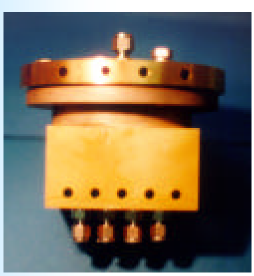
High-viscosity dispensers (Corma)

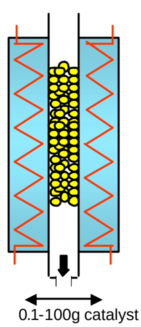


Stage-I and -II tools for hydrothermal synthesis (hte)

courtsey, hte AG, Heidelberg

Development of reactor technology

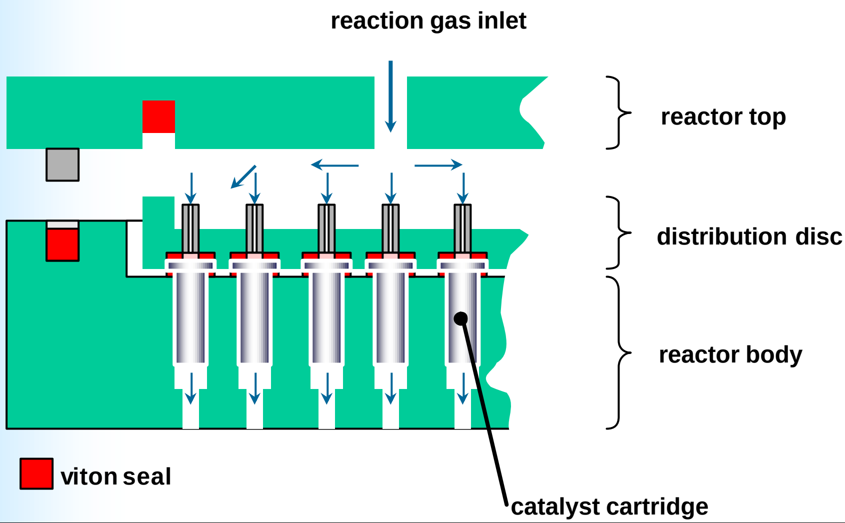




- gas inlet from top
- separated outlets into capillaries
- multiport valves
- various analytical techniques possible

C. Hoffmann et al., J.Catal. 198, 348 (2001)
C. Hoffmann et al., Angew.Chem.Int.Ed.Engl. 38, 2800 (1999)

Details of MPI Reactors

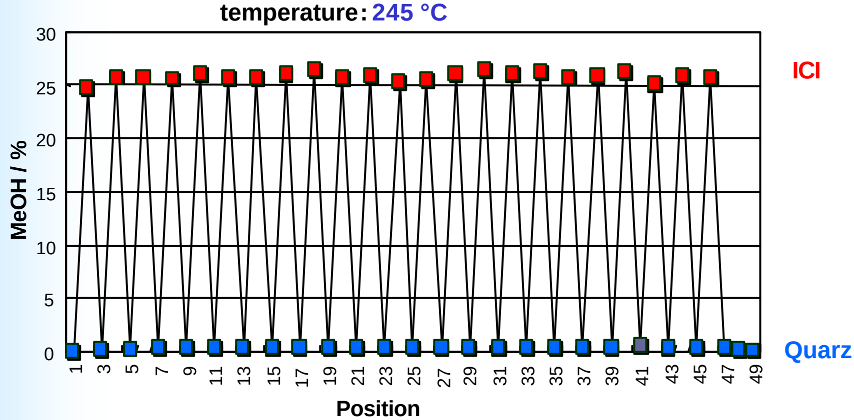


Reproducibility of System

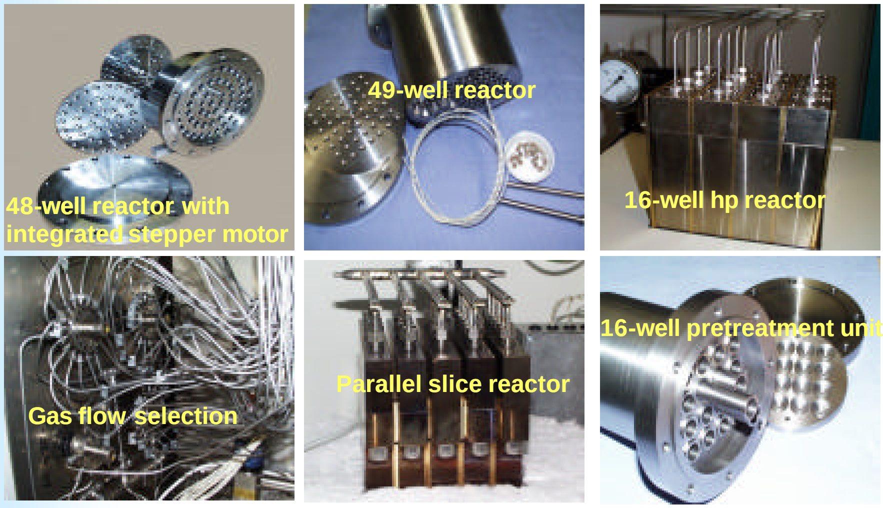
Reaction conditions

pressure: 45 bar

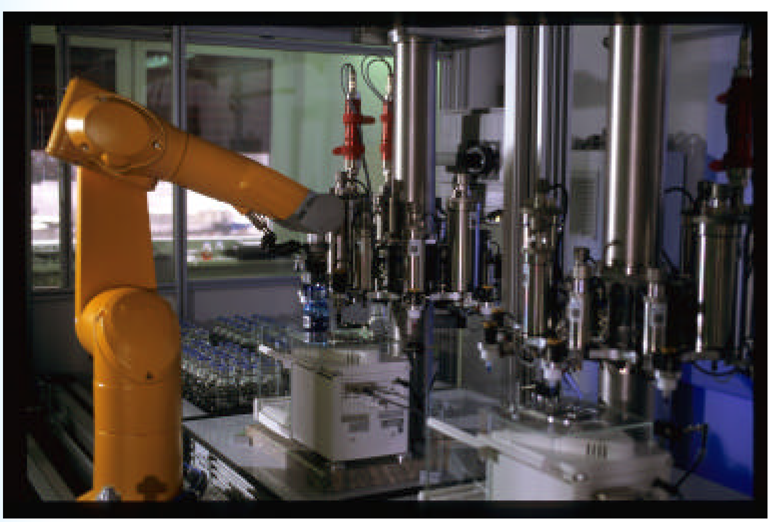
temperature: 245 °C



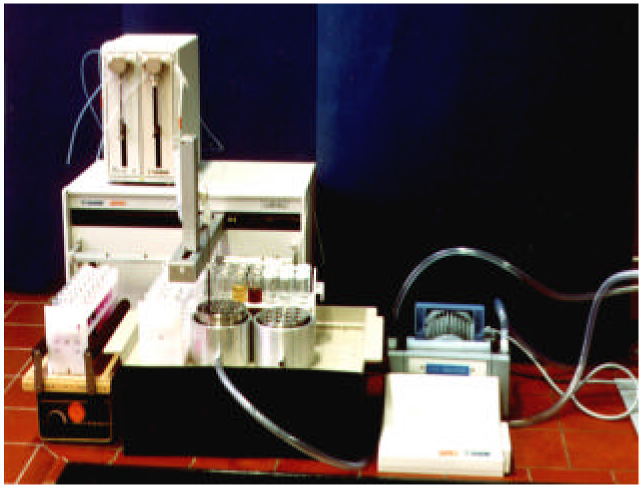
Stage-II Reactor Technology



Automated Synthesis

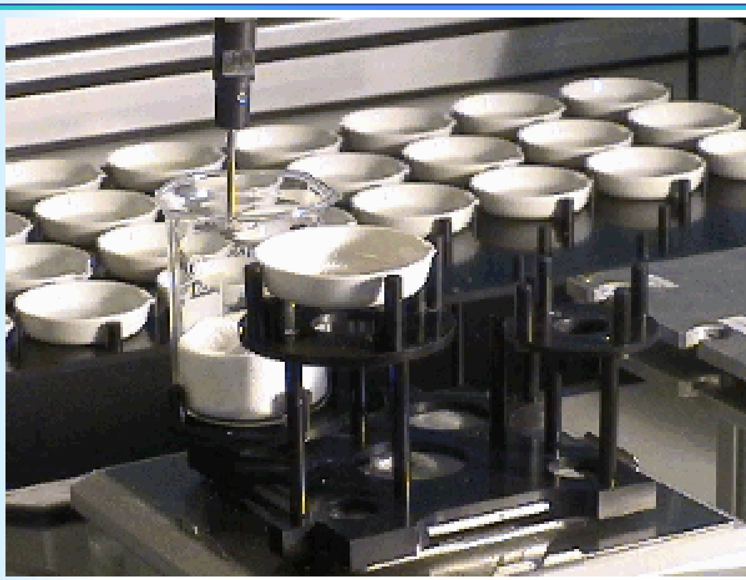


Automated Synthesis



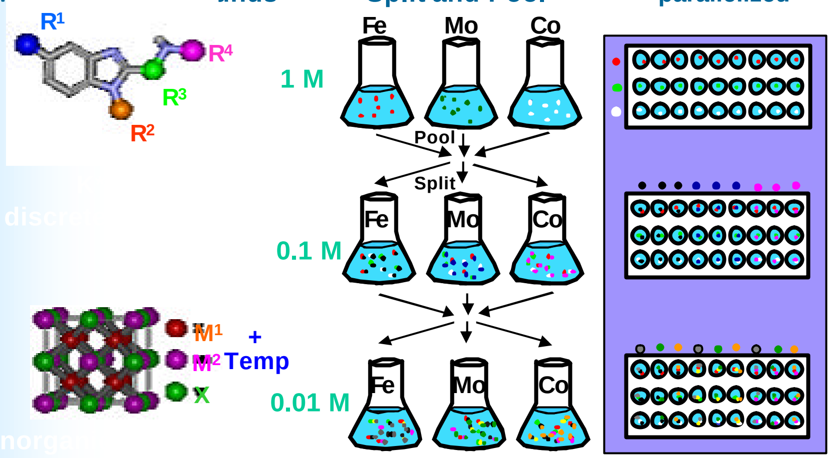
C. Hoffmann et al., Angew.Chem.Int.Ed.Engl. 38, 2800 (1999)

Solids Handling

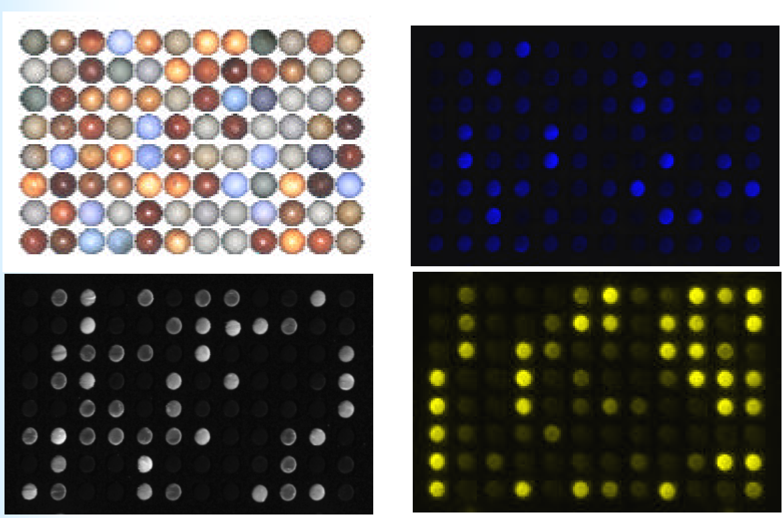


Combinatorial Chemistry

M   unds   Split-and-Pool   parallelized

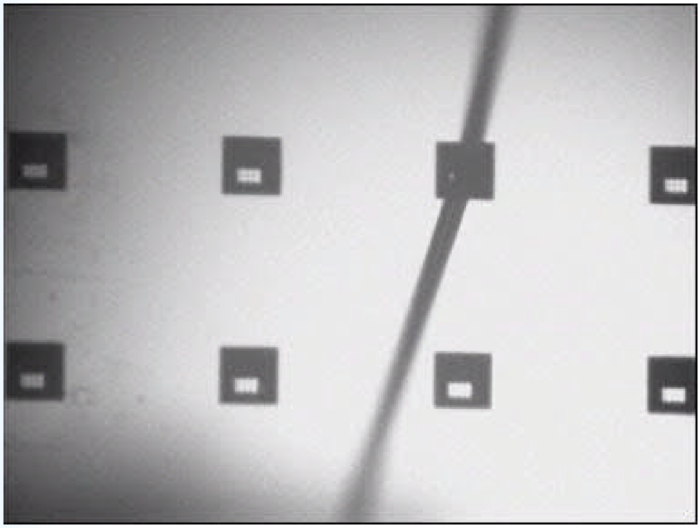


Read-out by XRF



J. Klein et al., Appl. Catal. A-General 254, 121 (2003)

High integration: Single bead reactor



Many Thanks for your Attention!