„Polymer-Dispersionen“

Klaus Tauer

Definitions

Meaning & properties of polymer dispersions

Preparation of polymer dispersions

Polymer Dispersions

Polymer:

any of a class of natural or synthetic substances composed of very large molecules, called macromolecules, that are multiples of simpler chemical units called monomers. Polymers make up also many of the materials in living organisms, including, for example, proteins, cellulose, and nucleic acids.

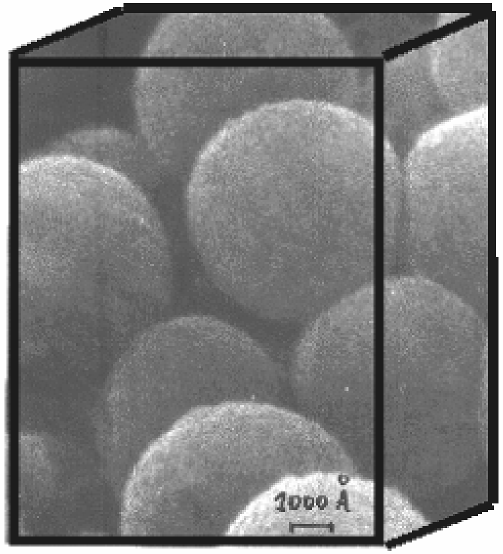
Dispersion:

(physical chemistry) a special form of a colloid:
i.e. very fine particles (of a second phase) dispersed in a continuous medium

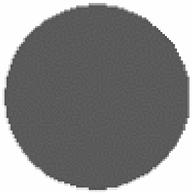
the most popular / famous / best-known case of a polymer dispersion is a LATEX

a latex is produced by heterophase polymerization, where the most important technique is emulsion polymerization

What is a Polymer Dispersion?



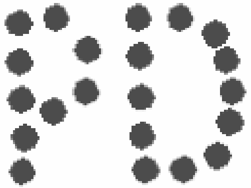
macroscopic



1 g Polystyrene

$V = 0.952\ cm^3$

Dispersion



$D = 1{,}22\ cm$

$N = 1$

$O = 4{,}767\ cm^2$

0,002 DM*)

$D = 50 \cdot 10^{-7}\ cm$

$N = 1{,}455 \cdot 10^{16}$

$O = 1{,}143 \cdot 10^{6}\ cm^2$

$1{,}8 \cdot 10^{3}$ DM a) *)

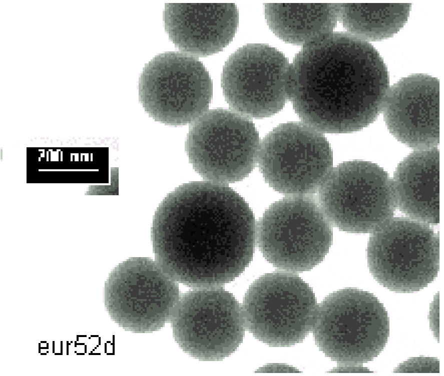
a) Polyscience, Inc. catalog 1995

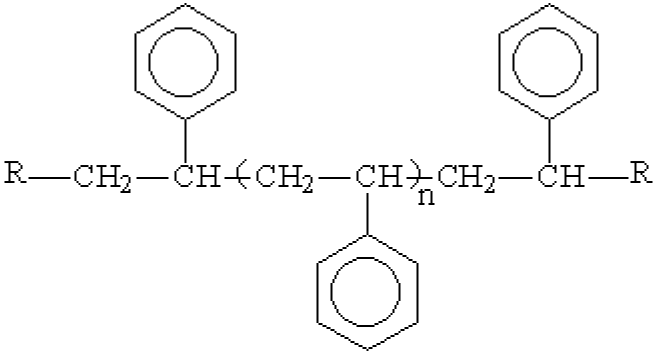
N polymer particles with an average volume V_P dispersed in a liquid of volume V_W

the liquid is called dispersion medium or continuous phase or serum or homogeneous phase

*) 1 DM = 1.95583 €

Molecular Composition of a Latex




$R-CH_2-CH-(CH_2-CH)_n-CH_2-CH-R$

solids: 50 %, D = 200 nm ,
M_N = 6 10^5 g mol^{-1}, styrene

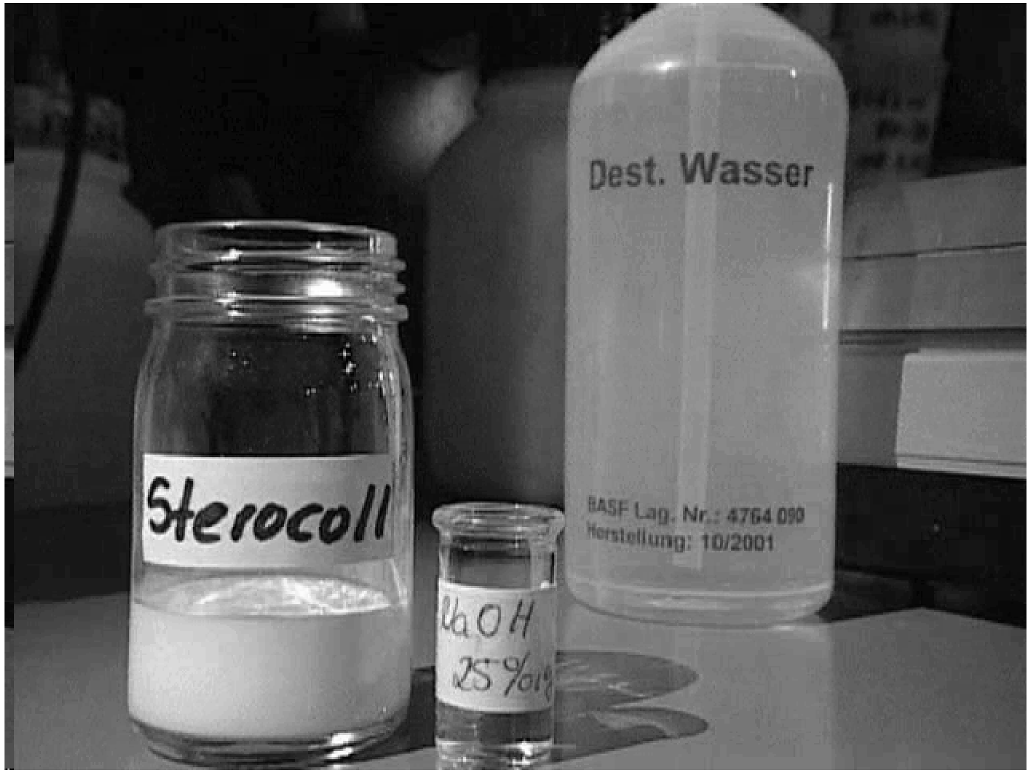
N ~ 2.3 10^{14} cm^{-3}	4400 macromolecules per particle	n ~ 6000

General:

N ~ 10^5 - 10^{15} cm^{-3}	1 - 10^{12} macromolecules per particle	n ~ 1 - 10^6

polymer dispersionen:

high concentration of polymer with low viscosity



thickener (BASF AG, Ludwigshafen)

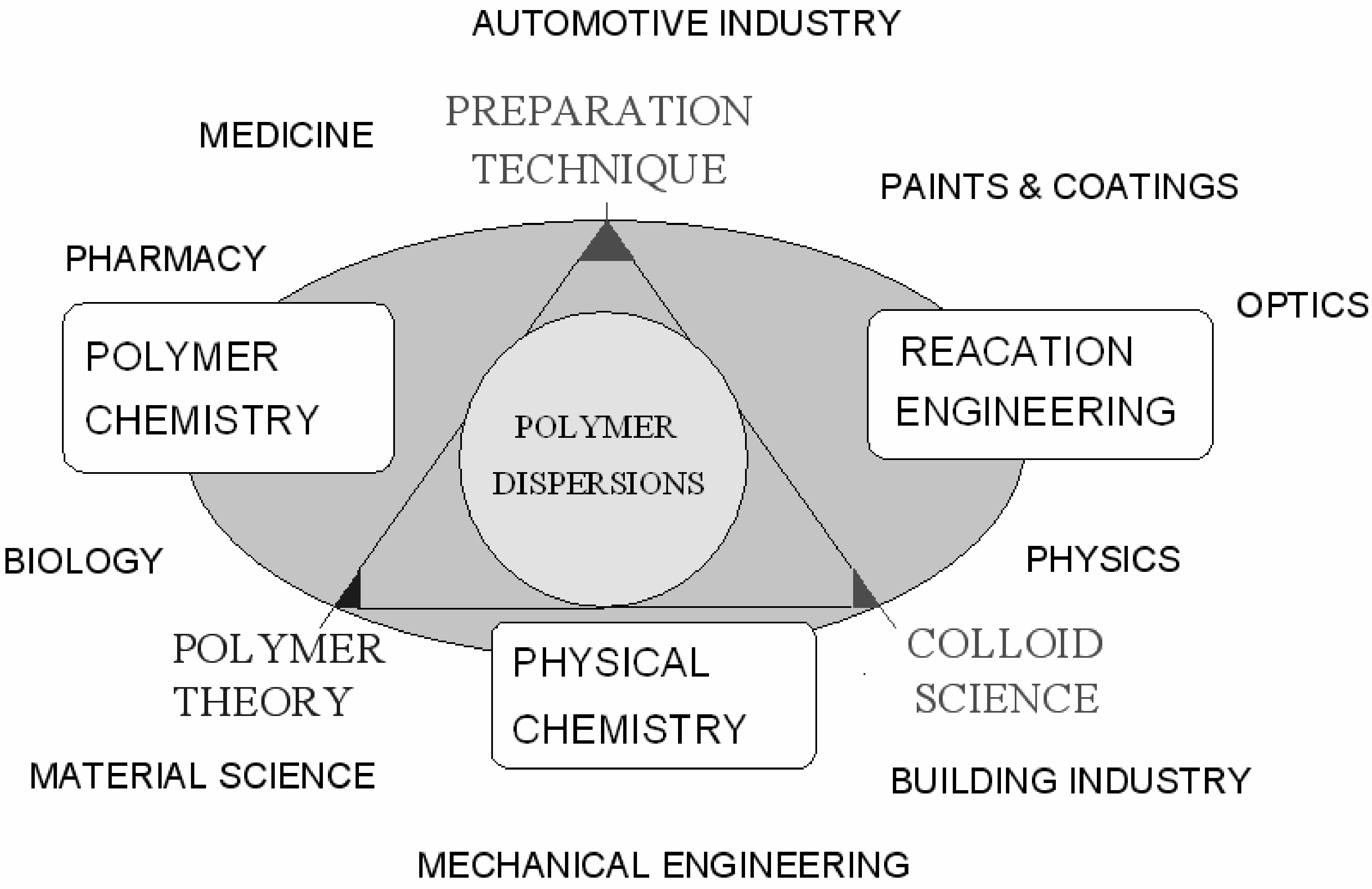
Virtual EASE 2003/1 „Thickening agent“

Sterocoll is an acidic aqueous polymer dispersion containing polymer particles rich in caroxylic acid groups. It is used as thickening agent.

First the polymer dispersion is diluted with water to lower the polymer content from 30 % to 5 %. It is still a white liquid having low viscosity.

By addition of a small amount of an aqueous sodium hydroxide solution the pH is increased and the caroxylic acid groups are negatively charged. This makes the polymer particles soluble in water and a polymer solution is formed. At the same time the viscosity strongly increases due to the unfolding of the polymer molecules. At the end a clear gel is obtained.

The Meaning of Polymer Dispersions



AUTOMOTIVE INDUSTRY

MEDICINE

PREPARATION TECHNIQUE

PAINTS & COATINGS

PHARMACY

OPTICS

POLYMER CHEMISTRY

POLYMER DISPERSIONS

REACATION ENGINEERING

BIOLOGY

PHYSICS

POLYMER THEORY

PHYSICAL CHEMISTRY

COLLOID SCIENCE

MATERIAL SCIENCE

BUILDING INDUSTRY

MECHANICAL ENGINEERING

→ each application needs a polymer dispersion with special properties

important application properties:

viscosity

dilatancy (BASF AG, Ludwigshafen)

viscosity-psd

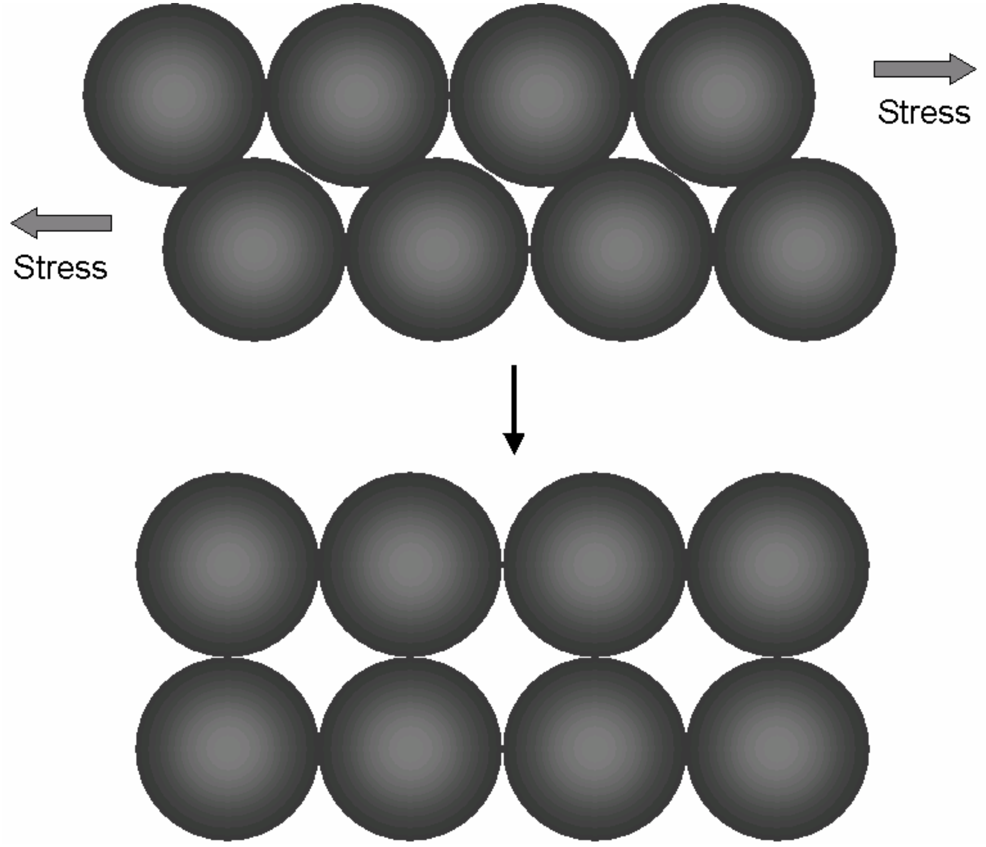
„Dilatancy“

Dilatancy is a rheological phenomenon. A dilatant liquid shows viscosity raise as the shear rate is increased. Or in other words when a rod or a stirrer is moved at higher velocity in the liquid it thickens.

With the polymer emulsion shown in the experiment the effect has been driven to an extreme. The emulsion consists of small polymer particles of ca. 300 nm. As long as the shear rate is low e.g. during pouring or slow stirring it stays thin. The particles order themselves into rows or planes that can pass each other with only little friction.

The liquid flows easily. As the rod is rapidly pulled out the applied shear rate increases, the order of the particles is completely destroyed. They interlock and can not move independently any more. The whole system is converted into a solid like state. It now can transmit forces that the beaker can be lifted.

“stress makes tough”



- stress shifts the particle layers in highly concentrated emulsions so that the space between the particles increases
- water cannot redistribute quickly enough
- subsequently the latex solidifies (walking on the beach)

important application properties:

viscosity

viscosity-psd (BASF AG, Ludwigshafen)

dilatancy

„Diversity matters“

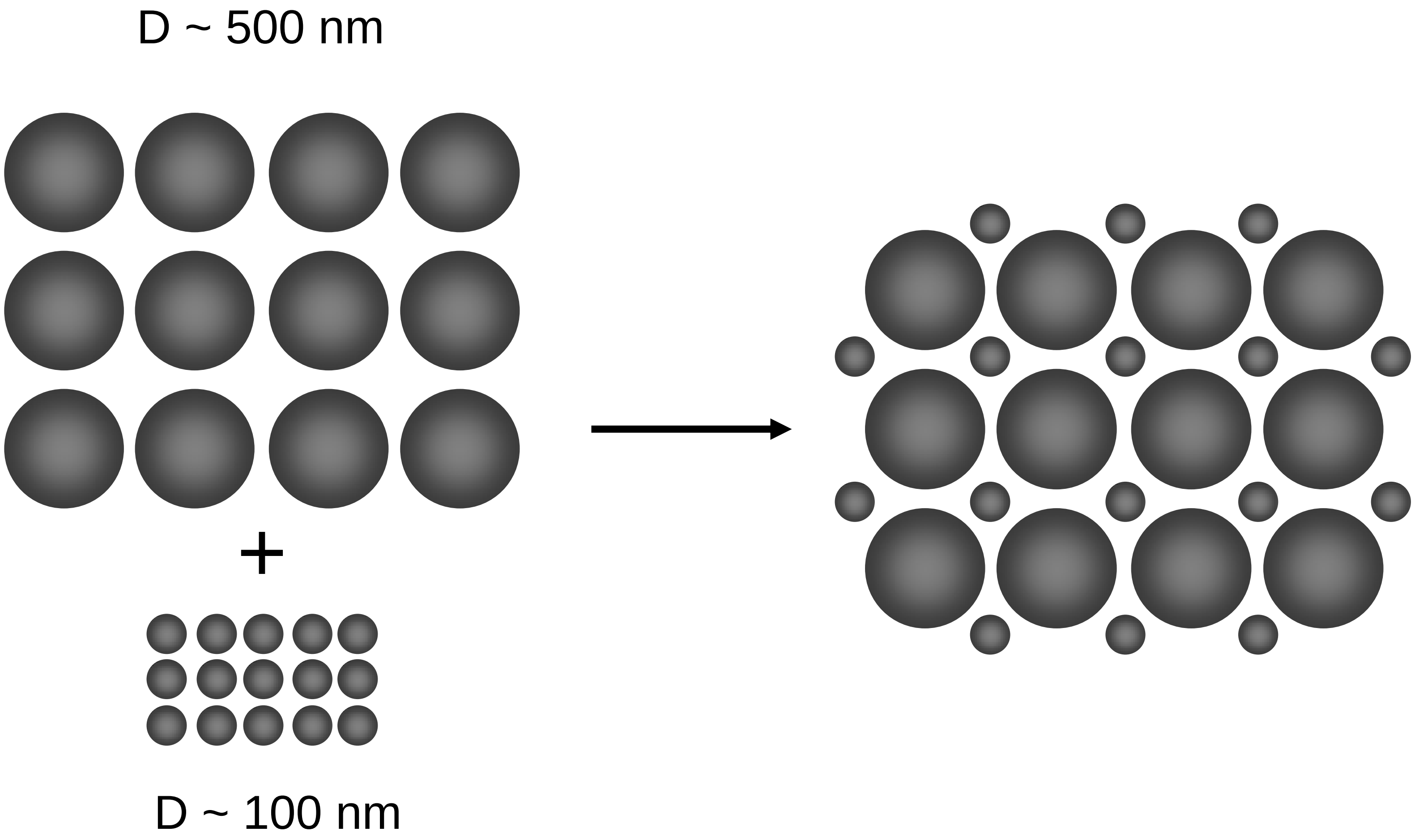
This experiment shows that the viscosity of a polymer colloid strongly depends on particle size distribution.

The first polymer colloid contains small polymer particles with a diameter below 100 nm. The second consists of particles with a diameter of bigger than 500 nm. Both polymer colloids are pasty, their viscosities are high.

After mixing the resulting dispersion has a bimodal particle size distribution and the viscosity is much lower than either one before.

The small particles fill up the space between the big ones and the more diverse mixture is flowing more freely.

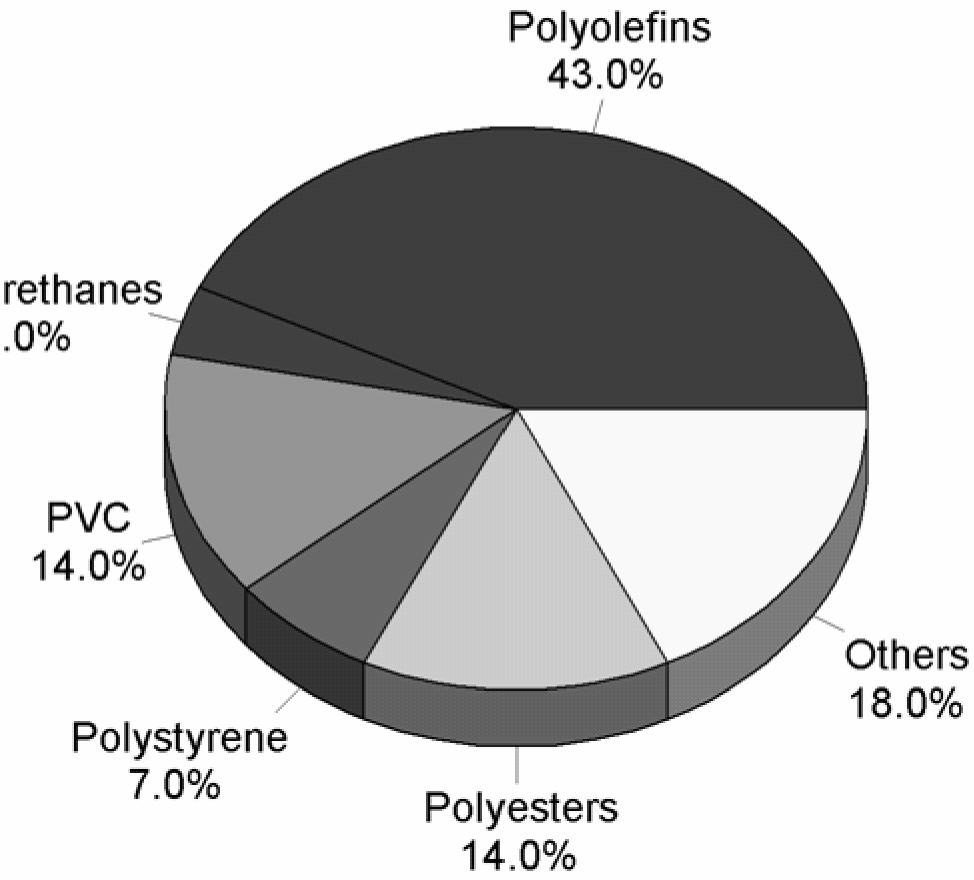
“thick + thick = thinner”



- the smaller particles distribute evenly between the larger particles
- subsequently water is “released” and the dispersion diluited

World Production of Polymers

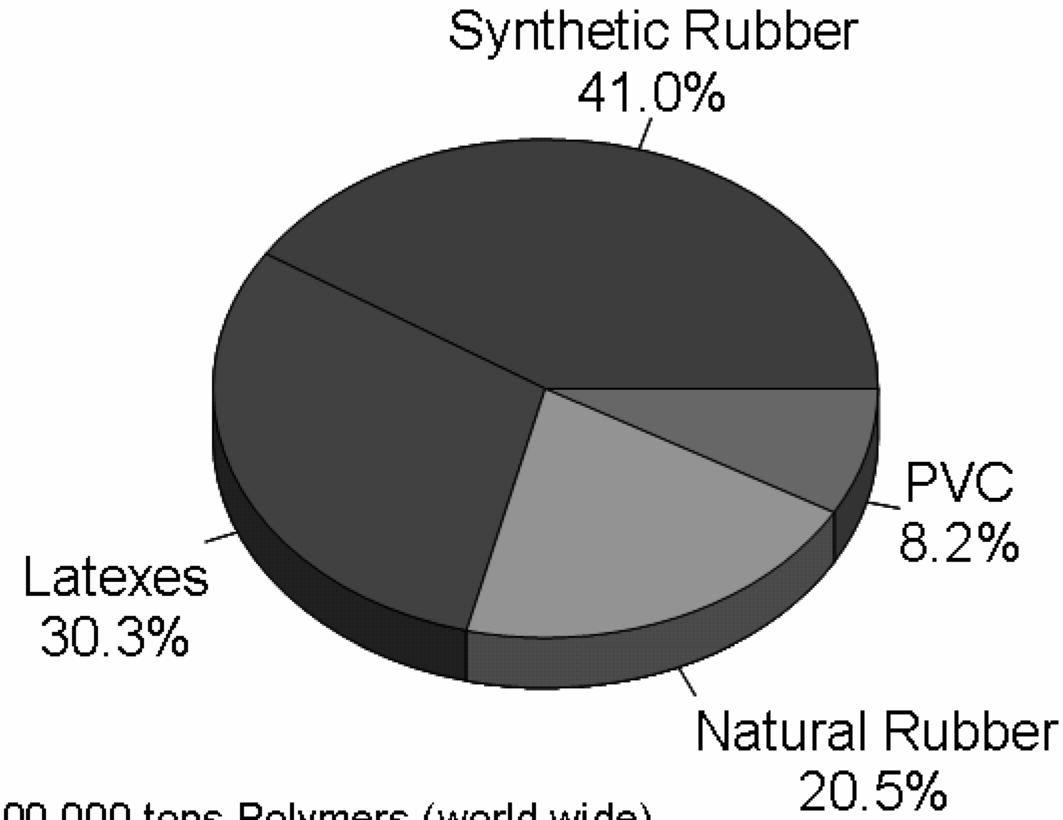
Yearly production: ~$190 \cdot 10^6$ tons



P. Baum, J. Engelmann Nachrichten aus der Chemie, Weinheim, 49/3 (2001) 368f

Emulsion Polymerization Products

Total Amount ca. 25.000.000 tons (world wide)

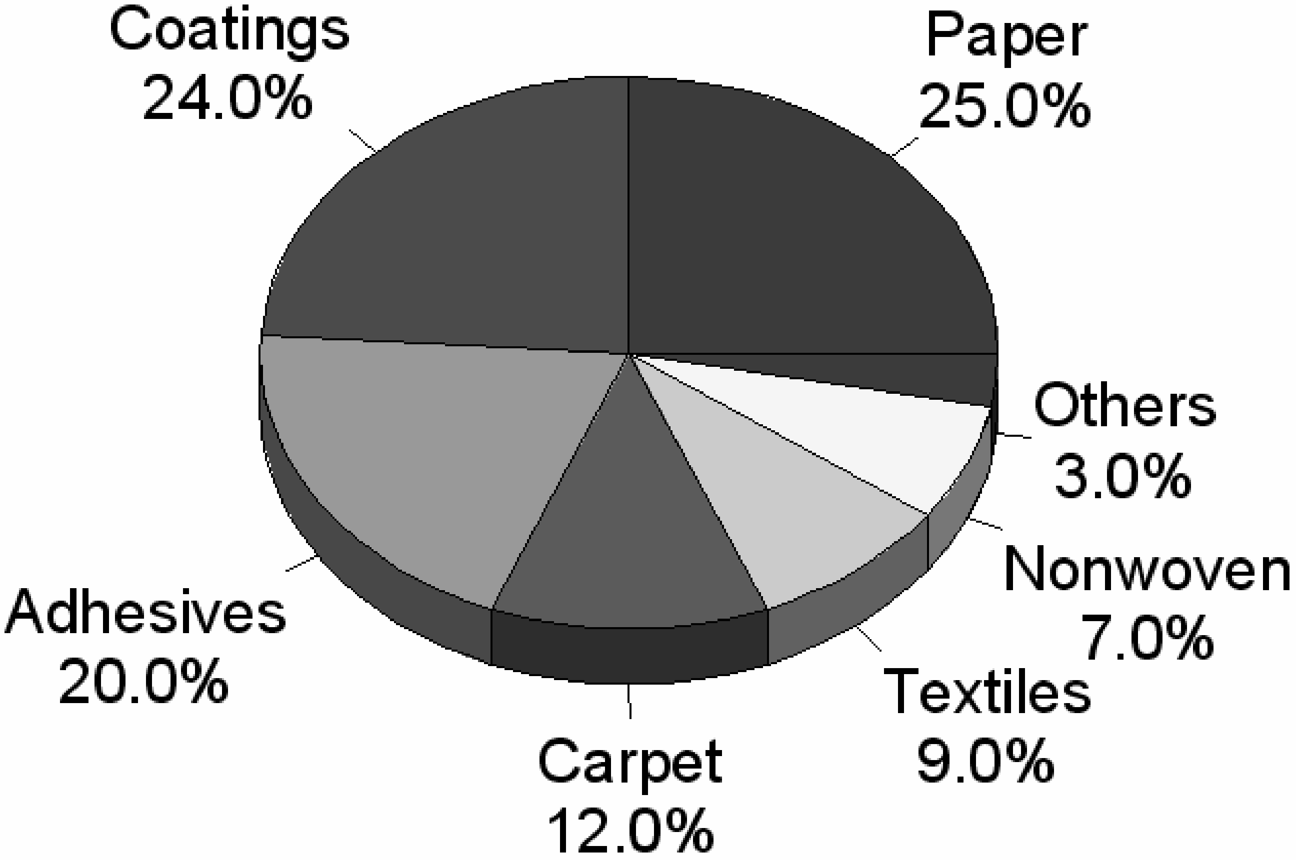


ca. 190.000.000 tons Polymers (world wide)

D. Bassett (NATO ASI Recent Advances in Polymeric Dispersions, Spain 1996)

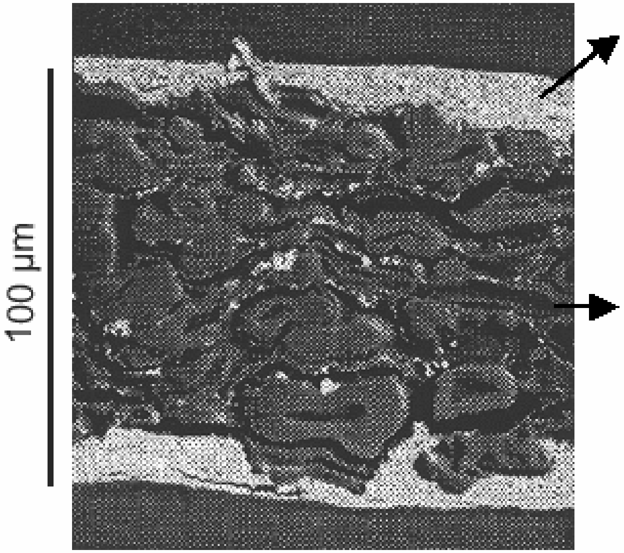
Latex Applications

100% = 7.400.000 tons per year



D. Bassett (NATO ASI Recent Advances in Polymeric Dispersions, Spain 1996)

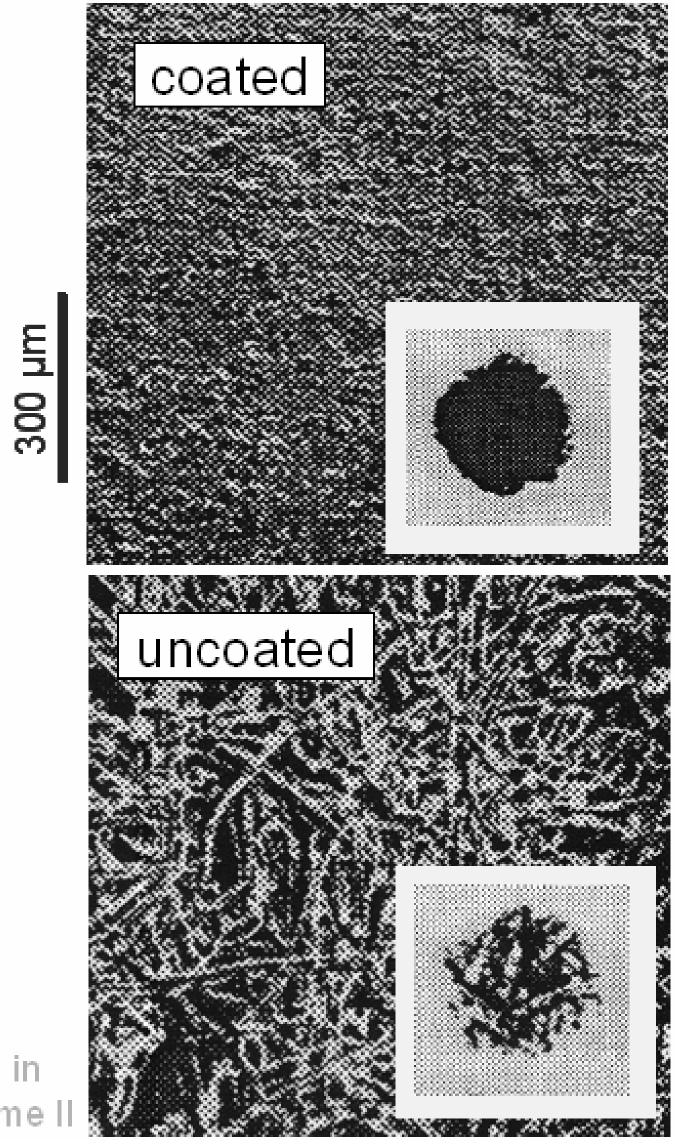
No Good Quality Paper Without Latexes



coating (latex binder + pigment 20/80 w/w up to 4/96 w/w) and air

paper fibers
air

paper with a halftone dot



coated paper is a fiber-reinforced pigment-binder-air composite

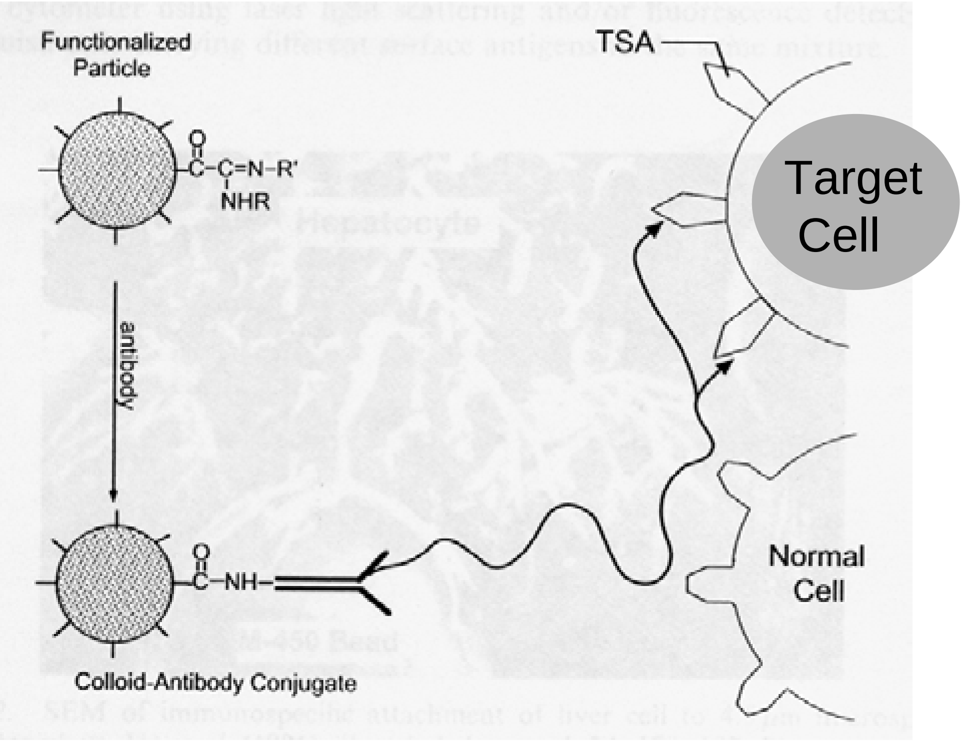
paper consumption:
USA 330 kg per head China 20 kg per head
⟶ there is to expect an increase in paper production of at least $4\ 10^{11}$ kg if the paper consumption will be equal in China and the US

Do Ik Lee (Dow Chemical Company) Nato ASI "Recent Advances in Polymeric Dispersions" June 23 - July 5, 1996, Proceedings Volume II

Biomedical Applications - Principle

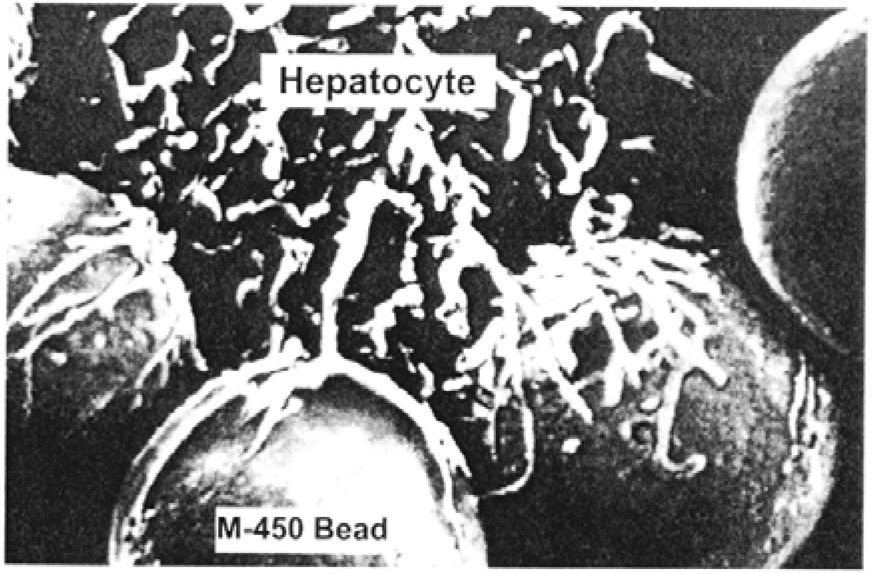
benefits of latex particles for medicine & biotechnology

take advantage of the large interfacial area and the possibility to tailor both surface and volume properties



separation by means of magnetic latex particles with special surface functionalities

Biomedical Applications - Examples



R.M. Fitch “Polymer Colloids” , Academic Press, 1997, 164-172

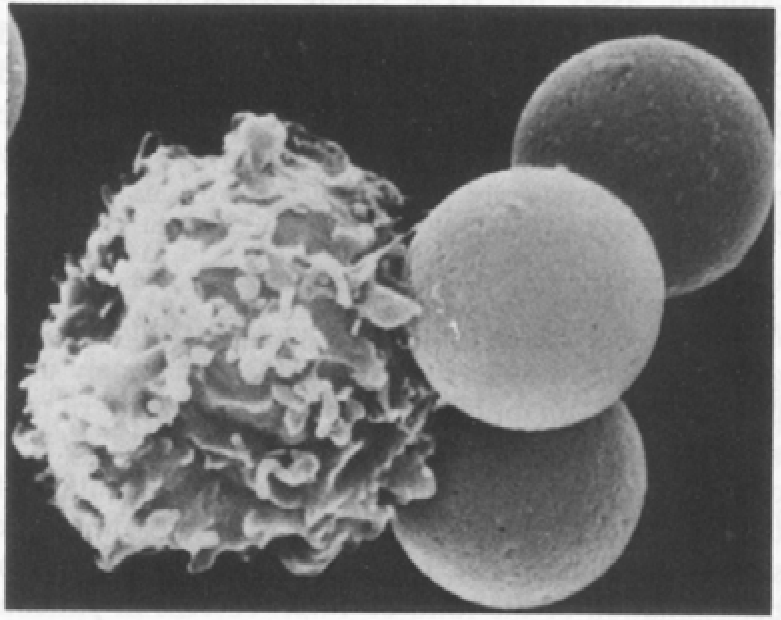


Fig. 3. Neuroblastoma cell isolated by means of M-450 Dynabeads®.

J. Ugelstad et al. Polymer Intern. 30 (1993) 157-168

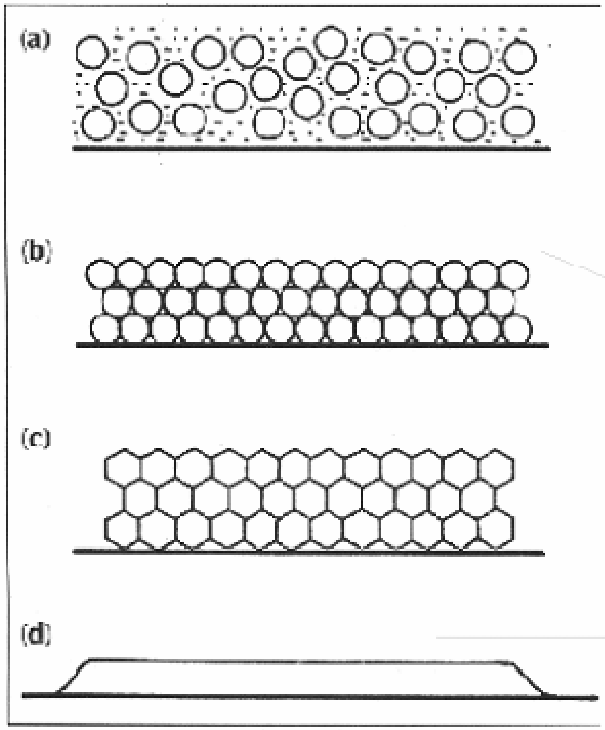
- treatment of cancer of the nerve cells (neuroblastoma)

- bone marrow is taken from patient and slurried with magnetic, monosized 4.5µm particles which are immunospecific for the neuroblastoma cell surface

Film Formation

Synthetic Latexes

Schematic drawing



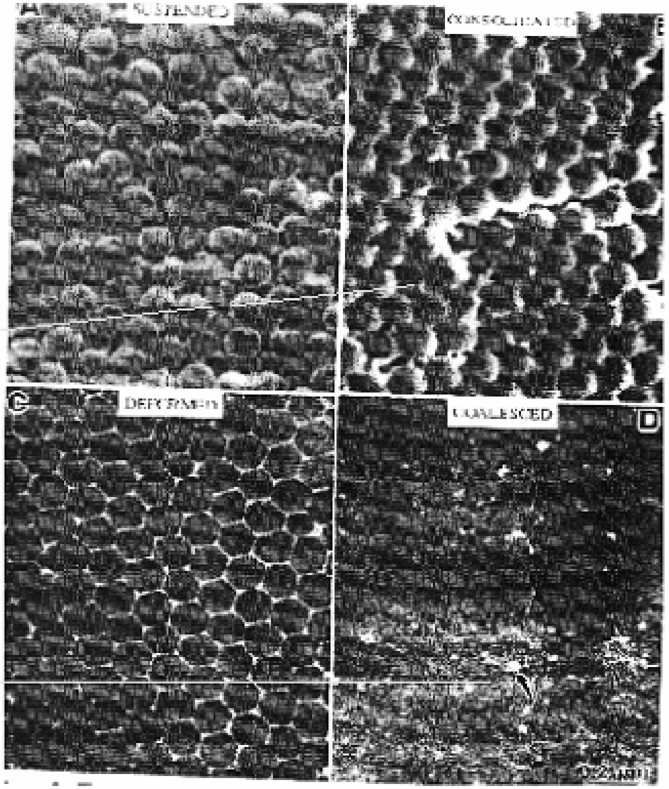
Suspended

Consolidated

Deformed

Coalesced

STY-BD-AA latex

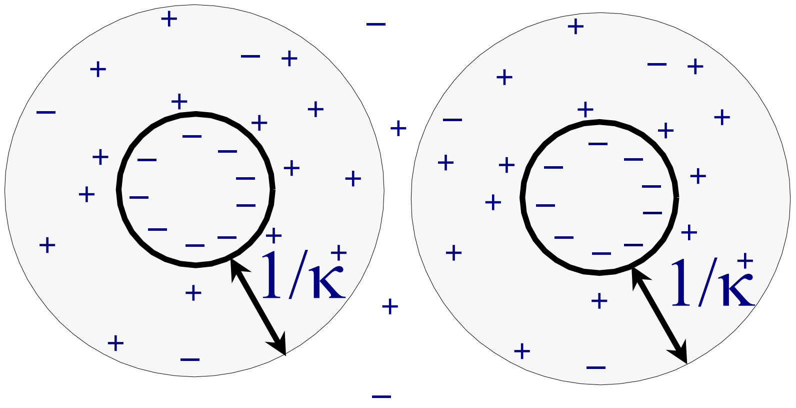


Ö.Pekcan, TRIP 2 (1994), 236-243

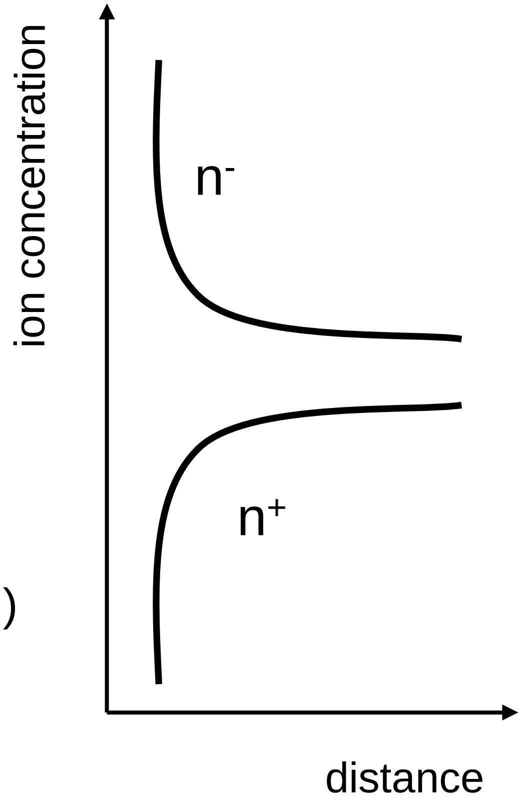
K. Takamura et al. TAPPI proceedings,
Coating Conference 1995, 391-405

Stabilization of Colloidal Particles - 1

most important case:



electrostatic

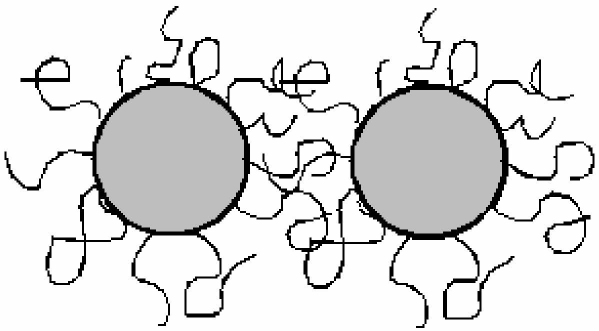


$$V_{int}(h) = \pi \cdot a\left(\underline{-\frac{H_{121}}{12\pi} \cdot \frac{1}{d_{PP}}} + \underline{\frac{64 \cdot k_B \cdot T \cdot C_0 \cdot \Gamma_0^2}{\kappa^2} \exp(-\kappa \cdot d_{PP})}\right)$$

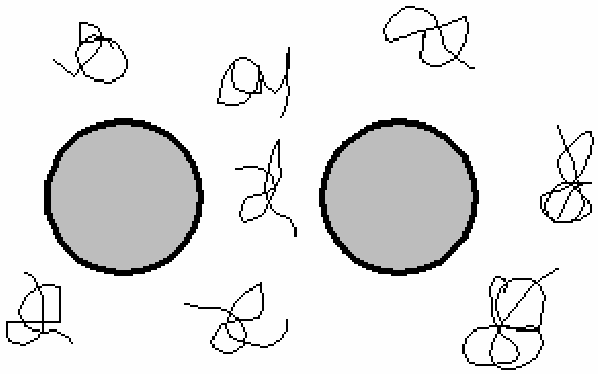
$$\Gamma_0 = \tanh\left(\frac{z \cdot e \cdot \Phi}{4 \cdot k_B \cdot T}\right)$$

D.F. Evans, H. Wennerström "The Colloidal Domain", VCH 1994, p. 336

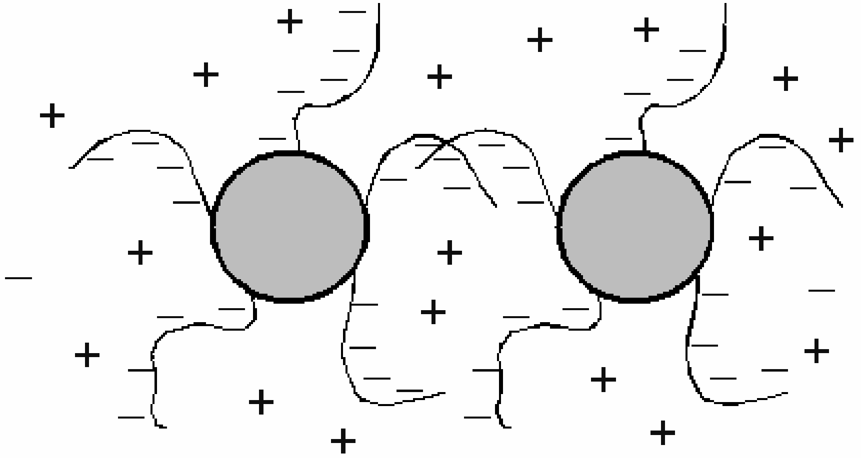
Stabilization of Colloidal Particles - Charges + Polymers



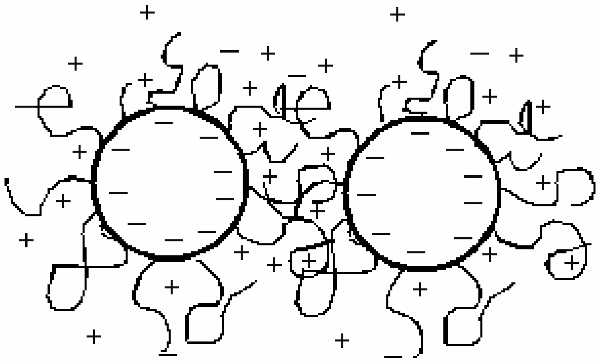
steric
adsorbed, tethered



depletion stabilization.



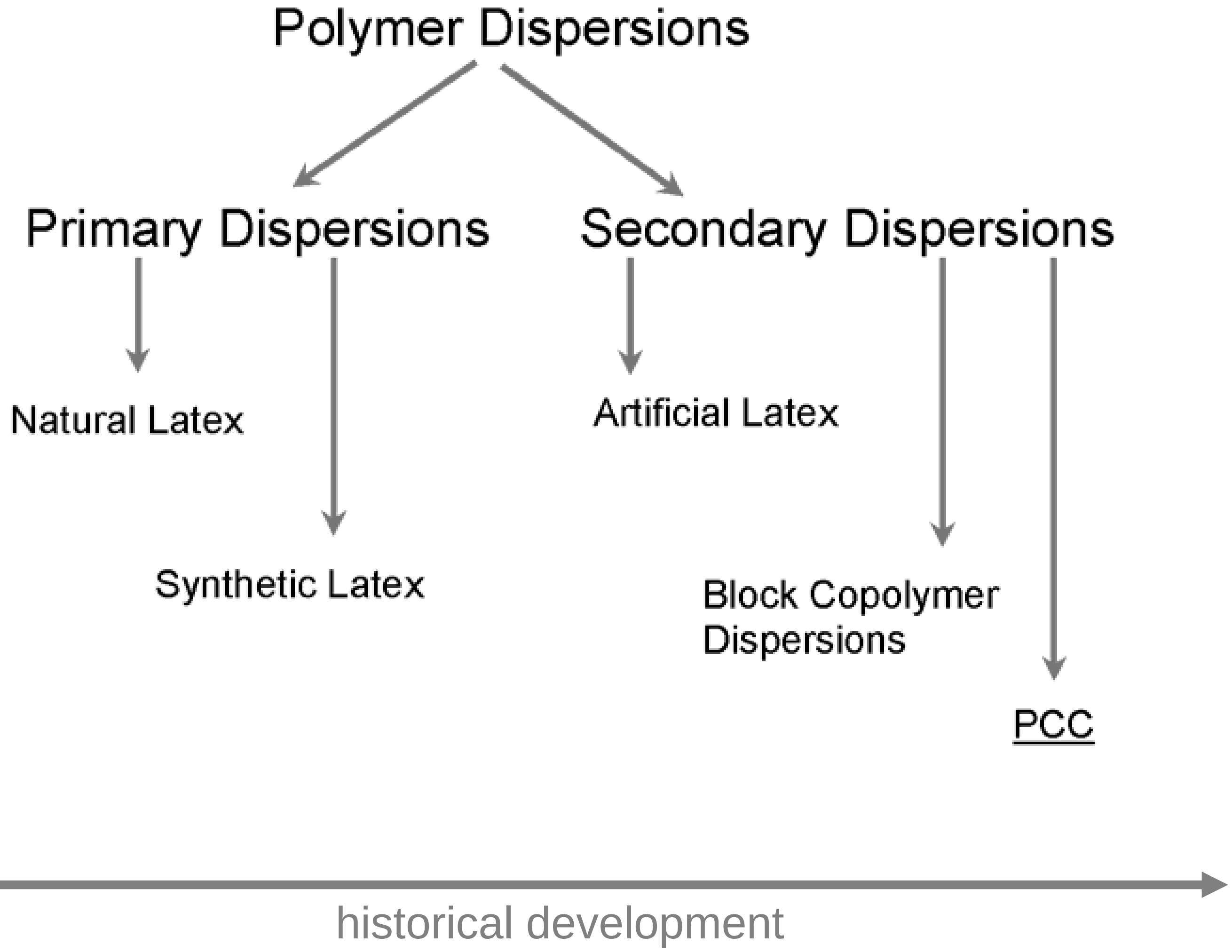
charged polymer, adsorbed or tethered



charges on particle surface and
polymer adsorbed or tethered

Polymer Dispersions

a family tree



Polymer Dispersions

Primary Dispersions

Secondary Dispersions

Natural Latex

Synthetic Latex

Artificial Latex

Block Copolymer Dispersions

PCC

historical development

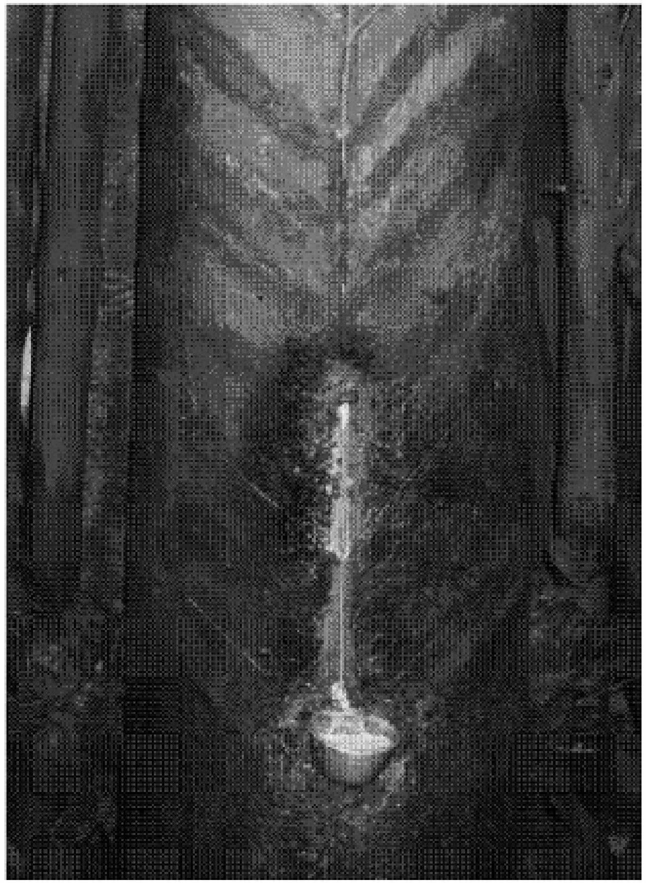
Natural Rubber (NR)

Occurence: in over 1000 species of plants (dikotyledonen)
as white liquid (milky sap) = natural latex

European plants: Gänsedistel (sonchus oleraceus)
salad (lactua sativa)

Economic importance: hevea brasiliensis tree
sole source of natural rubber (99%)
height: 20 m; diameter: 0.7 m
productivity: 10 g latex a day (33% solid)

The Rubber Tree Reactor



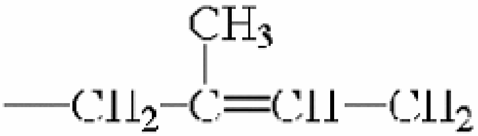
Natural rubber is produced in a system of tubular vessels in the tissue of the tree. Freshly collected latex contains all the enzymes necessary for the formation of rubber from the sugars photosynthesized in the leaves of the tree.

Continuous tubular reactor (L: 20m; D: 0.7m)
Pressure: 1.38 bar
Productivity: 10 g/day
World production: 5 million tons/year

Application: rubber with high elasticity
Price: about 1 US-$ per kg

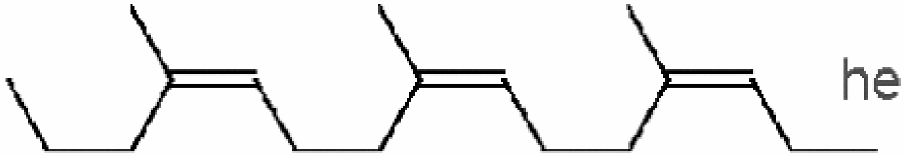
Natural Latex Polymer

- enzymatic catalysed biosynthesis



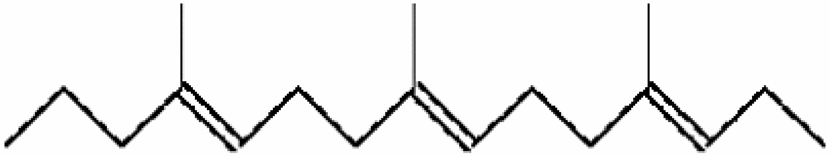
$$-CH_2-\overset{\overset{\textstyle CH_3}{|}}{C}=CH-CH_2$$

polyisoprene repeating unit



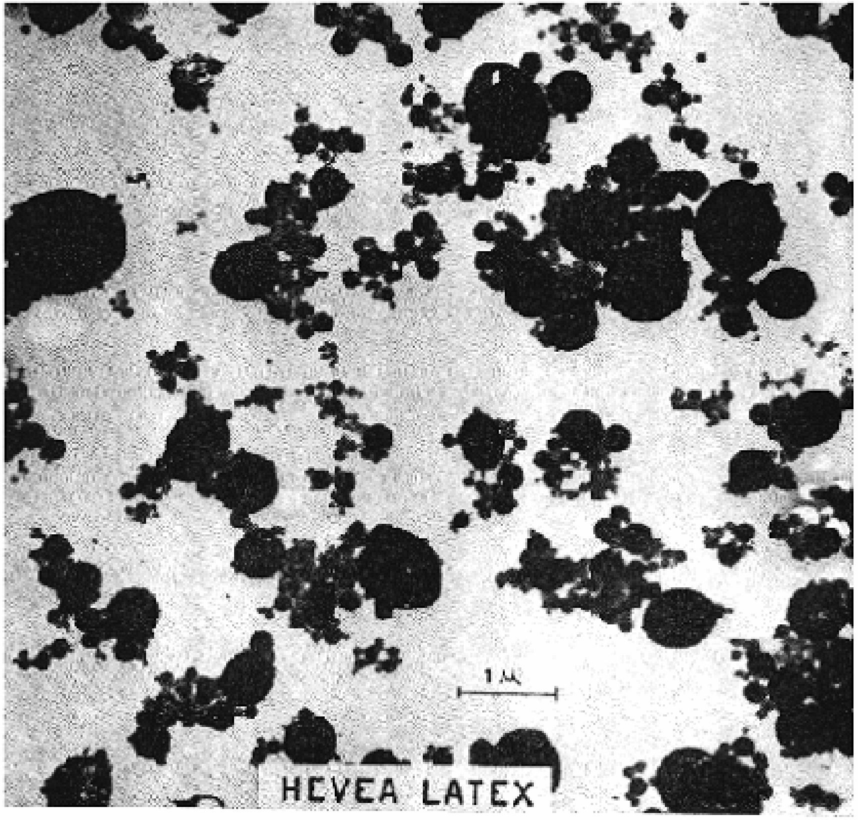
hevea brasiliensis, caoutchouc

cis-1,4-polyisoprene



guttapercha, balata

Natural Latex



The natural latex of the Hevea brasiliensis tree is a cytoplasmic system consisting of cis-polysioprene particles in an aqueous phase electro-sterically stabilized by proteins (1-2%) and phospholipids (0.4-0.8%).

[pH: 6.5-7.0; ρ: 0.98 g cm^{-3}; SC: 33%]

PSD: 50 nm up to 1.6µm
DP: 8.000 - 30.000

TEM photograph taken from F.A. Bovey, I.M. Kolthoff, A.I. Medalia, E.J. Meehan "Emulsion Polymerization", Volume IX High Polymers, Interscience 1955

Heterophase Polymerization Techniques

Technique	Components
Suspension Pm• Microsuspension Pm.• Dispersion Pm. Emulsion Pm.• Miniemulsion Pm. Microemulsion Pm.	Dispersion Medium Monomer Polymer Stabilizer

Technique	Components
Precipitation Pm.	Dispersion Medium Monomer Polymer

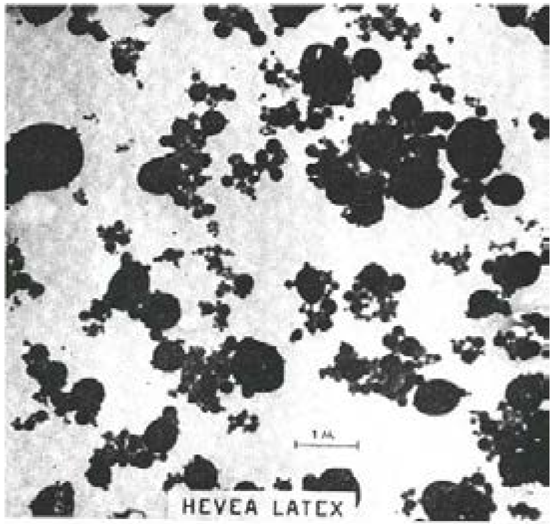
Technique	Components
Bulk Pm. Gas Phase Pm.	Monomer Polymer

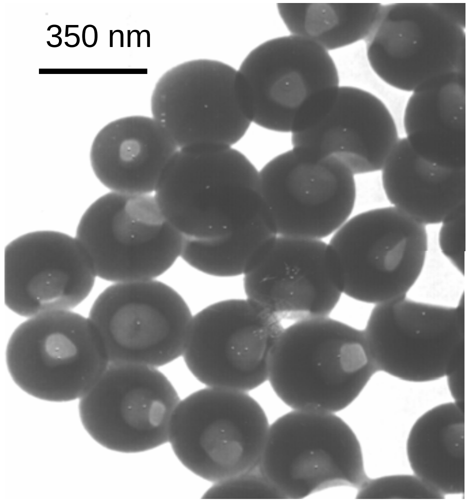
Basic Principle: polymer is insoluble / immiscible in the medium

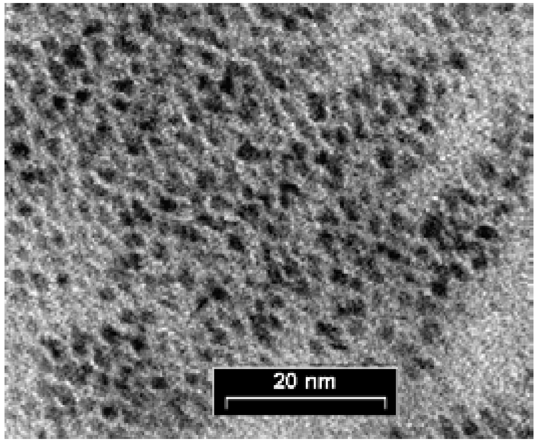
- • of technical importance

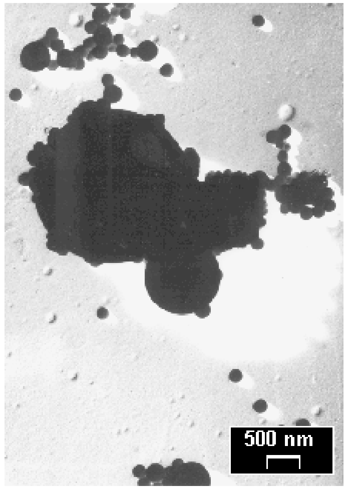
Heterophase Polymerization - A Simple Definition

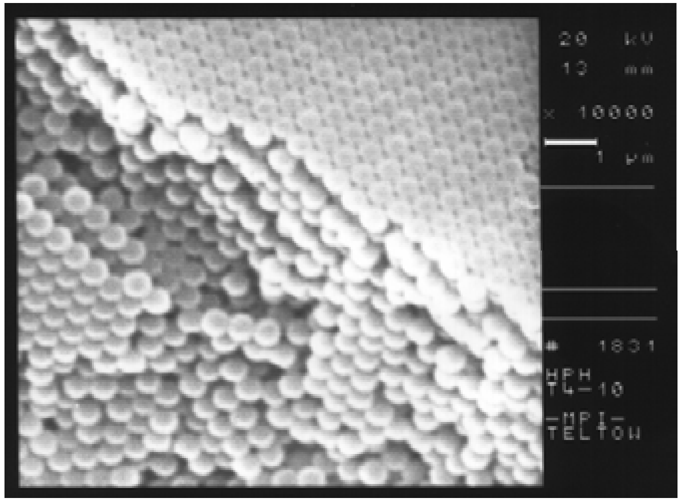
- a generic term for methods to produce different kinds of polymer particles:

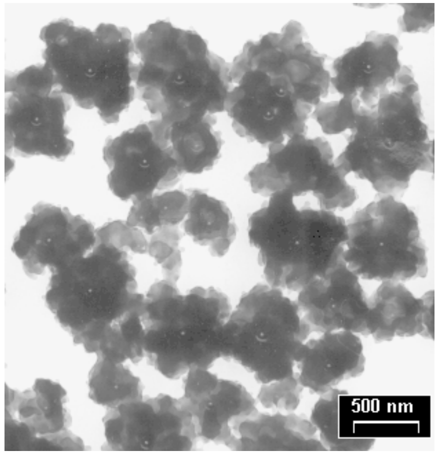




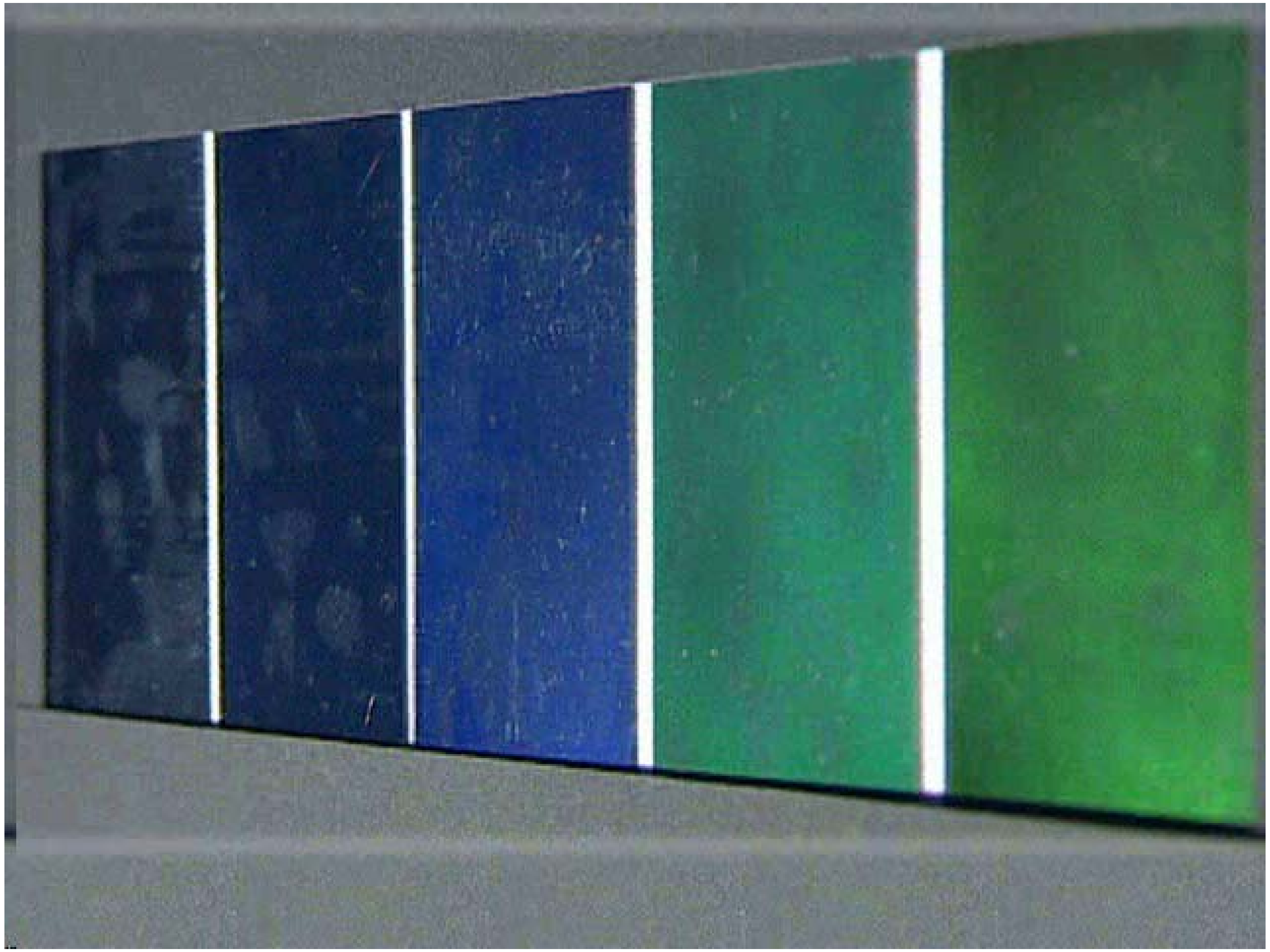








monodisperse particles



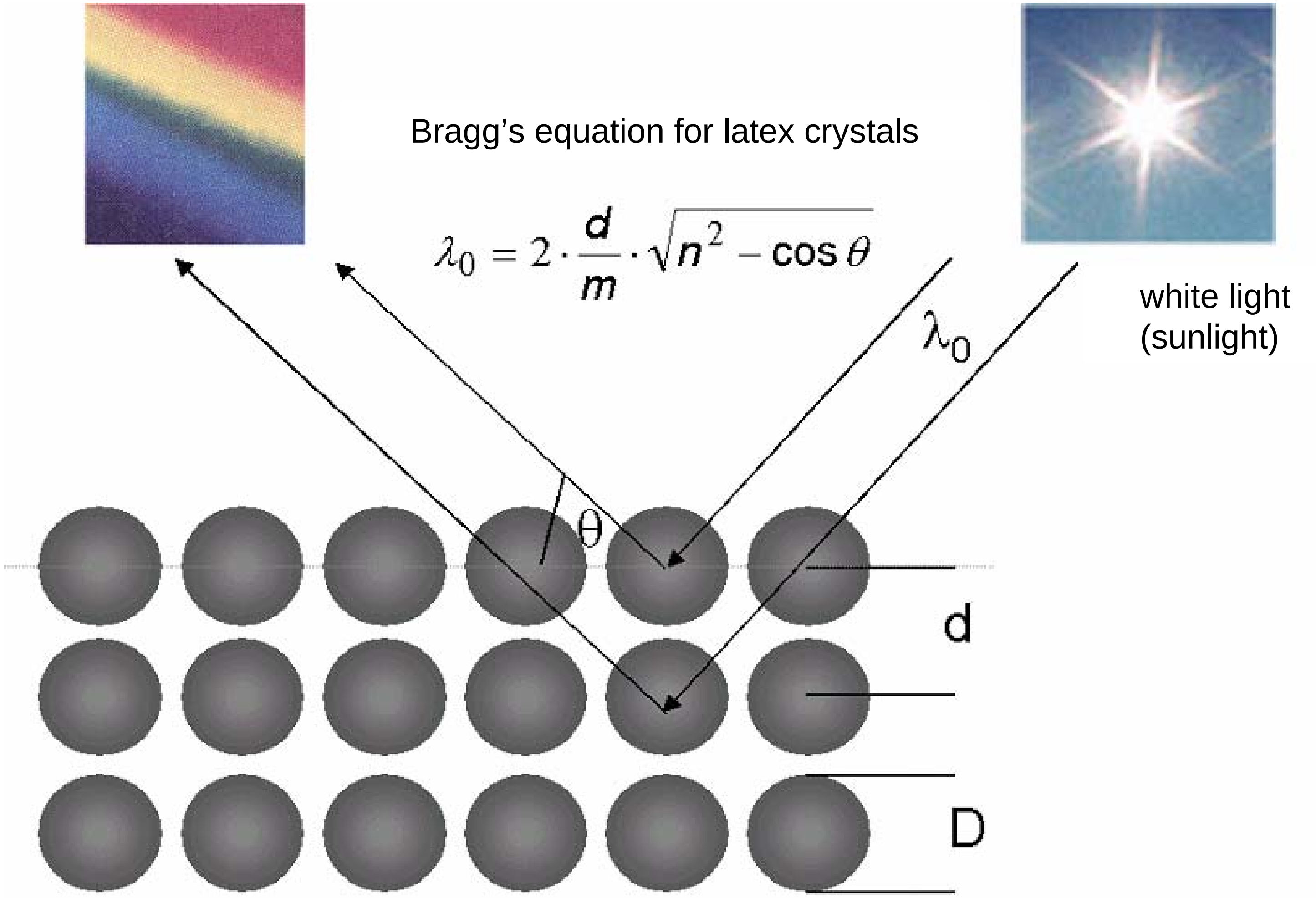
color without dyes (BASF AG, Ludwigshafen)

„Color by transparent latex particles“

Monodisperse polymer particles can arrange in a quasi crystalline ordered structure and produce an angle dependent color effect due to Bragg diffraction at the 'crystal' planes. When the lattice parameter is comparable with the wavelength of visible light and a refractive index difference between the particle and the matrix exists, an intensive iridescent color will be observed. The polymer films used here were made from an emulsion made by two step emulsion polymerisation. A crosslinked hard core particle is formed in the first step, followed by the film forming outer phase in the second step. Both the mechanical properties and the color effects of the films could be varied by changing the particle size and the thickness of the outer phase.

The color changes from red through yellow to green the more acute the viewing angle is. This is because the apparent distance between two particles decreases the more oblique the angle of observation. Also the amount of shell material and thus the distance between the nanoparticles is changed, and results in different colors. As the size of the core-shell particles decreases, the color, when observed from a vertical perspective, changes from red through yellow to green and even blue. Depending on the viewing angle, the same area appears for example either as glowing red or bright green. The particle size has to be accurately chosen, since even minor changes of about 20 nanometers have a clear effect on the color.

“colors without dyes”



Bragg’s equation for latex crystals

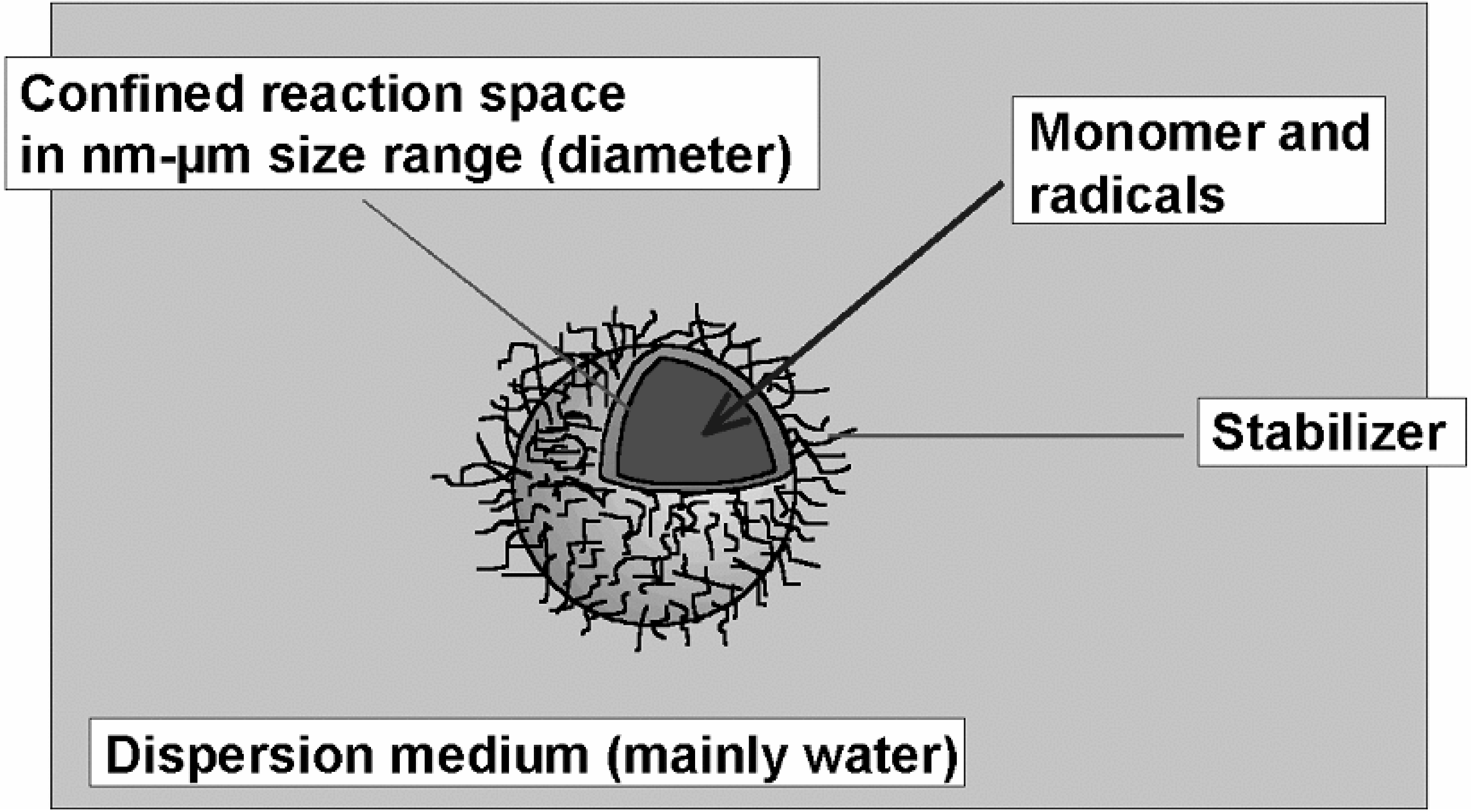
$$\lambda_0 = 2 \cdot \frac{d}{m} \cdot \sqrt{n^2 - \cos\theta}$$

white light
(sunlight)

reflexion (and color) depends on the wave length of incoming light and the observation angle

Common Features of Heterophase Polymerizations

Heterogeneous system; spatial density differences;
at least two phases; transport processes; equilibria;....



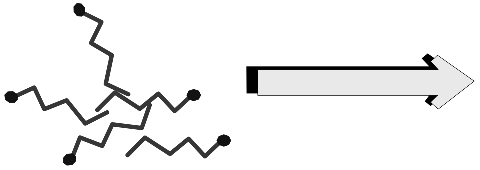
Confined reaction space in nm-µm size range (diameter)

Monomer and radicals

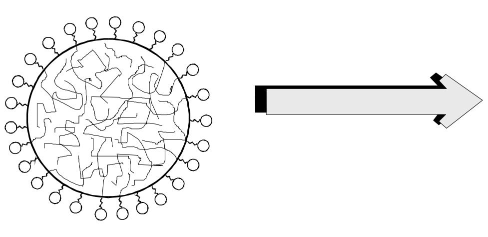
Stabilizer

Dispersion medium (mainly water)

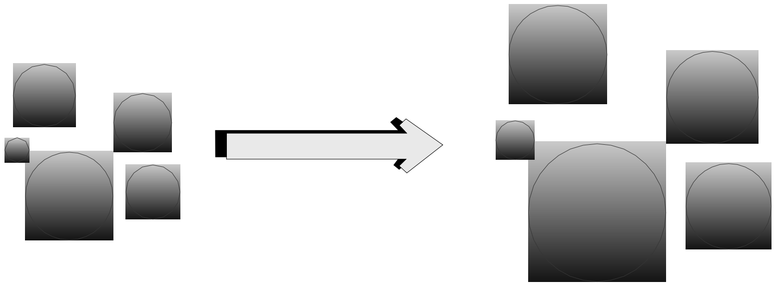
Curriculum Vitae of a Latex Particle



nucleation



swelling



growth

some unusual examples
(regarding morphology)

Advantages of Heterophase Polymerization Techniques

- Easiness of polymerization heat removal
- Viscosity of the reaction mixture is low and independent of the polymer molecular weight
- Monomer and emulsion feed procedures are possible as the monomer consumption takes place outside the monomer droplets
- Monomer concentration at the reaction loci can be kept stationary at its highest level so that the rate of polymerization is high during the entire reaction
- The particle size distribution as well as the average particle size can be tailored over wide ranges
- Product properties can be changed nearly unlimited

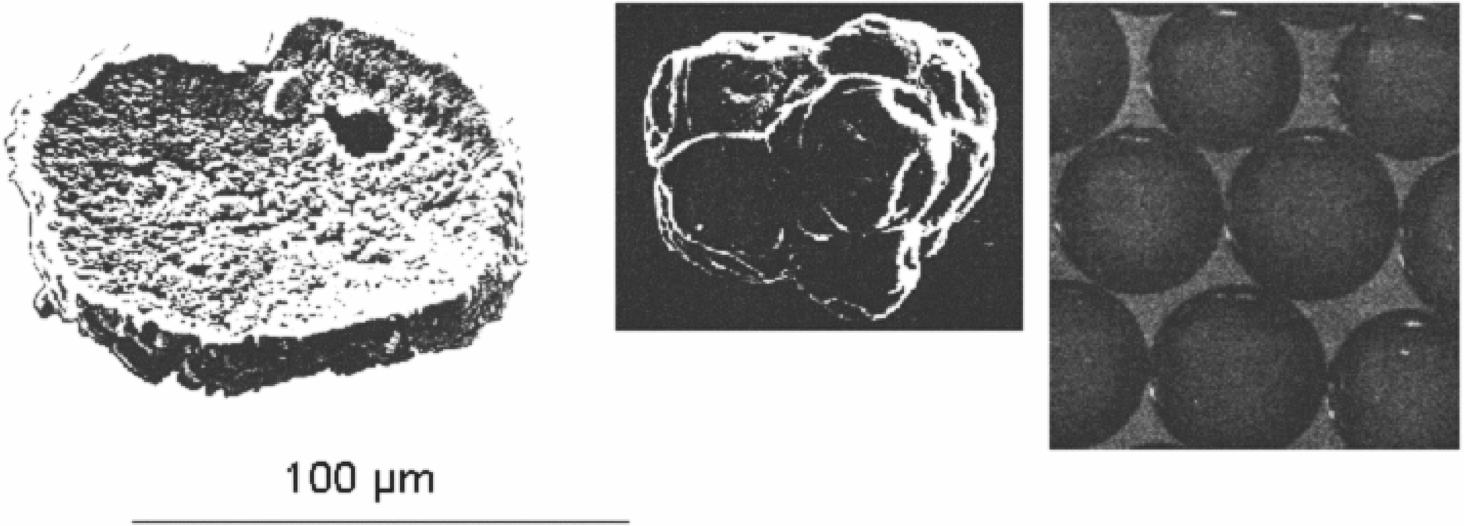
→ most important mechanism today: radical polymerization

Suspension Polymerization

- Water, monomer, oilsoluble Initiator, protective colloid (water soluble polymers: Polycarboxylic acids, cellulosic materials, poly(vinylalcohol))
- Reaction product is a slurry of suspended polymer particles with a particle size in between 50 - 400 µm
- Particle size is determined by monomer typ, stabilizer, and agitation
- Technical very important (styrenic ion exchange resins, VC homo and copolymers, tetrafluorethylene, vinyl acetate)
- Bulk polymerization in the monomer droplets
- Reactor sizes up to 200 m^3, cycle times before cleaning the reactor around 500; radical scavengers at the reactor walls to prevent fouling and water phase polymerization

Suspension Polymerization

Particle Morphology



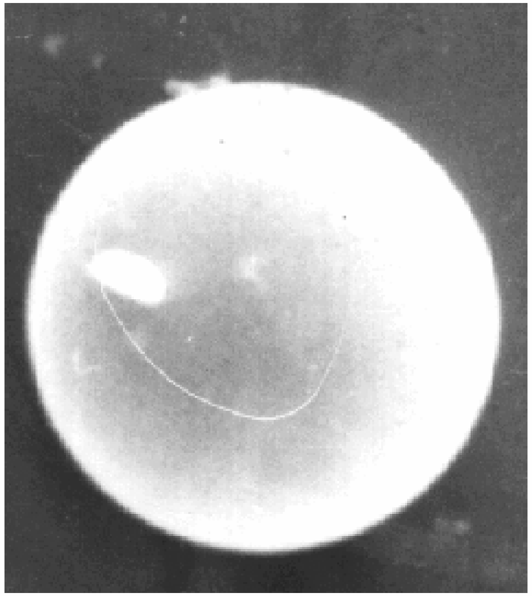
Encyclopedia Polymer Science and Engineering, Vol. 16, John Wiley &Sons 1989

Microsuspension Polymerization

- Smaller droplet sizes than in suspension polymerization
- Microsuspension preparation with homogenizers; stabilization of the monomer droplets
- Special surfactant system (mixture with polymeric stabilizers PVAL)
- Particle sizes in the µm-range
- Monomer soluble initiators
- Crucial point: to avoid emulsion polymerization
- Technical important for the production of special PVC-types

Example: Microsuspension Polymerization

Staining a monomer emulsion



Vinyl Chlorid droplet
emulsifier free polymerization
diameter 13.1 µm

B.R. Paulke, PhD 1985

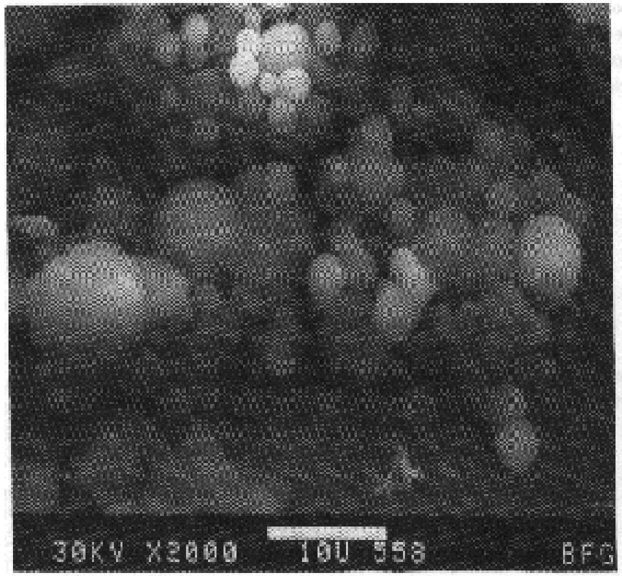


FIG. 4. Vinyl chloride droplets in the microsuspension recipe.

µ-emulsion: 40%VC, 59% water,
1 suspension agent, 1100 rpm 30 min.
bar indicates 10 µm

H.W.H. Yang, J.Macromol.Sci.-Phys. B20 (1981) 199-206

Polymerization of or in monomer emulsions

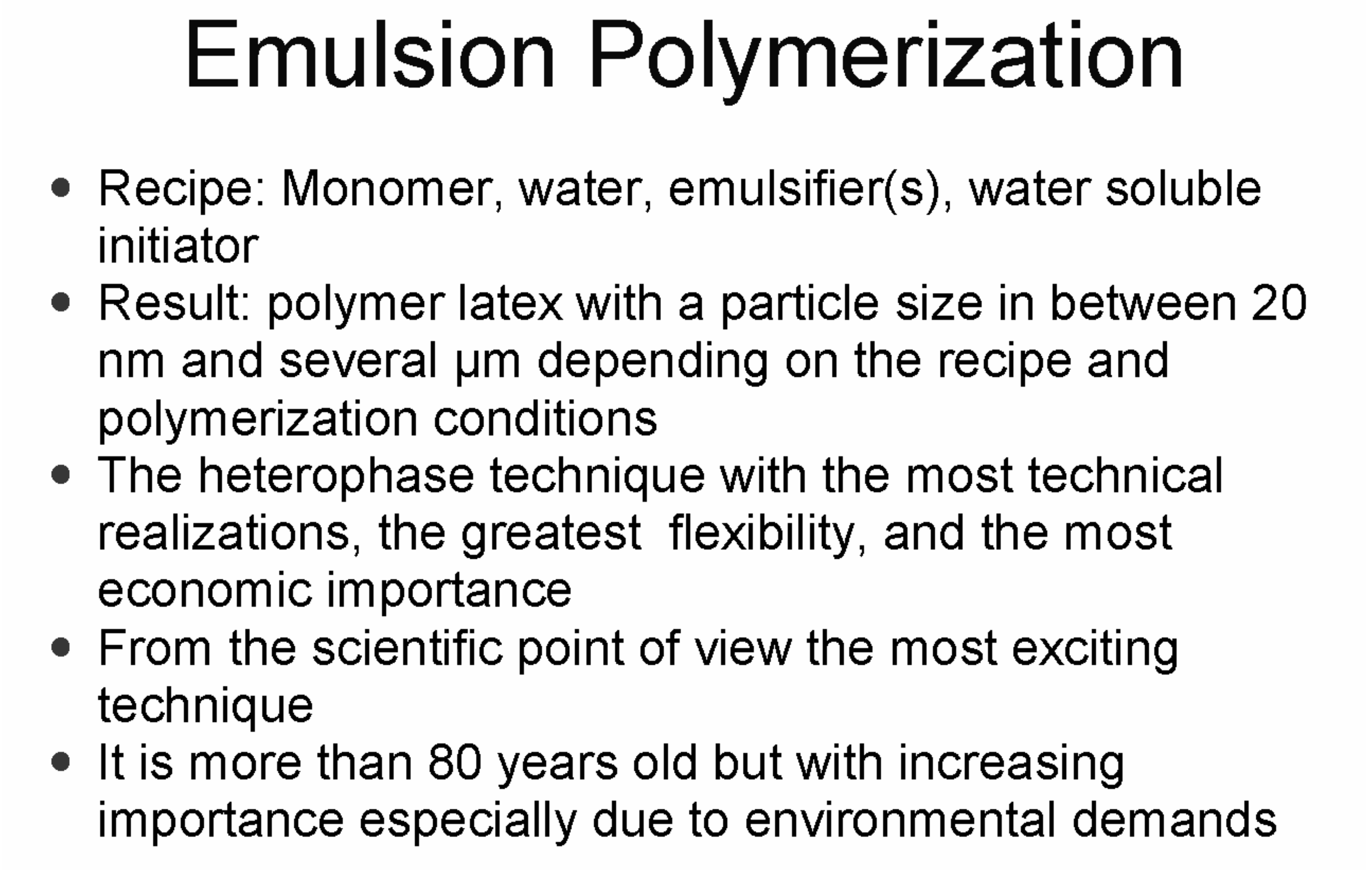
Question: whether or not it is possible to convert the characteristic features of monomer droplets into that of polymer particles???

Answer: yes, by seed and feed techniques, even in large scale

Suspension, miniemulsion and emulsion polymerization

?? ↓ ??

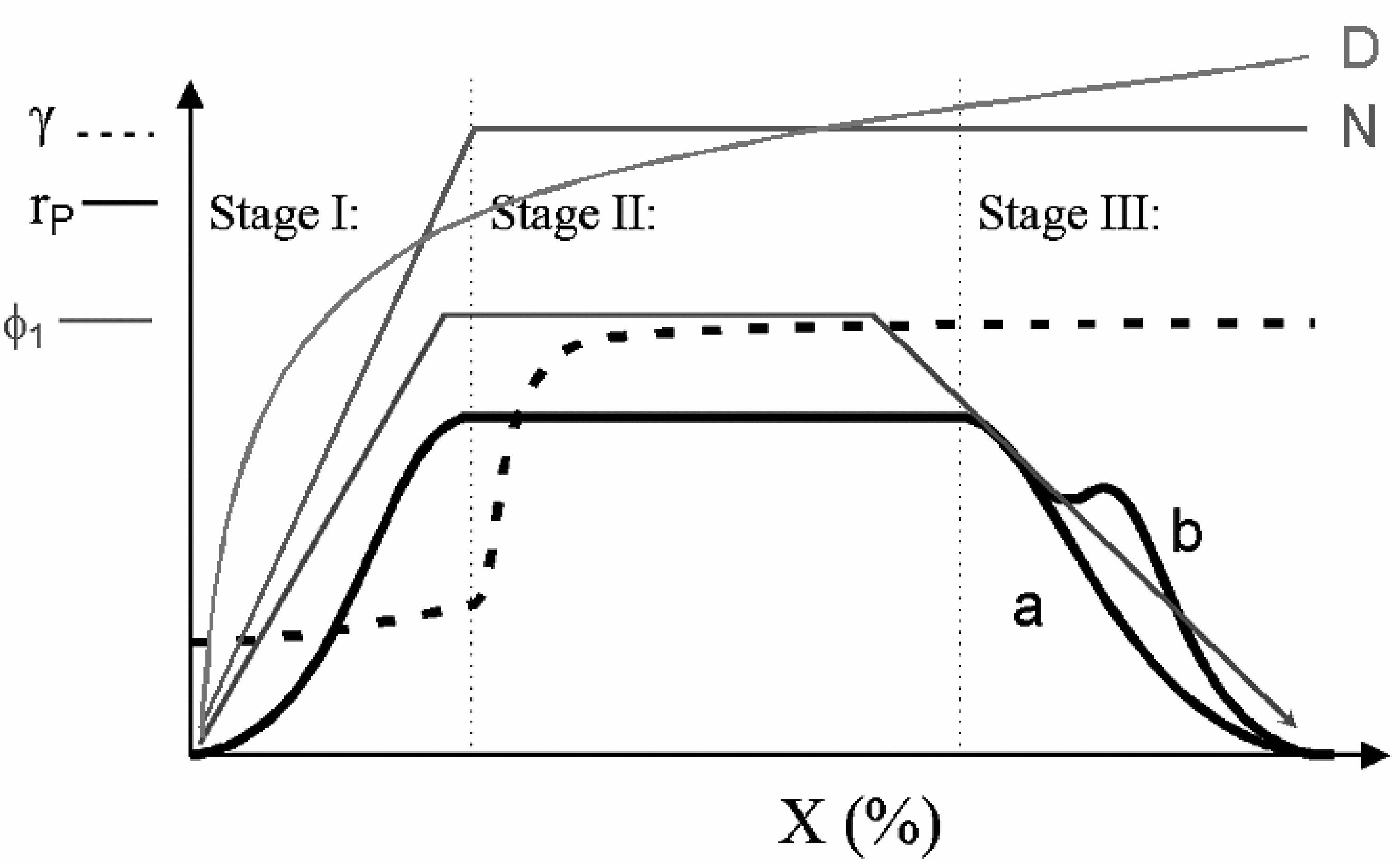
to preserve the droplet properties during polymerization
(in the sense to make a 1:1 copy)



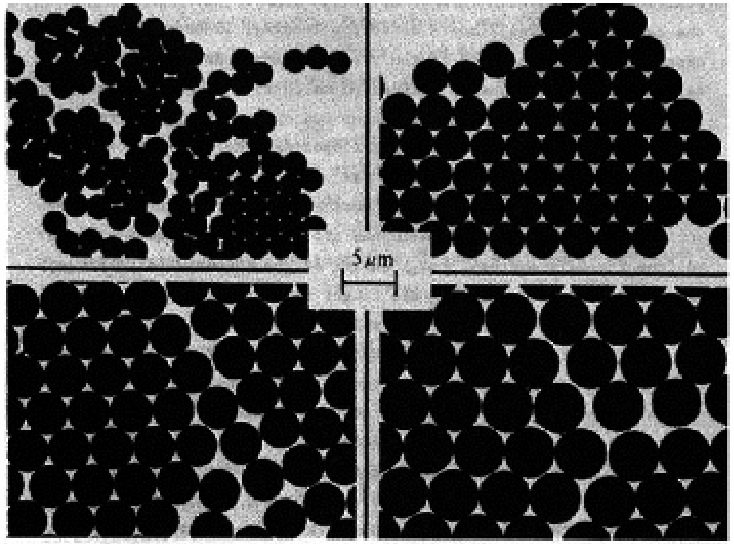
Emulsion Polymerization

- Recipe: Monomer, water, emulsifier(s), water soluble initiator
- Result: polymer latex with a particle size in between 20 nm and several µm depending on the recipe and polymerization conditions
- The heterophase technique with the most technical realizations, the greatest flexibility, and the most economic importance
- From the scientific point of view the most exciting technique
- It is more than 80 years old but with increasing importance especially due to environmental demands

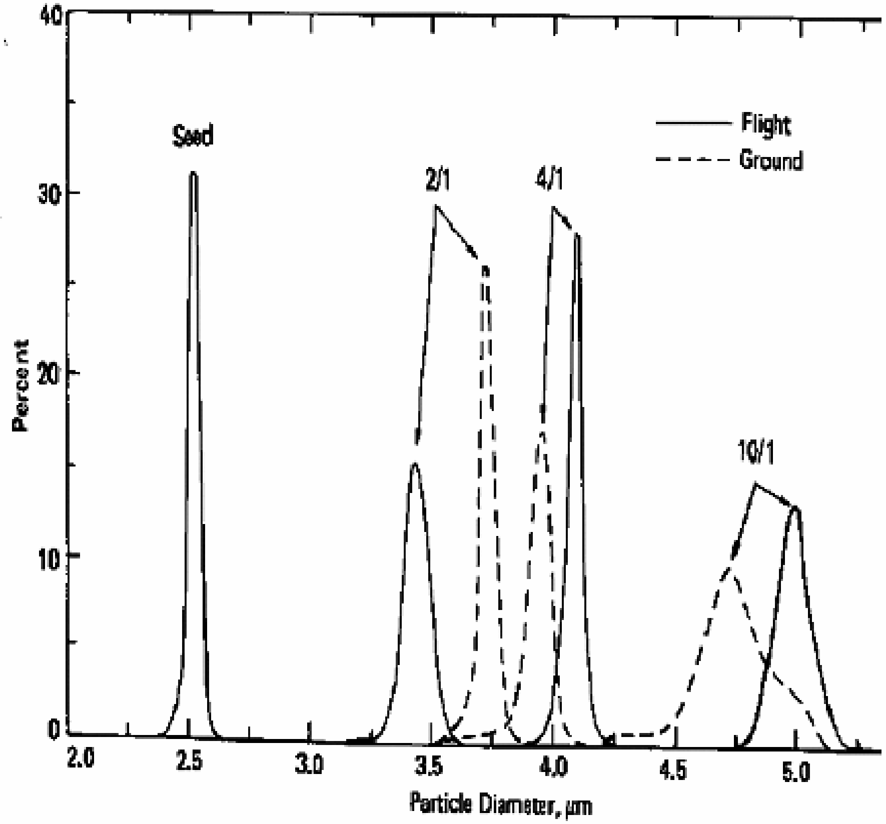
Ideal Behavior of an EP



Space emulsion polymerization - but **worldly** results



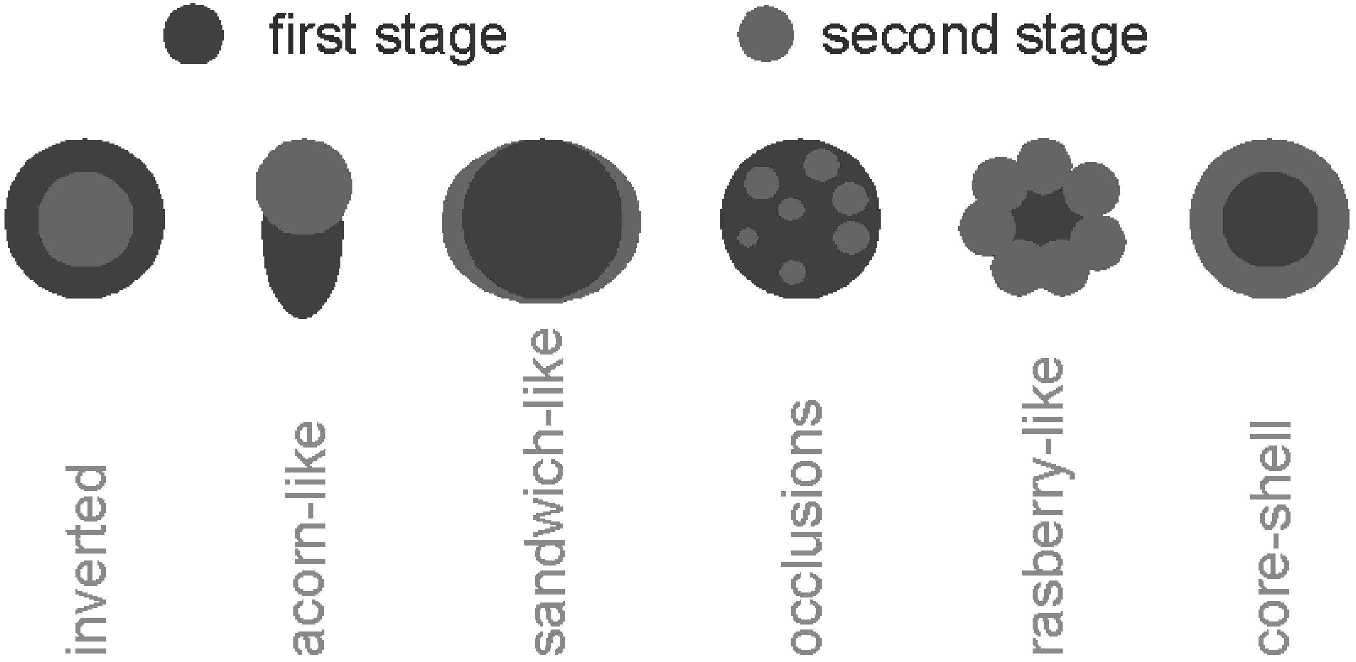
J. W. Vanderhoff et al. J. Disp. Sci. Technol. 5 (1984) 231-246



1983, in zero gravity aboard the Challenger STS-6: the first products ever made in space - polystyrene latexe particles (certified as standard reference materials for calibrating microscopic objects); J. W. Vanderhoff & M. S. El-Aasser (Lehigh University, USA)

Particle Morphologies in a Two Stage Emulsion Polymerization

Schematic Drawing of Various Morphologies



S.Lee, A. Rudin J. Poym. Sci.: Part A: Polym. Chem. 30 (1992) 865-871

Core - Shell Particles (1)

Problem: a hydrophilic core and a hydrophobic shell

polystyrene (2nd stage monomer)

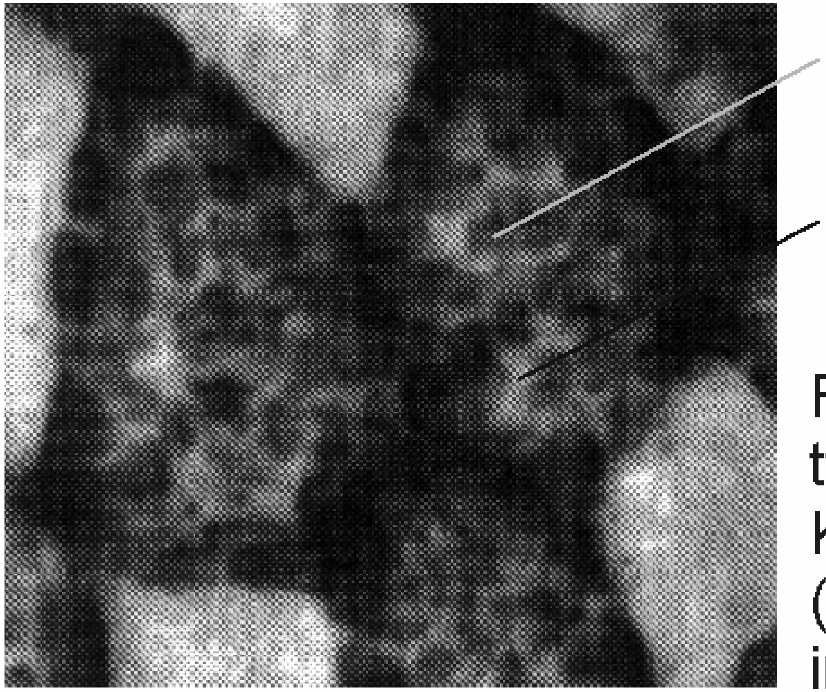
PMMA (1st stage monomer)

Successful solution:
two stage semi-batch polymerization
with slow monomer-emulsion feed and
redox initiation at 21°C
(high core viscosity and low mobility
inside the core, respt.)

S.Lee, A. Rudin J. Poym. Sci.: Part A: Polym. Chem. 30 (1992) 2211-2216

Core - Shell Particles (3)

Problem: a hydrophilic core and a hydrophobic shell

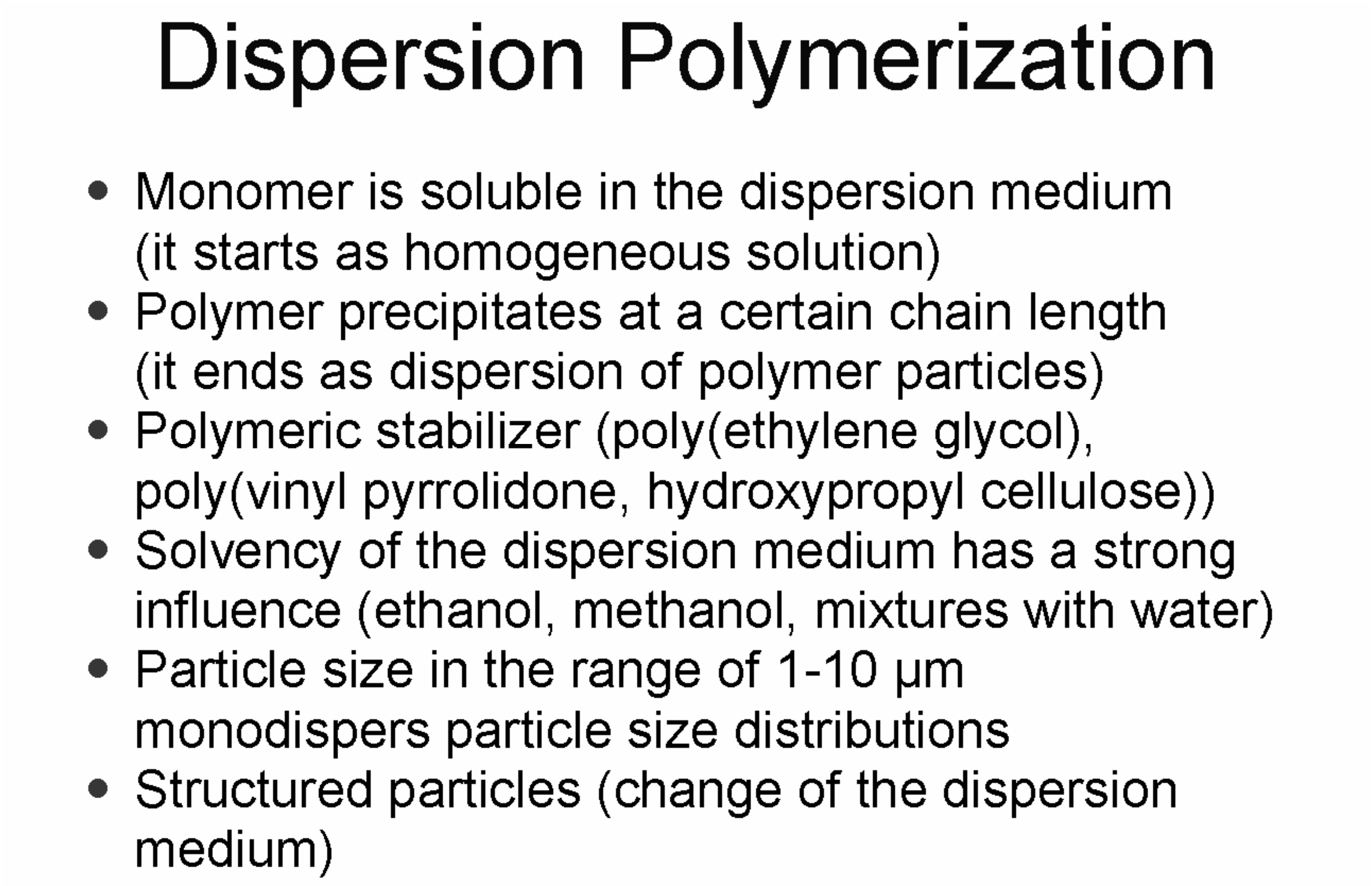


polystyrene (2nd stage monomer)
dark areas

PMMA (1st stage monomer)
bright areas

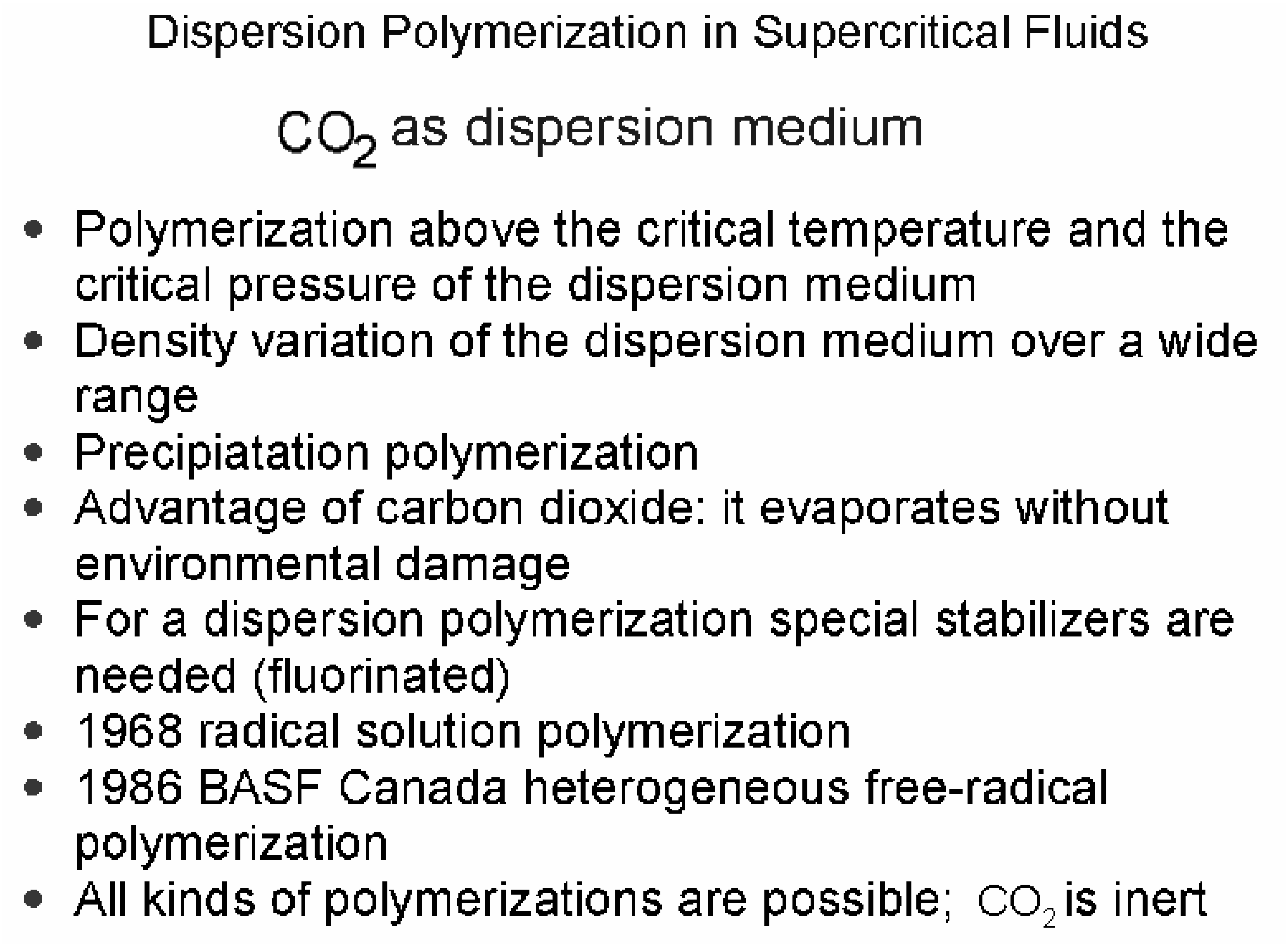
Failure:
two stage batch polymerization with KPS initiation at 60°C (low core viscosity and high mobility inside the core, respt.)

S.Lee, A. Rudin J. Poym. Sci.: Part A: Polym. Chem. 30 (1992) 2211-2216



Dispersion Polymerization

- Monomer is soluble in the dispersion medium (it starts as homogeneous solution)
- Polymer precipitates at a certain chain length (it ends as dispersion of polymer particles)
- Polymeric stabilizer (poly(ethylene glycol), poly(vinyl pyrrolidone, hydroxypropyl cellulose))
- Solvency of the dispersion medium has a strong influence (ethanol, methanol, mixtures with water)
- Particle size in the range of 1-10 µm monodispers particle size distributions
- Structured particles (change of the dispersion medium)



Dispersion Polymerization in Supercritical Fluids

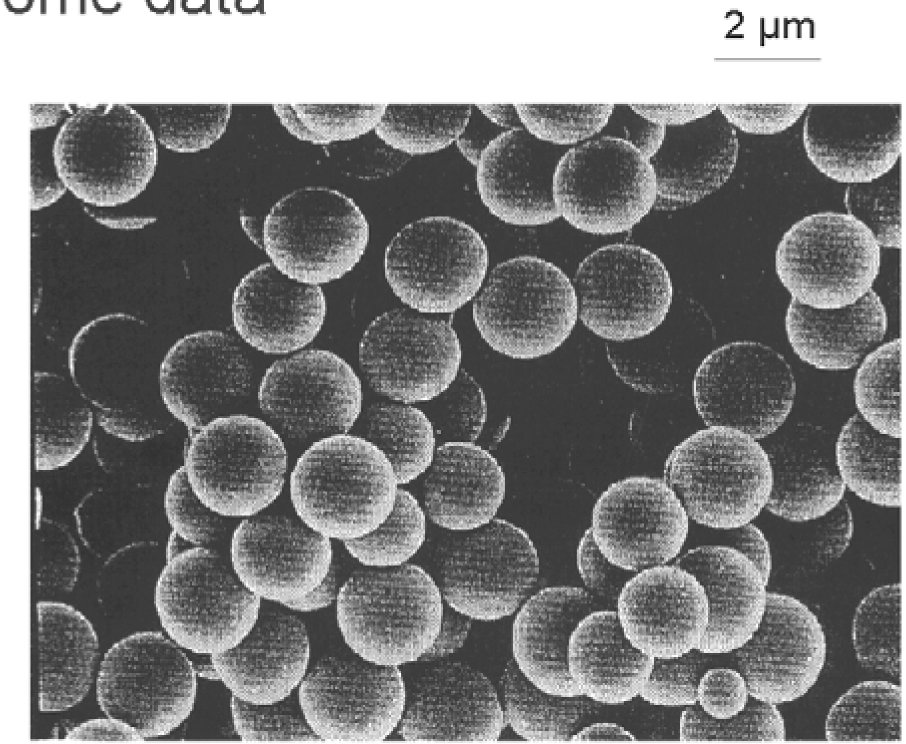
CO_2 as dispersion medium

- Polymerization above the critical temperature and the critical pressure of the dispersion medium
- Density variation of the dispersion medium over a wide range
- Precipiatation polymerization
- Advantage of carbon dioxide: it evaporates without environmental damage
- For a dispersion polymerization special stabilizers are needed (fluorinated)
- 1968 radical solution polymerization
- 1986 BASF Canada heterogeneous free-radical polymerization
- All kinds of polymerizations are possible; CO_2 is inert

Dispersion Polymerization in Supercritical Fluids

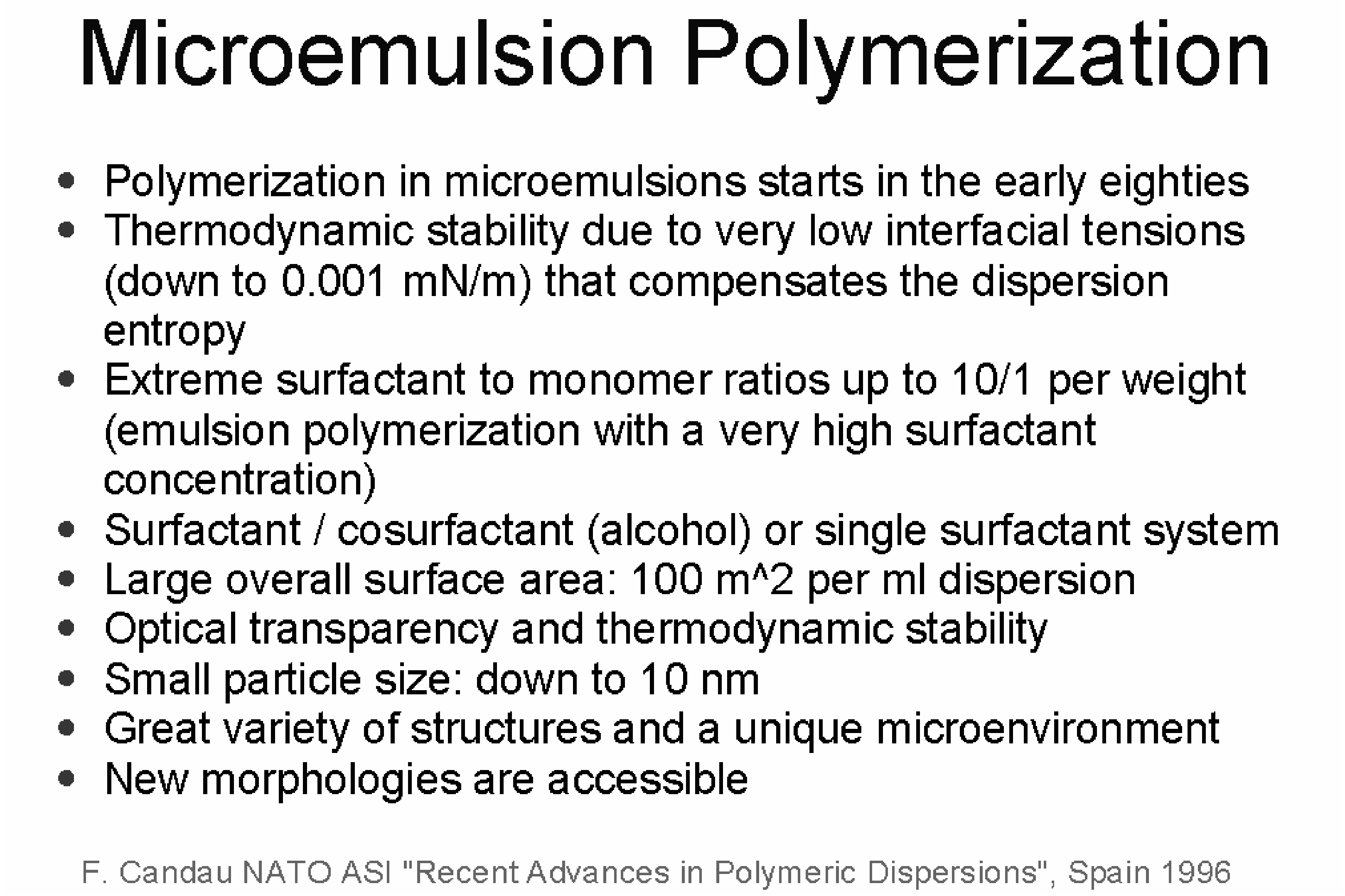
Some data

Solvent	T_{crit} (°C)	P_{crit} (bar)
CO_2	31.1	73.8
C_2H_6	32.2	48.8
C_3H_8	96.7	42.5
C_4H_{10}	152.0	37.8
$CHClF_2$	96.2	49.9



PMMA particles prepared in CO_2

K.A. Shaffer, J.M. DeSimone TRIP Vol.3, (1995) 146-153



Microemulsion Polymerization

- Polymerization in microemulsions starts in the early eighties
- Thermodynamic stability due to very low interfacial tensions (down to 0.001 mN/m) that compensates the dispersion entropy
- Extreme surfactant to monomer ratios up to 10/1 per weight (emulsion polymerization with a very high surfactant concentration)
- Surfactant / cosurfactant (alcohol) or single surfactant system
- Large overall surface area: 100 m^2 per ml dispersion
- Optical transparency and thermodynamic stability
- Small particle size: down to 10 nm
- Great variety of structures and a unique microenvironment
- New morphologies are accessible

F. Candau NATO ASI "Recent Advances in Polymeric Dispersions", Spain 1996

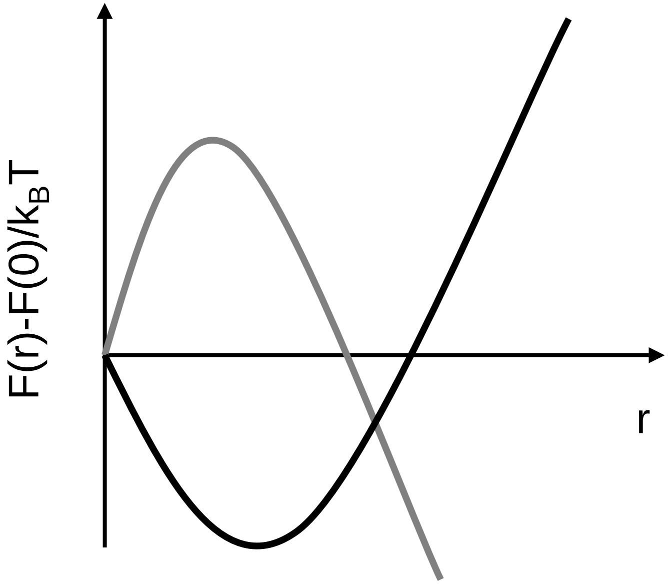
μ-Emulsion Droplets

droplet thermodynamics (classical textbooks)

$$F = -\Delta P \cdot V + \sigma \cdot A = -\frac{4\cdot\pi}{3}\Delta P \cdot r^3 + 4\pi \cdot \sigma \cdot r^2$$

$$\frac{\partial F}{\partial r} = 0$$

$$\Delta P = \frac{2\sigma}{r_c}$$



$$F = -\frac{4\cdot\pi}{3}\Delta P \cdot r^3 + 4\pi \cdot \sigma \cdot r^2 + 8\pi\kappa\left(1-\frac{r}{r_s}\right)^2 + 4\pi \cdot \bar{\kappa}$$

(Helfrich, 1973)

Microemulsion Polymerization

Some basic results

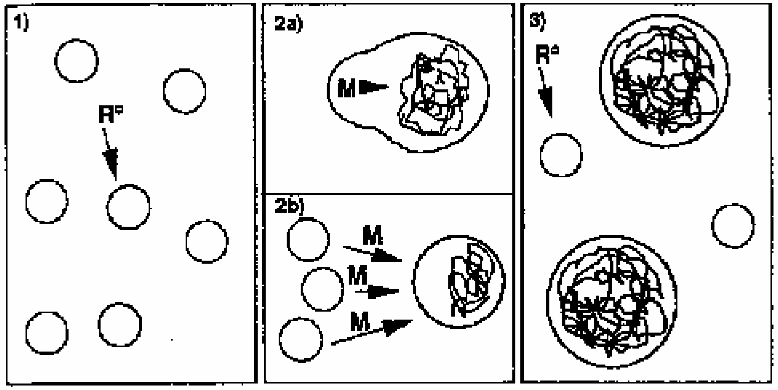


Figure 3. **Microemulsion polymerization mechanism : 1) Before polymerization : monomer swollen micelles (d ~ 5-10nm). 2) Polymer particle growth a) by collisions betwee particles ; b) by monomer diffusion through the continuous phase. 3. End o polymerization : polymer particles (d ~ 40nm) + small micelles (d ~ 3nm).**

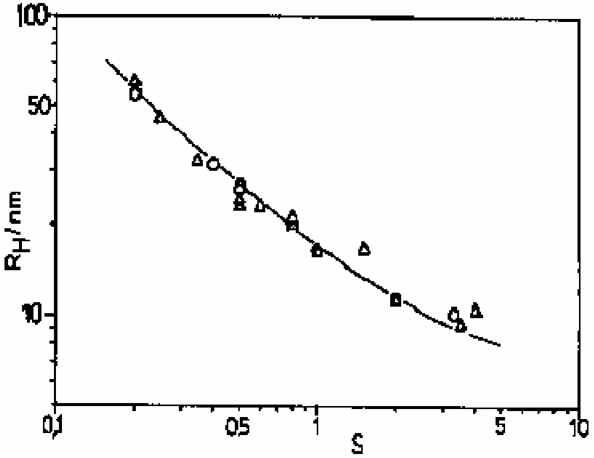


Figure 3. Hydrodynamic radius r_H of the latices in dependence of the relative amount of surfactant S for DTMA (Δ) and CTMA (O). The straight line represents the calculated behavior corresponding to eq 1 and an interlayer thickness b = 3.5.

F. Candau NATO ASI "Recent Advances in Polymeric Dispersions", Spain 1996

M. Antonietti et al.
Macromolecules 24 (1991) 6636-6643

µ-EP common case

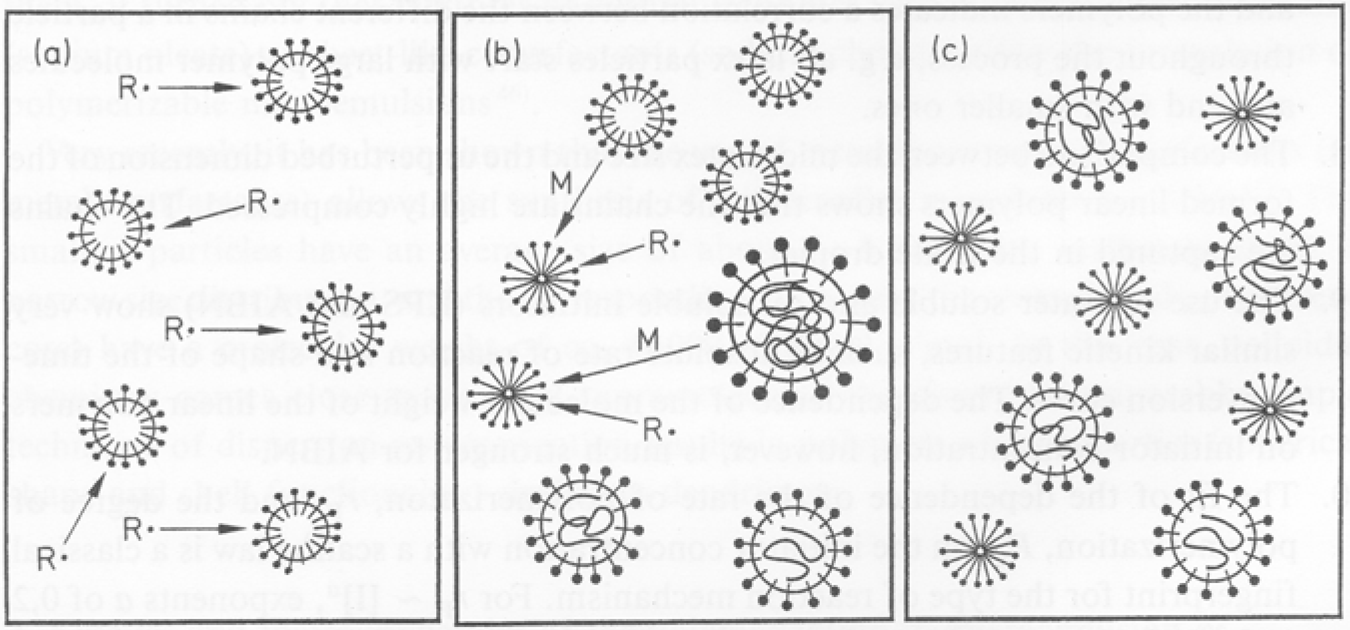


Fig. 1. Schematic scenario of the CLF-model: (a) Parental microdroplets of equal size are initiated by radicals formed in the aqueous phase. (b) Monomer transport from unpolymerized microdroplets through the aqueous phase results in growth of particles containing a polymer-chain. Empty micelles are formed which allow continuous nucleation of new latex particles. (c) At the end of the polymerization, latex particles larger than the primary microdroplets coexist with a large surplus of empty micelles

Microemulsion - Results

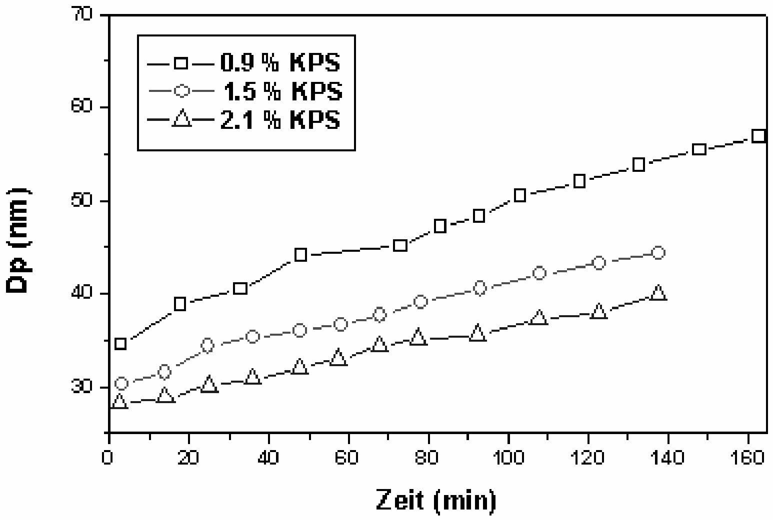
[KPS] (%)	UMSATZ (%)	D_P (nm)	N_P 1/mL
1.50	22.06	54.0	5,1241 E+13
	51.31	52.0	1,3332 E+14
	65.43	49.0	2,0587 E+14
	99.16	45.0	3,9671 E+14
0.90	23.22	58.0	2,0847 E+14
	49.02	55.0	2,2163 E+14
	65.54	53.0	2,4254 E+14
	98.53	51.0	2,6671 E+14
0.30	23.87	61.0	3,7131 E+13
	55.75	59.0	9,5845 E+13
	63.54	57.0	1,2137 E+14
	95.37	55.0	2,0266 E+14

batch

Recipe:
97.216 g water
1.488 g SDS
0.496 g AOT
0.012 g KPS
0.9 g BuA

32.067 g BuA (feed)

semibatch



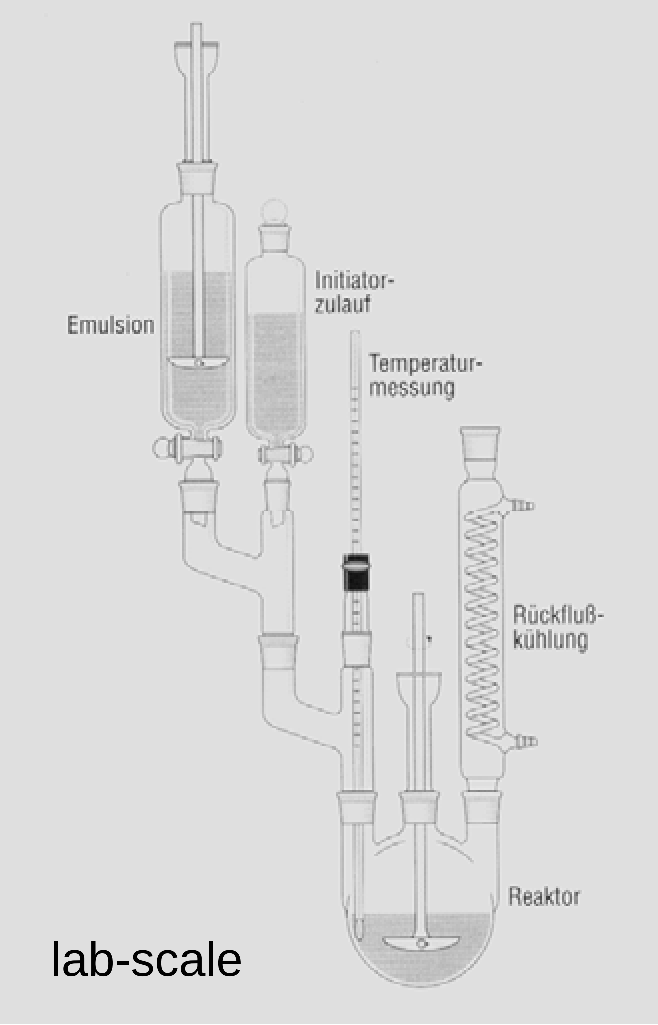
Reactors & Procedures

Emulsion Polymerization

- In principal emulsion polymerization doesn't require any special apparatus
- But for special products you need sophisticated recipes and procedures
- The wide variety of emulsion polymerization based products requires a wide variety of recipes and procedures
- Batch, semi-batch, and continuous procedures have been developed
- Seed procedures are very popular to avoid the uncertainties of particle nucleation

Labscale Reactors

Semi-Batch Reactors



lab-scale

D. Distler “Wäßrige Polymerdispersionen”
Wiley-VCH, 1999

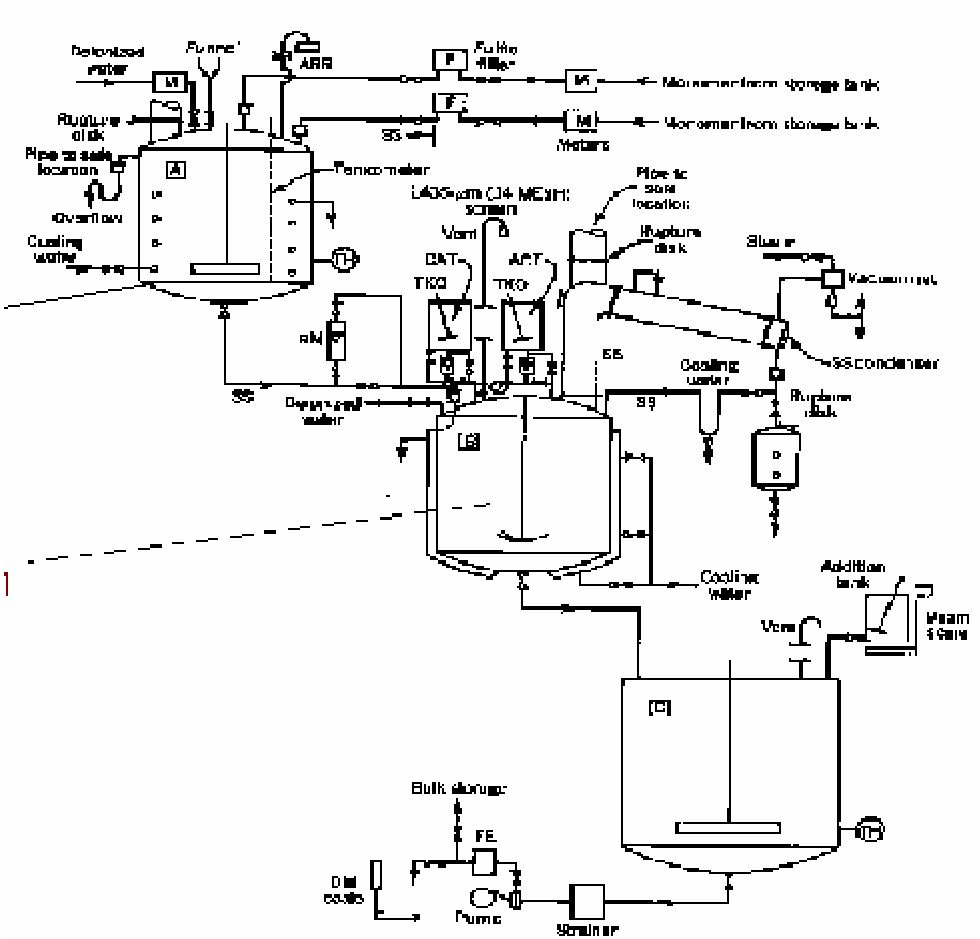


Fig. 5. Plant for emulsion polymerization (Rohm & Haas CM-101 (A&D, Vessel A is the same size as B; vessel C is 1.25 the size of B. SS = stainless steel; F = filter; M = meter; RM = rotameter; TKO = tankometer; CAT = initiator; ACT = activator; FE = filtration equipment; P = pressure indicator; TH = thermometer; ARR = flame arrestor.

Encyclopedia of Polymer Science
and Engineering,Volume 6, J. Wiley&Sons 1986

Continuous Emulsion Polymerization

18 **EMULSION POLYMERIZATION** **Vol. 6**

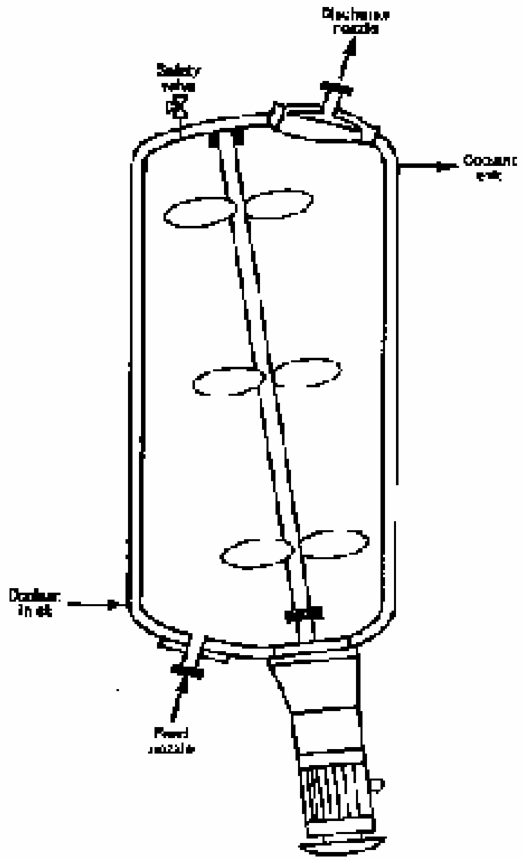


Fig. 10. Bayer continuous reactor for chloroprene (19).

Continuous processes are used for high production amounts with constant quality; easiness of on-line control; Problems: sustained oscillations of latex properties may occur

Encyclopedia of Polymer Science and Engineering,Volume 6, J. Wiley&Sons 1986

Continuous loop reactors (CLR)

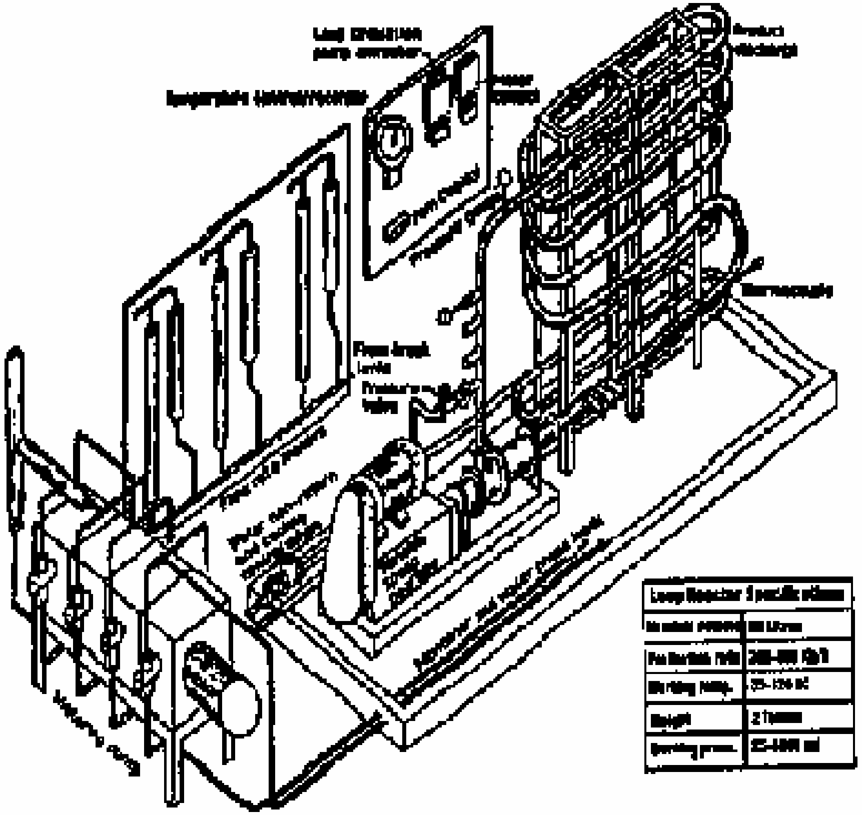


Figure 1. Industrial unit [7].

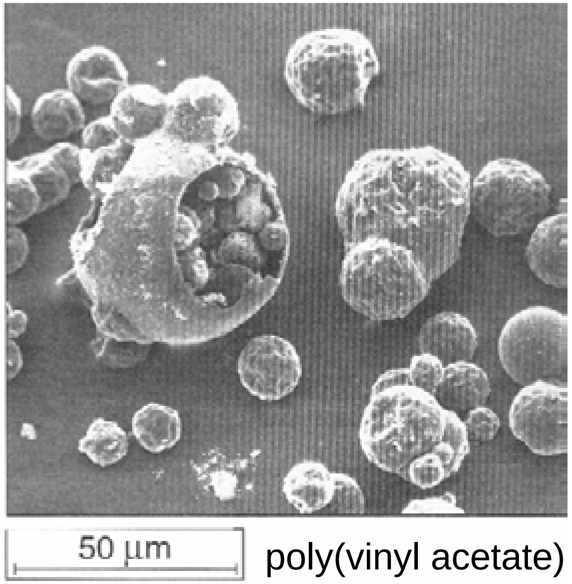
Currently nine commercial reactors are in operation; most of them are single pipe 50 l reactors with a production of 2.500 t/y.

Advantage: large heat transfer area; great flexibility due to short residence times; a 50 l CLR can replace a 5.000 l batch reactor

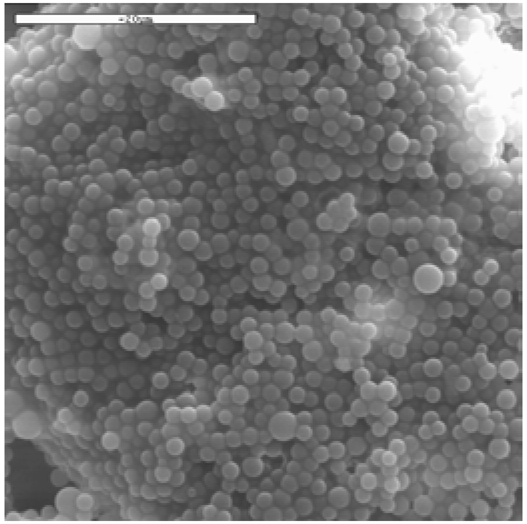
J.M. Asua NATO ASI "Recent Advances in Polymeric Dispersions", Spain 1996

Summary

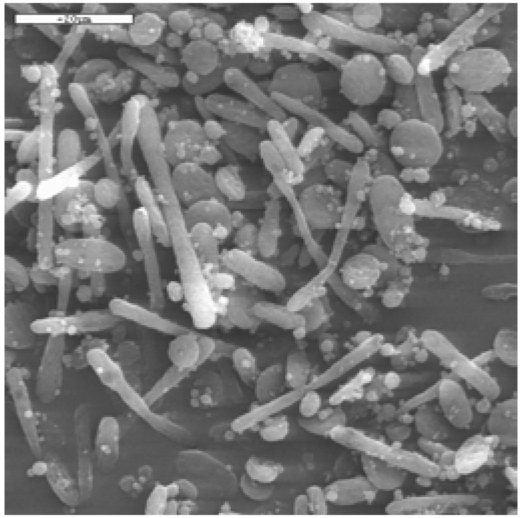
polymer dispersions are a fascinating area of colloid science



poly(vinyl acetate)



Lmph2o2b, polystyrene



eur82-h, polystyrene

D. Distler “Wäßrige Polymerdispersionen”
Wiley-VCH, 1999

MPI, Golm

aqueous polymer dispersions are the future form of all polymers

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P. A. Lovell, M. S. El-Aasser eds.; Wiley 1997

„Heterophase Polymerization“
in „Encyclopedia of Polymer Science and Technology“, 3rd edition
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K. Tauer