Modern Solvent Systems in Industrial Homogeneous Catalysis

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Water can be used very advantageously as the solvent in homogeneous catalytic reactions and thus gives rise to a specific class of aqueous biphasic reactions among two-phase reactions. This new use of water has two very positive consequences: an advantageous effect on the selectivity of the homogeneous catalytic reactions and the opportunity, for the first time, to "immobilize" the homogeneous catalyst by means of the "liquid support" water, then to separate it simply and immediately from the reaction products after its task is complete and thus to return it to the catalysis cycle. Apart from the industrial use of hydroformylation (oxo process), fine chemicals are also being increasingly prepared by the aqueous, homogeneously catalyzed biphasic technique.

Keywords: Hydroformylation, Oxo process, Aqueous biphasic homogeneous catalysis.

1
Introduction

1.1
Motivation for Work

Water cannot be regarded as a "modern solvent" in *all* cases, although there are indications of a renaissance in its use in organic chemistry [1–4]. This inter-

esting development has been influenced by, inter alia, the introduction of water as a solvent in aqueous biphasic homogeneous catalysis where it has revolutionized the process methodology and does indeed represent a "modern solvent".

Until about 20 years ago, homogeneously catalyzed reactions were the domain of organic phases and solvents. One reason for this was that the catalysts employed – apart from acid/base systems, usually sensitive and frequently thermally unstable organometallics [5–7] – were almost always hydrolytically labile, and the combination of homogeneous catalytic systems with water seemed illogical and either had little to recommend it or harbored no promise at all. On the contrary, in hydroformylation (oxo process), which has for decades been the most important application of homogeneous catalysis (1980 production: about 5 million metric tons per year [8], 1998: over 6 million metric tons per year [9]), the catalyst was usually decomposed by means of aqueous reactants and the catalyst cycle was thus deliberately interrupted (brief description in [10]). This is all the more surprising since there were indications of particular (positive) effects of an interaction between water and homogeneous organometallic catalysts [11]. Even earlier, in the new, cobalt-catalyzed oxo process, it had been recognized that during the hydroformylation significant amounts of water led to advantageous effects (the use of water-soluble catalyst precursors as in the BASF process [12] or the early Ruhrchemie process [13], the yield-increasing cleavage of initially formed formic esters by means of aqueous sodium formate solutions [14], etc).

All these observations were empirical, individual results of unsystematic experiments. Since water had been judged, as mentioned, to be incompatible with the metal carbonyl catalysts of the oxo process, this solvent was not a seriously considered alternative. This paper points the way to the introduction of water as a future-oriented solvent for industrial homogeneous catalysis. Applications of phase transfer catalysis will not be considered here (since they require additional, cost-increasing phase transfer agents), but the emphasis will be placed on aqueous biphasic homogeneous catalysis and its status and possibilities.

1.2
Background

Compared to the "classical" oxo process (classical in respect of the organic phase usually employed), the use of water was a revolutionary development following a report by Manassen entitled "Heterogenizing Catalysts" in 1973 [15]. This expressed the vision of a biphasic process in words for the first time: "A heterogenized catalyst allows much greater versatility (…). (…). However, the use of two immiscible liquid phases, one containing the catalyst and the other containing the substrate, must be considered. The two phases can be separated by conventional means and high degrees of dispersion can be obtained through emulsification. This ease of separation may be particularly advantageous in situations where frequent catalyst regeneration or reactivation is required."

This quotation indicates that the extraordinarily important advantage, in terms of process technology, of a catalyst phase which is immiscible with the

reaction products was the actual impetus for the biphasic catalysis process outlined by Manassen. It is therefore possible to separate the reaction products from the homogeneous catalyst phase by simple phase separation (decantation) immediately after the reaction is complete and to recirculate the catalyst. This provides a very elegant solution to the age-old problem of homogeneous catalysis, namely the separation of the reaction products from the catalyst which is, by definition, homogeneously dissolved in them (cf. Fig. 1).

This concept allows the important advantages of homogeneous over heterogeneous catalysts to be utilized for the first time. Particular mention should be made here of the significantly greater variability of homogeneous catalysts which enables them to be tailored to the requirements of the desired reaction by means of steric and/or electronic modification (cf. Table 1).

It is the opportunity to understand the mode of action of homogeneous catalysts by modeling under realistic conditions and to comprehend their structure/activity relationships by varying parameters that makes homogeneous catalysis so interesting to the modern researcher. Biphasic catalysis makes the decisive disadvantage of homogeneous catalysis obsolete, something which has been unsuccessfully attempted for decades by "heterogenizing", i.e. by anchoring the intrinsically homogeneous catalysts on a matrix (support) having a heterogeneous structure and thus immobilizing them [16]. These attempts were doomed to failure because the strong and continually changing stresses on the bond between the catalyst metal and support lead to weakening of this bond and thus, finally, to leaching of the metal (cf. Fig. 2, [17]).
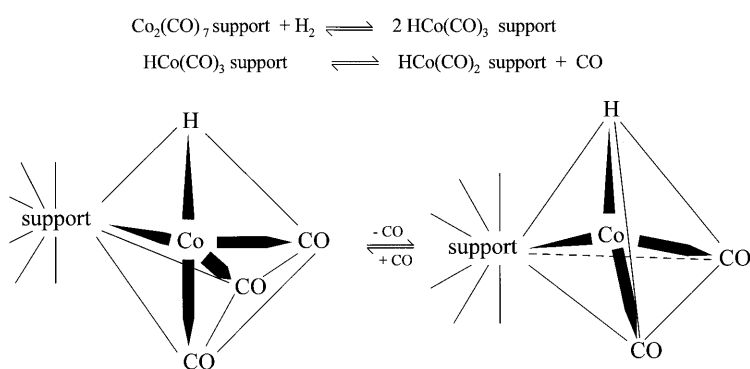
Biphasic catalysis, not anchoring on solid supports, was recognized as providing the fundamental means for combining all the advantages of homogeneous
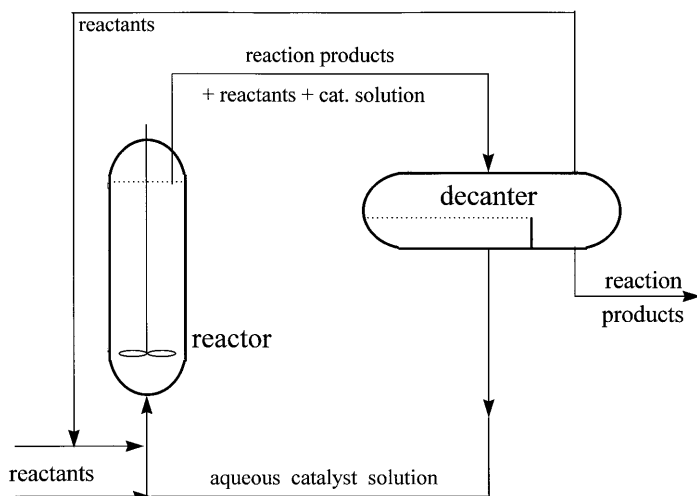
Fig. 1. Biphasic concept: the reactor (*left*) is supplied with the reactants; in the phase separator (*right*), the reaction products and the catalyst phase are separated. The catalyst phase is returned by a short route to the reactor

Table 1. Homogeneous vs. heterogeneous catalysis: the advantages and disadvantages

	Homogeneous catalysis	Heterogeneous catalysis
Activity (relative to metal content)	High	Variable
Selectivity	High	Variable
Reaction conditions	Mild	Harsh
Service life of catalysts	Variable	Long
Sensitivity toward catalyst poisons	Low	High
Diffusion problems	None	High
Catalyst recycling	Expensive	Not necessary
Variability of steric and electronic properties of catalysts	Possible	Not possible
Mechanistc understanding	Plausible under random conditions	More or less impossible

$$Co_2(CO)_7 \text{ support } + H_2 \rightleftharpoons 2 \text{ HCo(CO)}_3 \text{ support}$$

$$HCo(CO)_3 \text{ support} \rightleftharpoons HCo(CO)_2 \text{ support} + CO$$

Fig. 2. Alternation between supported trigonal-bipyramidal hydridotricarbonylcobalt and tetrahedral hydridodicarbonylcobalt during the course of the catalytic cycle

catalysis. To avoid confusion, it should be emphasized at this point that the cata-lysis of the reactions under consideration here (e.g. hydroformylation) is *homog-eneous* in nature even in the case of modification of the biphasic process. This can easily be proven by the fact that *all* criteria of a homogeneously catalyzed reaction are met (their catalysts are, inter alia, molecularly dispersed "in the same phase", they are unequivocally characterized chemically and spectro-scopically, and go through a detectable catalyst cycle; they permit unequivocal reaction kinetics, etc., cf. [5]). Nevertheless, the catalyst (not the *catalysis* which remains homogeneous!) is *heterogeneous* in relation to the reactants (a catalyst solution is brought into contact with immiscible liquid or gaseous reactants), the participants in the reaction are *heterogeneous* in relation to one another, name-ly gaseous and liquid, and the reaction product is also present in a different liquid phase from the catalyst, i.e. in *heterogeneous* form. Thus, in the final

analysis, the reaction is a three-phase reaction which is described (by tacit agreement!) as "biphasic" only because a gas phase is not counted separately in catalytic reactions.

The term "biphasic catalysis" has established itself only slowly, especially since the first commercial applications (by Shell in the SHOP process, [18]) named the process thus only tentatively (and in obviously rarely read patent applications).

Aqueous biphasic catalysis represents the most important special case of biphasic processes. Virtually in parallel to the propagation of biphasic catalysis, publications by Joó and his research group describing homogeneously catalyzed hydrogenations (and selective hydrogenations) in water appeared [19]. As catalytically active complexes, use was made of Rh compounds which had been modified by means of the monosulfonated derivative of triphenylphosphine (known as TPPMS, see below). The first experiments aimed at developing a hydroformylation process based on biphasic catalysis go back to Kuntz, then at Rhône-Poulenc [20]. The important factor, which finally brought success, in Kuntz's work was his clever and ingenious combination of the following features:

(1) the choice of rhodium as central atom of the oxo catalyst. This choice corresponded to the spirit of the times after, in 1975/76, the first oxo plants of Celanese [21] and Union Carbide [22] had commenced operation on the basis of Rh catalysts of the Wilkinson type [23] and their selectivity advantages had become evident,

(2) modification of the ligands of the homogeneous oxo catalyst by means of phosphines, which was likewise known from the Shell oxo process (albeit using cobalt as central atom [24]) and the example of Wilkinson [25], and

(3) the decisive choice of water as reaction medium and "mobile" or "liquid" support and thus as second phase in the process.

The experimental work of Kuntz struck on the ligand TPPTS (3,3,′ 3″[phosphinidyne]benzenesulfonic acid, trisodium salt, the triply sulfonated homologue of TPPMS), today the standard ligand in aqueous homogeneous applications (Fig. 3), and thus the opportunity of modifying the oxo-active $HRh(CO)_4$ by means of this readily water-soluble ligand (solubility: about 1100 g l^{-1}) so as to make the entire metal complex catalyst $HRh(CO)L_3$ water soluble and, even more importantly, to leave it in the aqueous phase without leaching.

The studies by Joó and Kuntz had a peculiar fate. It may well have been due to the remoteness from practice and the lack of incentive for new variants of hydrogenation processes that Joó's work almost became lost in the academic world. Likewise, the importance of the preliminary work of Kuntz was recognized neither by his own company nor by the academic community, which may well be attributed to the fact that the results were recorded in patents and academic teachers and researchers are reluctant to take notice of such apocryphal literature. There was therefore a need for an industrial impetus and the readiness to carry out process development work based on these studies. This occurred after 1982 in collaborative work between Ruhrchemie AG and Rhône-Poulenc (RCH/RP) [26]. The combination of a basic idea from Rhône-Poulenc with the competence of a team at the then Ruhrchemie AG with ex-
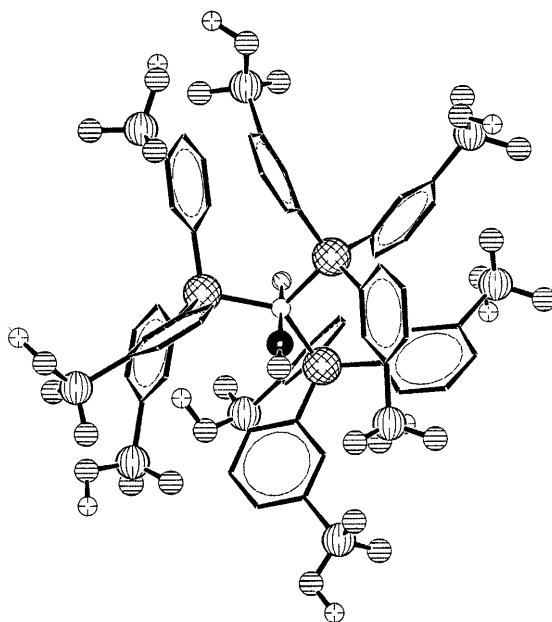
Fig. 3. TPPTS and the corresponding oxo catalyst

perience in the field of the oxo process and the translation of laboratory results into industrial practice led within two years to successful pilot plant development, the construction of the first production plant and its startup in July 1984 [27–29]. This very rapid progress was made possible only by decisive improvements in the basic idea, by processing improvements, the scale-up factor employed (1:24,000) and the systematic use of "simultaneous engineering". Looking back after 15 years, a very positive picture can be presented [27 e].

Kuntz's recourse to water as solvent for a two-phase process was extraordinarily fortunate from both a chemical and process engineering point of view. Water displays particular advantages as solvent in processes during the course of which reactants and reaction products of different polarities participate or are formed [1–4]. A look at the properties of water which are important in this respect (cf. Table 2) shows this very clearly.

Water as a solvent has several anomalous features (e.g. anomalous density, the only nontoxic and liquid "hydride" of the nonmetals, melting point varying with pressure, dielectric constant) and with its two- or even three-dimensional structure has still not been fully researched.

Of direct importance for the aqueous biphase processes are the physiological (entries 2, 4 of Table 2), economic (1, 3, 6), ecological/safety-related (2, 4), process engineering (1, 6, 7, 9, 11, 12, 13), and chemical and physical properties (1, 5, 6, 8, 10, 12, 14) of water. The different properties interact and complement each other. Thus water, whose high Hildebrand parameter [31, 32] and high polarity advantageously influence organic chemical reactions (such as hydro-

Table 2. Properties of water as a liquid support of aqueous two-phase catalysis [29, 30]

| Entry |
| --- |
| 1 polar and easy to separate from unpolar solvents or products; polarity may influence (improve) reactivity |
| 2 inflammable, incombustible |
| 3 ubiquitious and with suitable quality available |
| 4 odour- and colourless, making contamination easy recognizable |
| 5 formation of hexagonal two-dimensional surface structure and a tetrahedral three-dimensional molecular network, which influence the mutual (in)solubility significantly; chaotropic compounds lower the order by H-bonding breaking |
| 6 high *Hildebrand* parameter as unit of solubility of non-electrolytes in organic solvents |
| 7 density of 1 g cm^{-3} provides a sufficient difference to most organic substances |
| 8 very high dielectric constant |
| 9 high thermal conductivity, high specific heat capacity and high evaporation enthalpy |
| 10 low refractive index |
| 11 high solubility of many gases, especially CO_2 |
| 12 formation of hydrates and solvates |
| 13 highly dispersable and high tendency of micelle formation; stabilization by additives |
| 14 amphoteric behaviour in meanings of Brønsted |

formylation), has sufficiently high polarity and density differences compared to organic (reaction) products to enable separation of the phases after the homogeneously catalyzed reaction.

On the other hand the high solvent capability for many compounds and gases, in some cases boosted by solvate or hydrate formation or by hydrogen bonding, facilitates reactions in the two-phase system. The chaotropic properties of many chemical compounds prevent the H_2O cage structures necessary for the formation of solvates and thus facilitate the transfer of nonpolar molecules from nonaqueous and aqueous phases.

Water is non-combustible and nonflammable, odorless and colorless, and is universally available: important prerequisites for the solvent of choice in catalytic processes. The dielectric constant or the refractive index can be important in particular reactions and in analyzing them. The favorable thermal properties of water make it highly suitable for its simultaneous double function as a mobile support and heat transfer fluid, a feature that is utilized in the RCH/RP process (see below).

Thus water as a solvent not only has the advantage of being a mobile support and simultaneously actually "immobilizing" the catalyst while retaining the homogeneous mode of reaction but, in particular, has positive effects on the environmental aspects of hydroformylation [33].

If the reactants and reaction products have polarities which are *very* different from that of water, special measures have to be taken in order to be able to continue to employ a two-phase process using water as solvent. This is the case in the hydroformylation of higher olefins ($> C_5$). The fall in the solubility in water associated with an increasing number of carbon atoms in the olefins used (and also in the resulting aldehydes) leads to a pronounced decrease in the reactivity (cf. Fig. 4).
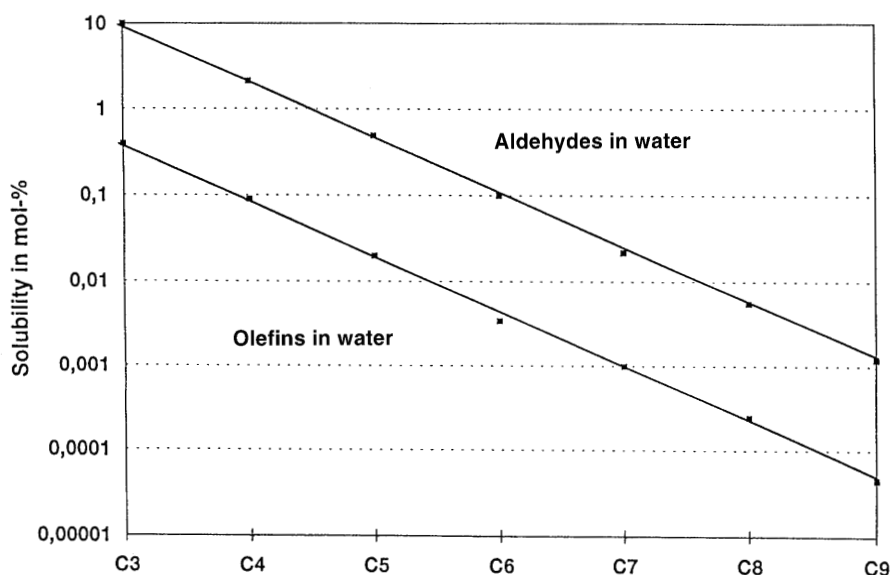
Fig. 4. Dependence of the solubility in water on the number of carbon atoms in the olefins used and in the resulting aldehydes [34]

There is still a dispute among experts as to the place in which the biphasic aqueous reaction actually takes place, although it is very probably not the bulk of the liquid but the interfacial layer between the aqueous and organic phases. In the case of aqueous biphasic hydroformylation, this question has been decided by methods of reaction modeling and comparison with experimentally proven facts, thus leading to scale-up rules and appropriate kinetic models as a basis for optimal reactor design [34].
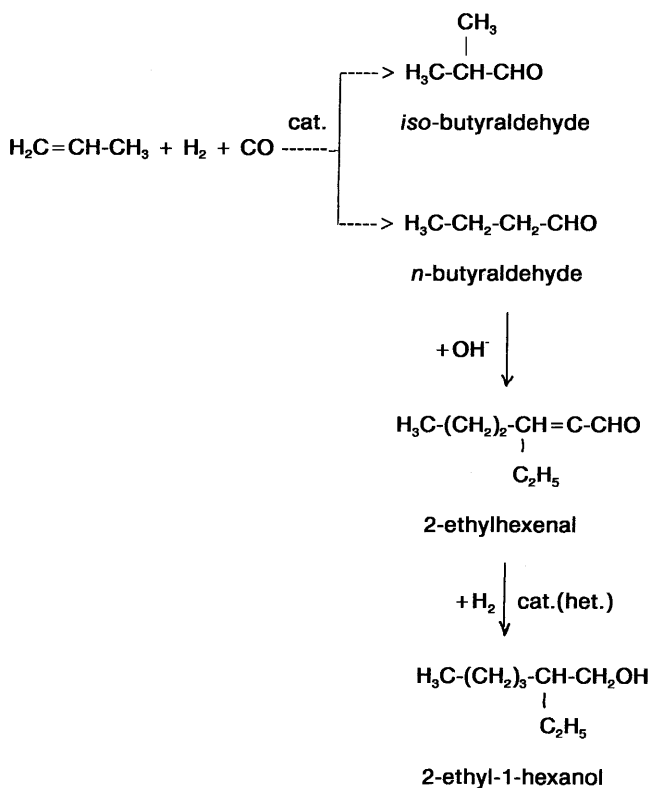
2
State of the Art

2.1
Hydroformylation of Lower Olefins

The most important and oldest application of aqueous biphasic, homogeneous catalysis is hydroformylation (oxo process, Roelen reaction). This process is used to produce *n*-butyraldehyde, the desired main product of the reaction of propylene, which is converted by aldolization into 2-ethylhexenal and this is finally hydrogenated to give 2-ethylhexanol (2-EH), the most economically important plasticizer alcohol (Scheme 1):

2–EH is esterified with phthalic acid to produce the standard plasticizer dioctyl phthalate (DOP). With a capacity of roughly 5 million metric tons per year, *n*-butyraldehyde is among the most important applications of homogeneous catalysis [9, 35].

$$CH_3$$
$$|$$
$$\text{----}> H_3C\text{-}CH\text{-}CHO$$

iso-butyraldehyde

$$H_2C=CH\text{-}CH_3 + H_2 + CO \text{ ------} \quad \overset{\text{cat.}}{\vert}$$

$$\text{-----}> H_3C\text{-}CH_2\text{-}CH_2\text{-}CHO$$

n-butyraldehyde

$$+OH^- \downarrow$$

$$H_3C\text{-}(CH_2)_2\text{-}CH=C\text{-}CHO$$
$$|$$
$$C_2H_5$$

2-ethylhexenal

$$+H_2 \quad \text{cat.(het.)} \downarrow$$

$$H_3C\text{-}(CH_2)_3\text{-}CH\text{-}CH_2OH$$
$$|$$
$$C_2H_5$$

Scheme 1   **2-ethyl-1-hexanol**

The hydroformylation of propylene was an obvious choice as the first application of the new aqueous biphasic catalysis technology for several reasons:

(1) There is a balanced ratio of nonpolar reactants (such as propylene) and polar reaction products (butyraldehydes) which is particularly favorable for a two-phase application.
(2) The inherent problem of homogeneous catalysis, viz. the unsatisfactory separation of catalyst and reaction product, had not been optimally solved even not in the newer variants (e.g. Union Carbide's LPO process [36]).
(3) Other process engineering aspects of the processes also no longer met modern requirements after what was then over ten years of use. This applied particularly to the thermal balance of the LPO process and, after several energy crises, to its waste of energy.
(4) The more recent results of organometallic research with their possibilities for tailoring the oxo catalyst (especially in the area of very active and even more selective catalysts) could not be optimally applied to the LPO process, mainly because in this process the catalyst was still subjected to high thermal stresses during recycling.

It is therefore not surprising that the combination of modern *chemical* and *process engineering* developments in the aqueous biphasic oxo process led to the optimal technical solution. Among all the conceivable ways of designing a process in process engineering terms (discussion in [37]), the configuration based on the simplest scheme (Fig. 1) (known as the Ruhrchemie/Rhône-Poulenc process) is the most elegant and the most inexpensive.

TPPTS is the ideal ligand modifier for the oxo-active $HRh(CO)_4$. Without any expensive preformation steps, three of the four CO ligands can be substituted by the readily soluble, nontoxic (LD_{50}, oral: > 5000 mg kg^{-1}) TPPTS, which yields the hydrophilic oxo catalyst $HRh(CO)[P(m\text{-sulfophenyl-Na})_3]_3$ (Fig. 5). The fundamentals of the Ruhrchemie/Rhône-Poulenc oxo process and of the new TPPTS-modified Rh hydrido carbonyl complex have been described in a series of publications [25, 27, 30, 33, 34], cf. Fig. 6.

Compared to the classical and other variants of the oxo process, including thermal separation of the oxo reaction products from the catalyst, the procedure is considerably simplified. Owing to the solubility of the Rh complex in water and its insolubility in the oxo reaction products, the oxo unit is essentially reduced to a continuous stirred tank reactor followed by a phase separator (decanter) and a stripping column. Details of the process are available in the literature [27e–g].

The catalyst is not sensitive to sulfur or other oxo poisons. Together with the simple but effective decanting operation which allows organic impurities and other byproducts to be removed at the very moment of separation, accumulation of activity-decreasing poisons in the catalyst solution is prevented. Therefore, no special pretreatment or even purification steps are necessary. The oxo catalyst $HRh(CO)(TPPTS)_3$ is produced within the oxo reactor simply by reacting suitable Rh salts with TPPTS without any additional preformation step. Typical reaction conditions and compositions of crude products from the RCH/RP process based on a 14-year average are compiled in Table 3.
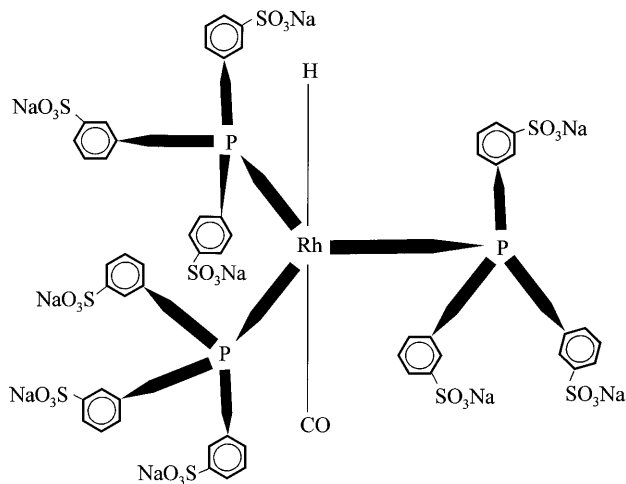
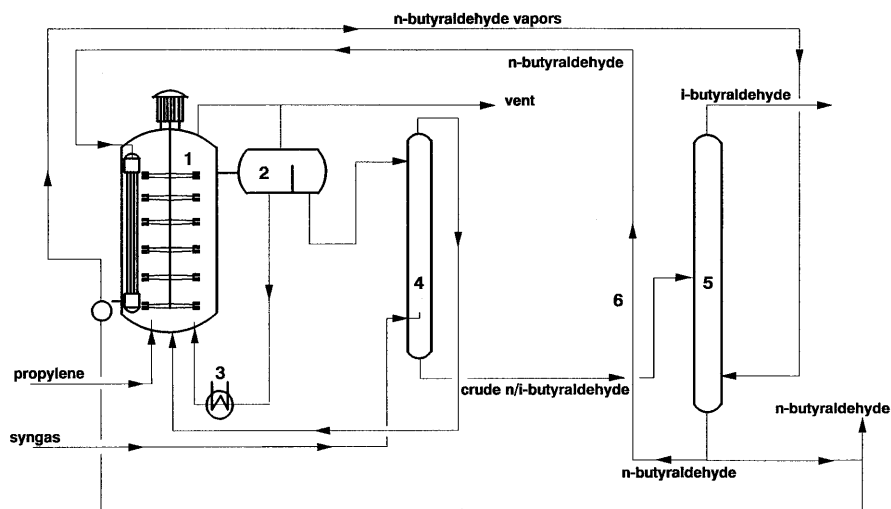**Fig. 5.** The active catalyst of Ruhrchemie/Rhône-Poulenc's new oxo process

Fig. 6. Flow diagram of the RCH/RP process [27e]

Table 3. Reaction conditions and results of RCH/RP process (15-year, average)

Parameter	Typical values
Temperature (°C)	120
Total pressure (Mpa)	5
CO/H_2 ratio	1.01
Ratio water/organic phase	6
Energy efficiency[a]	100
Conversion (%)	95
Results	
iso-Butanal (%)	4.5
n-Butanal (%)	94.5
Butanols (%)	< 0.5
Butyl formates (%)	traces
Heavy ends[b] (%)	0.4
n/iso ratio	95:5

[a] Exclusive of radiation and convection losses.
[b] Mainly 2-ethyl-3-hydroxyhexan-1-al.

The high selectivity of propene hydroformylation toward both the very highly valued C_4 *aldehydes* and the *sum of C_4 products* is a decisive factor. Both phenomena are the result of modifying the catalyst as compared to the classical oxo processes (see above). The high selectivity toward *the sum of C_4 products* is a specific result of biphasic operation and of the free availability of water during hydroformylation. The *n/iso* ratio, which is important for hydroformylation

reactions and which in other modern Rh-based processes is approx. 90:10, is over 95:5. Attention may be drawn to the particularly elegant thermal coupling of the cooling circuit to the use of the (exothermic) heat of reaction which makes the process a net steam supplier, together with the decisive environmental advantages [25].

During its active life, the rhodium catalyst is situated in the oxo reactor system and no aliquot parts are withdrawn and worked up simultaneously as in other oxo processes. The catalyst is "immobilized" and Rh losses are low in the ppb range; the Rh content of the crude aldehyde also corresponds to losses of less than 2 kg Rh (valued presently at roughly \$40,000) over the first period of 10 years with an output of 2 million metric tons of n-butanal. Like every technical and "real" catalyst, the complex $HRh(CO)(TPPTS)_3$ and the excess ligand TPPTS undergo a certain degree of decomposition, which determines the catalyst's service life as measured in years. Factors influencing the results are shown elsewhere [27 e], together with comparative manufacturing costs which indicate a decisive reduction of 10 % compared to other oxo processes with their relatively complex operation. This underlines the favorable nature of the aqueous two-phase reaction system.

Starting in 1999, the Ruhrchemie/Rhône-Poulenc process will be operated in plants having a capacity of about 600,000 metric tons per year, which corresponds to over 10% of the annual world production of C_4 products; the first licensed plant is operating in Korea (Hanwha Chem. Corp.). On the Ruhrchemie site, a butene hydroformylation plant [to produce n-valeraldehyde (pentanal)] is also operating without problems.

2.2
Hydroformylation of Higher Olefins

Compared to the conversion of propylene into n-butyraldehyde, the hydroformylation of higher olefins is, at a world production of about 1 million metric tons per year, of significantly less importance [9] and is concentrated (apart from small amounts of C_7-aldehyde from hexenes) on the reaction of C_8 and higher olefins. As shown in Fig. 4, the solubility in water of such olefins and the aldehydes containing one more carbon atom is about three powers of ten lower than that of propylene. This makes mass transfer more difficult, a fact which is held responsible for the reduced activity of the higher starting olefins in the aqueous two-phase process [41]. Attempts were initially made to deal with this problem by means of solubilizers [38], measures such as ultrasound which increase mixing [39], or specially tailored, e.g. surfactant, ligands [40]. Without going into the underlying dispute between experts as to the location of the aqueous two-phase catalytic reaction (cf. [34]), it may be mentioned that many other specific measures have been proposed, of which an arbitrary and incomplete selection is shown in Table 4.

The great number of very different proposals which address widely differing points in the oxo process does prove that there is currently no single ideal way of reacting higher olefins in aqueous biphasic hydroformylations. In addition, the oxo products, which are under a great deal of cost pressure, tolerate no cost-

Table 4. Examples of proposed measures for improving the hydroformylation of higher olefins

Measure	Reference
Substitution of the standard ligand by a tailor-made one	42
Addition of salts	43
Variation of the cationic part of the ligand/amphiphilic ligands	44
Other central atoms	45
Application of thermoregulating or polymer ligands	46
Addition of co- or promoter ligands	47
Exploitation of the effect of molecular recognition	48
Application of supported aqueous phase catalysts	49
Biphasic operation with heterogenized or heterogeneous catalysts	50
Changes of the reaction engineering concept	51

increasing process modifications either in terms of material costs or capital costs. For this reason, additives such as solubilizers or surfactants (which have to be changed according to the starting olefin and recovered subject to losses) or fundamental alterations in the process employed in the oxo plants are relatively improbable from an economic point of view. Furthermore, the campaign operation which is not uncommon for higher olefins prohibits, for cost reasons, a change of catalyst system or even only of ligand system with changing feed olefins. It may be pointed out that pH control of the hydroformylation [54, 55], which is suggested by process engineering considerations and by the effects on reactivity and product composition, is not sufficient in the presence of the great polarity and solubility differences of the reactants.

In the hydroformylation of higher olefins, even using the aqueous biphasic method, it has to be assumed that, owing to the reduction in the reaction rate caused by decreasing solubility of the olefins, the actual reaction should be single phase and the separation should be two phase. From today's point of view, this leaves the following routes to a solution:

(1) The use of "thermoregulating" ligands of the type shown in Fig. 7 [46a].

Oxocatalysts which are modified by means of such ligands take advantage of a temperature-dependent "cloud point" associated with the phosphorus-bonded poly(alkylene glycol ether). Thus, above the cloud point, the ligand (and thus the catalyst complex) loses its hydration shell, just as in the case of other compounds
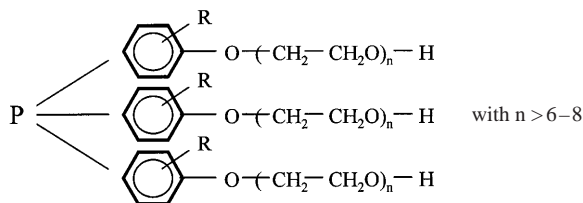
Fig. 7. Thermoregulating ligands as described by Jin and Fell [46 a]

of this type, causing the two-phase reaction mixture normally obtained when olefin is added to the catalyst solution to merge into a single phase, thereby initiating a rapid conversion that is no longer impeded by material transport problems. Subsequent lowering of the temperature causes the hydration shell to be reversibly restored, inducing the catalyst complex solution once again to separate out as an independent phase, this time from the reaction product, viz. the desired higher aldehydes (cf. Fig. 8 [52]).

Since the agent responsible for the merger and subsequent separation of the phases is the appropriately custom-designed ligand itself, there is no need to invest extra effort in the removal and recycling of an extraneous additive, and this must therefore be regarded as a promising avenue for further exploration on a commercially realistic scale. The means of solving the problem is thus the ligand tailored by chemical modification and the solution itself is the utilization of the physical effect of the cloud point.

(2) Another option is offered by the *chemical* solution. It is based on a problem-specific phase change between a two-phase and single-phase system by means of pH-controlled immobilization/re-immobilization [53]. The mode of action is demonstrated in Fig. 9.

In this procedure too, the actual oxo reaction is carried out without mass transfer problems in the monophase, but the actual separation is between two phases. This chemical variation of the process for reacting higher olefins can also include membrane steps [26], even if such additional process steps do involve the risk of drawbacks ranging from costs to material problems.
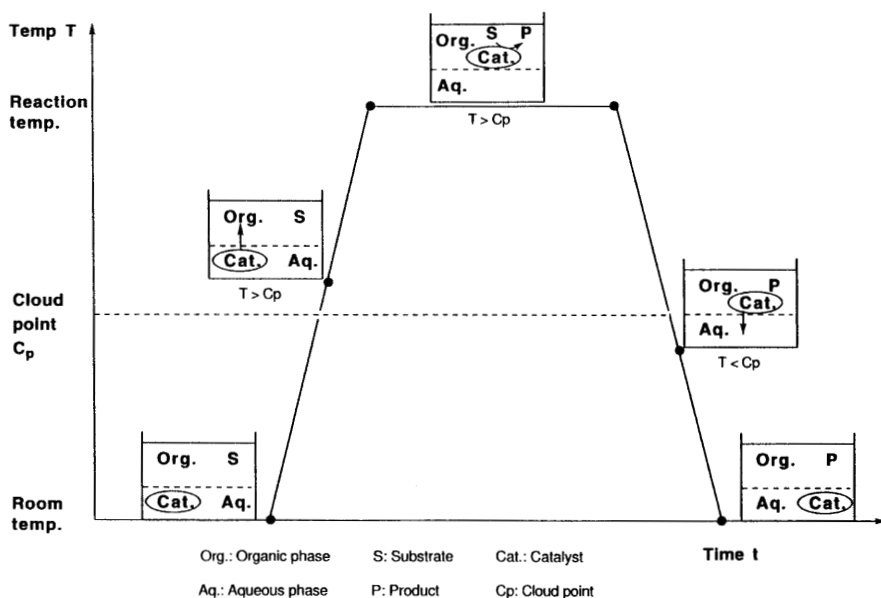

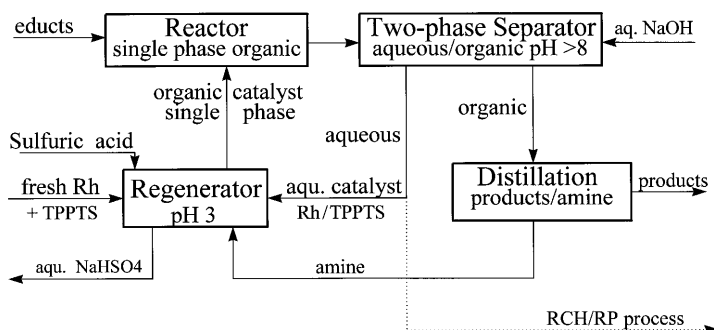**Fig. 8.** Phase change in the case of thermoregulating ligands

**Fig. 9.** Catalyst recycling by pH-induced phase separation

The development of thermoregulating ligands might well make a decisive contribution to solving the problems of aqueous, homogeneously catalyzed hydroformylations of higher olefins.

3
Water in Other Industrial Applications

Apart from the oxo process, a series of other reactions are carried out industrially, even if on a smaller scale. Kuraray carries out the hydrodimerization of butadiene and water to produce *n*-octanol (or 1,9-nonanediol) on a scale of about 5000 metric tons per year [55]. Applications which are significantly smaller up to now are, for example, the production of vitamin precursors by Rhône-Poulenc (cf. Scheme 2, [56]) and the production of substituted phenylacetic acids by carbonylation (Scheme 3) [57]) or of biaryls by Suzuki cross coupling (Scheme 4), both by Hoechst AG (now Clariant AG, [57, 58]).
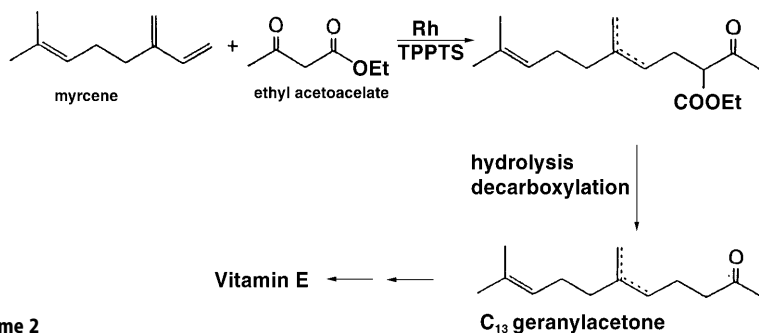
Scheme 2

Scheme 3

Scheme 4
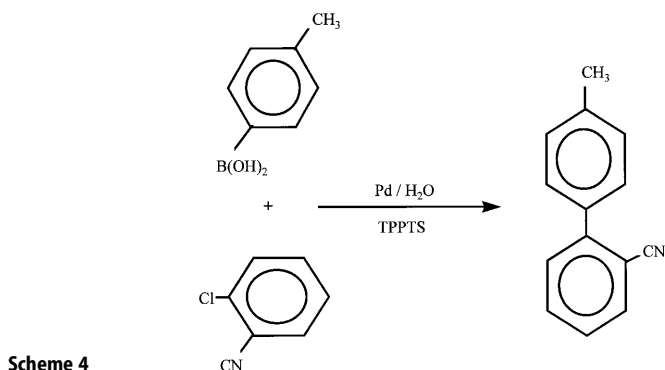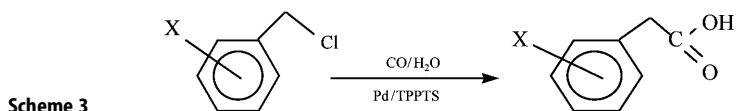
4
Other "Modern" Solvents

The enormous interest in a search for solvents other than the "classical" solvents for homogeneous catalysis – aroused by the success of aqueous biphasic catalysis – has produced some initial possibilities, namely "fluorous phases" [59], "nonaqueous ionic liquids" ("NAIL", [60]) and supercritical CO_2 ($scCO_2$, [61]). A feature common to all three variants is that, as a result of the unusual properties of the solvents employed and the ligands used for modifying the catalyst complexes (partially fluorinated or perfluorinated solvents or phosphines and organochloroaluminates), they likewise make possible an (advantageous, cf. above) *mono*phase reaction and a *two*-phase separation of catalyst and reaction product. However, to date evidence of industrial suitability, ease of handling and competitiveness is lacking for all three possibilities, and all three are expensive due to costly ligands and solvents. Estimation of costs for all three variants indicates that all of them are out of the question for use in cost-oriented hydroformylation of higher olefins. Applications in the field of fine chemicals, especially enantiomerically pure intermediates for pharmaceutical or agricultural applications, remain to be seen.

5
The Way Ahead

Water will retain and expand its importance as a new solvent for homogeneously catalyzed reactions because of the great process engineering advantages. Four focal points will be at the forefront:

(1) Academic research has to fill the knowledge gap between applied and fundamental research as soon as possible and, building on this, make new advances.

(2) In organometallic research, it will be important to find new ligands and ligand systems and examine them for their properties, their potential for custom design and their compatibility.

(3) Fundamental studies regarding the site of the reaction and on modeling the course of the reaction will remain significant for the process engineering of aqueous biphasic catalysis.

(4) Biphasic catalysis, specifically the aqueous variant, will increasingly provide the opportunity to better exploit the potential of homogeneous catalysis compared to the heterogeneous modus operandi and to increase its share of the totality of catalytic processes.

In future the aqueous biphasic processes will grow in importance because of the great advantages of this homogeneously catalyzed variant. Dimerizations, telomerizations, hydrocyanations, hydrosilylations, aldolizations, Claisen condensations, and a wide variety of C–C coupling reactions will be objectives above and beyond the currently used syntheses. Only the future will tell what importance asymmetric/enantiomeric conversions, especially hydroformylations, will have here, although initial experience is encouraging.

6
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