Anchored homogeneous catalysts: high turnover number applications

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Abstract

We have recently described a novel catalyst system comprised of a homogeneous complex anchored to a solid support using a heteropoly acid as the anchoring agent. This type of arrangement is particularly effective for anchoring enantioselective homogeneous catalysts since the catalytic species is attached to the support through the metal atom of the complex so no modification of the chiral ligand is needed. In the interest of obtaining as much information as possible in a reasonable time, almost all of the previously reported work involved reactions with substrate:catalyst ratios near 100 recognizing, though, that reactions with such low S:C ratios are not indicative of commercially important processes. We report here a number of dimethyl itaconate hydrogenations over the anchored complexes, Rh(DuPhos), Rh(Skewphos) and Rh(BoPhoz), which have been run as multiple batch processes using the same catalyst. The turnover numbers (TONs) in these reactions ranged from 1000 to 150 000. Analyses of many of these reaction mixtures showed that the amount of Rh was present at less than 1 ppm levels, frequently much less.
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1. Introduction

One of the major goals of catalytic research today is the development of enantioselective catalysts for use in the synthesis of chiral molecules. To date almost all of the successes in this field have involved chiral homogeneous catalysts [1,2]. While these species have great selectivity and are useful for promoting a variety of synthetically useful reactions, they are not generally used in large scale industrial processes. For such reactions, the most applicable catalysts are heterogeneous species which are easily separated from the reaction medium and have the potential for re-use. However, about the only synthetically useful reactions which are promoted by heterogeneous catalysts are the hydrogenations of various functional groups [3–5]. While a number of attempts have been made over the past 40 years to develop enantioselective heterogeneous catalysts, only two such systems are viable today and both of these are very substrate specific.

One is the enantioselective hydrogenation of β-ketoesters to the chiral β-hydroxyesters using nickel catalysts which had been modified by the addition of tartaric acid and sodium bromide. Further addition of pivalic acid to the modifying solution gave a system with which methyl ketones could be hydrogenated to the chiral alcohols [6,7]. The second heterogeneously catalyzed enantioselective reaction is the hydrogenation of α-ketoesters or acids to chiral α-hydroxyesters or acids using platinum catalysts which had been modified by the addition of one of the cinchona alkaloids [8–10]. This dearth of viable enantioselective heterogeneous catalysts has prompted the search for a method to convert the more generally selective homogeneous catalysts into species which are insoluble in the reaction mixture in order to facilitate the separation of the catalyst. While the first attempt at doing this was made over 30 years ago [11,12] with the quest still going on, there has been a general lack of success in this area [13–18].

The most common method used to 'heterogenize' a homogeneous catalyst has been to attach a ligand to a solid support material and then react these ligands with a metallic species to prepare the supported complex [19,20]. There are, however, several problems associated with this approach, the most important of which is that the metal ion is attached to the support by bonding through the ligand and is, therefore, prone to leaching, frequently to a rather large extent. Further, these catalysts are usually less active than the corresponding

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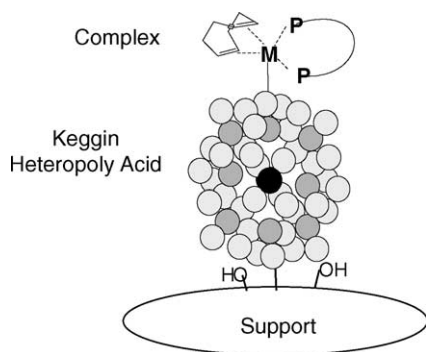*E-mail address:* augustro@shu.edu (R.L. Augustine).

Fig. 1. Cartoon showing the presumed structure of an anchored homogeneous catalyst.

homogeneous species. They also frequently lose their activity and selectivity on separation and attempted re-use [21–23]. The attachment of the ligand to a solid support is not applicable to all types of ligands and can be particularly difficult when one is attempting to produce an analog of an effective chiral ligand.

For general use in enantioselective synthesis, then, what is needed is a method by which a homogeneous catalyst can be anchored to a support material without the necessity of any ligand modification. Ideally, one should be able to anchor a pre-formed homogeneous catalyst to a support while retaining the activity and selectivity of the corresponding homogeneous catalyst even on extensive re-use. One way of doing this would be to attach the complex to the support through the metal atom. We have accomplished this by using heteropoly acids (HPAs) as the agents to attach catalytically active complexes to solid supports giving what has been termed "anchored homogeneous catalysts" [24–33].

These anchored homogeneous catalysts are composed of three components; a catalytically active organometallic complex, a support material and a heteropoly acid (HPA) which is used to anchor the complex to the support as depicted in Fig. 1. This approach has been used to prepare anchored catalysts from a wide variety of chiral and achiral complexes attached to several different types of supports [27–29] using the four commercially available HPAs as anchoring agents [32]. The present discussion will be concerned with the use of chiral rhodium complexes anchored onto either alumina or carbon using phosphotungstic acid (PTA) as the anchoring agent.

2. Experimental

2.1. Materials

The phosphotungstic acid (PTA) was obtained from Sigma–Aldrich and used as received. The alumina used for the support was a neutral gamma alumina obtained from Johnson Matthey. The carbon support was also obtained from Johnson Matthey. The dimethyl itaconate was obtained

from Acros and distilled under argon before use. All solvents were distilled under argon and stored in air-tight containers fitted with septa through which all transfers were made. If the solvent had been sitting for more than 1 day or 2 days after distillation, it was further degassed by bubbling argon through it for 45–60 min before use. The BoPhoz ligand was obtained from Eastman Chemical Co., the other ligands were purchased from Strem Chemicals and used to prepare the desired complexes following standard procedures. Samples of the anchored Rh(dppb) and Rh(Skewphos) catalysts were obtained from Johnson Matthey. Analyses were performed either by Johnson Matthey or Schwarzkopf Microanalytical Laboratory, Woodside, NY. The hydrogenations were run using the apparatus described previously [32]. More detailed information concerning these reaction systems can also be found on our web site: artsci.shu.edu/chemistry/cac.

The preparation of Rh(Me-Duphos)/PTA/Al$_2$O$_3$ was described previously [24,32]. This procedure was also employed to prepare the other anchored catalysts used in this study by replacing the [Rh(Me-DuPhos)(COD)]BF$_4$ with the appropriate complex and/or the alumina with carbon. The alumina supported catalysts routinely contained about 0.5% Rh while the carbon supported materials had about 0.9% Rh.

2.2. Catalytic hydrogenations

The procedure used for the heterogeneously catalyzed batch reactions was described previously [32]. Homogeneously catalyzed hydrogenations were run in this same manner using an amount of the soluble catalyst equal to the amount of active species on the anchored catalyst and monitoring H$_2$ uptake as described. In some homogeneously catalyzed hydrogenations, after the reaction had gone to completion an additional sample of the substrate was added to the reactor by syringe through a septum with the H$_2$ uptake monitored for the second and, sometimes, third reaction.

GC conditions: dimethyl itaconate; 0.1 μl sample injection, 30 m × 0.25 mm GTA column (Astec), injection port 250 °C, isothermal 90°, head pressure 15 psig, split ratio 50:1.

3. Results and discussion

Previous studies on the use of anchored homogeneous catalysts (AHCs) were concerned, primarily, with screening the effect which different reaction variables have on the activity, selectivity and stability of these catalysts. Almost all of these reactions were run with relatively low substrate/catalyst ratios (turnover numbers (TONs) with all of the reactions going to completion), typically between 50 and 100 [26–32]. It was found during this stage of the research that the AHCs were generally at least as active and selective as the homogeneous analogs, frequently even more so for a variety of chiral and achiral complexes. It was also found that in

Table 1

Comparison of reaction rate and product ee with the use of Rh(COD)(DuPhos)/PTA/C (**1**) and homogeneous Rh(COD)(DuPhos)$^+$BF$_4$$^-$ with respect to reaction TON and dmit concentration[a]

TON	MeOH (ml)	dmit (ml)	[dmit] (M)	Anchored catalyst **1**[b]		Homogeneous[c]	
				TOF (h^{-1})	ee (%)	TOF (h^{-1})	ee (%)
1000	15	1.4	0.7	4000	96	16500	96
5000	15	7.0	2.3	5700	96	28000	96
10000	15	14.0	3.4	6600[d]	96	23000	96
10000	100	14.0	0.9	4200[e]	96		
50000[f]	30	65	5.0	7000	96		
50000[g]	273	25	0.6			5000	97

[a] Reactions run at 50 psig of H$_2$ with catalysts containing 10 μmol of Rh complex.

[b] Reactions run at 50 °C.

[c] Reactions run at room temperature.

[d] Product contains 0.9 ppm Rh.

[e] Product contains <2 ppm Rh.

[f] Reaction run at 50 °C and 75 psig.

[g] Ref. [37], reaction run at 20 °C and 75 psig with 3.7 μmol of catalyst.

most instances it was necessary to pre-hydrogenate these anchored catalysts before introduction of the substrate [28].

It has since been realized that while the use of low TON reactions made it possible to obtain a great deal of information concerning the use of these anchored catalysts, in order to establish the viability of these catalysts for commercial applications it was necessary to use them in reactions involving much higher TONs.

In Table 1 are listed the turnover frequencies (TOF, h^{-1}) and product ee's obtained using both a homogeneous Rh(COD)(DuPhos)$^+$BF$_4$$^-$ and the corresponding anchored catalyst, Rh(COD)(DuPhos)/PTA/C (**1**) for the hydrogenation of dimethyl itaconate (dmit). The reactions were run at several different TONs with both catalyst systems. The first thing to notice is that the homogeneous catalyst is more active than is the anchored material but the product ee's are the same in every case. The second observation is that, as expected, the TOFs vary with the reaction TONs and the

substrate concentration. At the higher TONs the activity of the homogeneous catalyst decreases while the activity of the anchored catalyst increases with increases in the TON. A significant difference between the use of the homogeneous catalyst and the anchored species becomes apparent when the catalysts are re-used as shown by the hydrogen uptake curves in Fig. 2.

In Fig. 2a are shown the hydrogen uptake curves for the hydrogenation of dmit using the anchored Rh(DuPhos)catalysts, Rh(COD)(DuPhos)/PTA/C (**1**) and Rh(COD)DuPhos)/PTA/Al$_2$O$_3$ (**2**) with TONs of 10 000 for each run. The hydrogenations were repeated three times over the same sample of catalyst **1** (containing 10 μmol Rh)and four times over a sample of catalyst **2** (containing 20 μmol Rh). The TOF (h^{-1}) observed with the use of **1** at 50 °C was 6600 with a product ee of 96%. With **2** at room temperature the TOF (h^{-1}) was 1100 with an ee of 97%. Even though **1** was apparently more active than **2** there was still a considerable
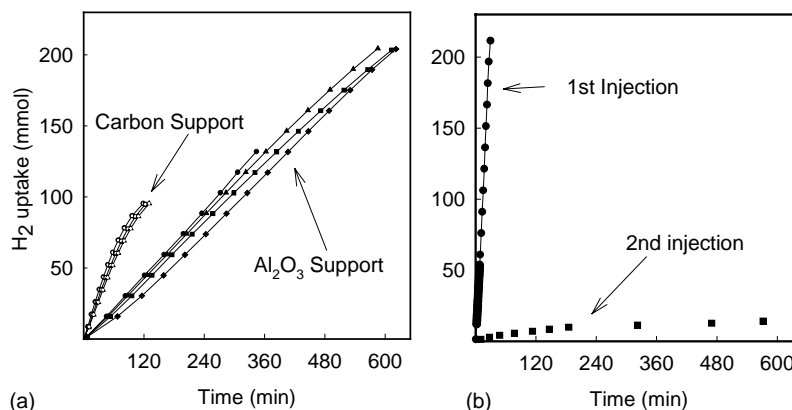

Fig. 2. Hydrogen uptake curves for the hydrogenations of dmit (10 000 TON) over: (a) the carbon supported **1** containing 10 μmol of the complex, Rh(COD)(DuPhos), hydrogenations run at 50 °C and 50 psig with 100 mmol of dmit in 15 ml of MeOH, and the alumina supported **2** containing 20 μmol of the active complex, hydrogenations run at room temperature and 50 psig with 200 mmol of dmit in 15 ml of EtOH; (b) 20 μmol of the homogeneous Rh(COD(DuPhos)$^+$BF$_4$$^-$ in 15 ml EtOH, hydrogenations run at room temperature and 50 psig with 200 mmol of dmit in the first injection. A second injection of 200 mmol of dmit was added after the first batch was completely hydrogenated.
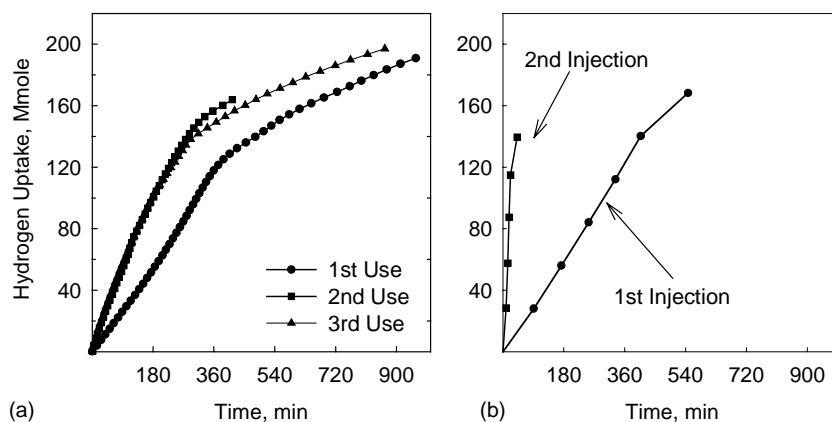
Fig. 3. Hydrogen uptake curves for the hydrogenations of 1-hexene (10 000 TON) run at 35 °C and 50 psig over: (a) anchored Rh(COD)(dppb)/PTA/Al$_2$O$_3$ containing 20 µmol of active complex, 200 mmol of 1-hexene in 15 ml of EtOH; (b) 20 µmol of Rh(COD)(dppb)$^+$BF$_4$$^-$ in 15 ml EtOH with 200 mmol of 1-hexene in the first injection. A second injection of 200 mmol of 1-hexene was added after the first batch was completely hydrogenated.

difference between the reaction rates using these anchored catalysts and that observed with the homogeneous catalyst, Rh(COD)(DuPhos)$^+$BF$_4$$^-$ as depicted in Fig. 2b. It should be noted, however, that these anchored homogeneous catalyst can be re-used several times without loss of activity or selectivity. Catalyst **1** promoted three such recycles with a total TON of 30 000 while with **2** a total TON of 40 000 was observed. The data in Fig. 2a also show that no catalyst deactivation was observed so further use of these catalysts was possible. The combined solutions from the reactions catalyzed by **1** were found to contain only 0.9 ppm of Rh. It is possible with our reaction solutions to visually detect as little as 2–3 ppm of complex. The reaction solutions produced by the use of **2** were water white indicating that there was also very little rhodium present there as well. This was also true of all of the other reaction mixtures from the AHC catalyzed hydrogenations described here. In fact, analysis of the individual reaction solutions from the dmit hydrogenations promoted by **2** showed that the amount of rhodium present was below the limit of detection, in this case <0.5 ppm.

While the homogeneous catalyst was more active in the hydrogenation of the first amount of dmit, when this substrate was fully hydrogenated and a second amount of dmit was added to the reaction mixture, no further hydrogenation was observed (Fig. 2b). This apparent change in catalytic activity of a homogeneous catalyst on addition of substrate after the first amount had been fully hydrogenated was also observed with a number of other homogeneous catalysts when used in high TON reactions, but the effect observed was not always of the type seen above for the DuPhos catalyst. For instance, the 10 000 TON hydrogenation of 1-hexene over the homogeneous catalyst Rh(COD)(dppb)$^+$BF$_4$$^-$ proceeded smoothly with a TOF of 9000 h^{-1} (Fig. 3b). However, addition of further 1-hexene after the first batch had been hydrogenated resulted in a dramatic increase in the reaction rate. Examination of the resulting reaction mixture showed the presence of very small black particles indicating that the catalyst had been reduced to metallic rhodium.

The hydrogenation of 1-hexene over the anchored catalyst Rh(COD)(dppb)/PTA/Al$_2$O$_3$ (Fig. 3a), on the other hand, took place with a TOF of 1250 h^{-1} with the catalyst capable of being re-used at least three times for a total TON of 30 000. This anchored catalyst remained yellow throughout all three reactions. The combined solutions from the hydrogenations promoted by the anchored catalyst contained 0.3 ppm of rhodium.

Fig. 4a shows the hydrogen uptake curves obtained for the hydrogenation of cyclohexene over an alumina anchored Wilkinson's catalyst. The three successive reactions, run using the same portion of catalyst, had a combined TON of 39 000 and a TOF of 3600 h^{-1}. The amount of rhodium present in these reaction solutions was below the limit of detection which, in this case, was <2 ppm. The hydrogen uptake data for the attempted 13 000 TON hydrogenation of cyclohexene over a homogeneous Wilkinson's catalyst is shown in Fig. 4b. Here, the catalyst completely lost its activity at about 40–50% conversion. This reaction was repeated five times with different samples of catalyst and cyclohexene with the same results observed each time.

We have also obtained data indicating that with a homogeneous Rh(COD)(Skewphos)$^+$BF$_4$$^-$ catalyst[1] the extent of deactivation appears to depend on the substrate concentration in the hydrogenation of dmit. As seen by the data in Fig. 5b when the homogeneous hydrogenation is run at a 1000 TON the reaction rate decreases with each subsequent addition of more dmit but re-use of the anchored catalyst, Rh(COD)(Skewphos)/PTA/Al$_2$O$_3$ (**3**), takes place with no loss in activity or selectivity. In a 3500 TON reaction, the homogeneous catalyst appears to be deactivated halfway through the hydrogenation of the second addition of dmit (Fig. 6b) but the anchored material, **3**, could be successfully re-used at least four times for a total TON of 14 000. In Fig. 7

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[1] Skewphos, also referred to as BDPP, is (2R, 4R)(+)-2,4-Bis-(diphenylphosphino)-pentane.
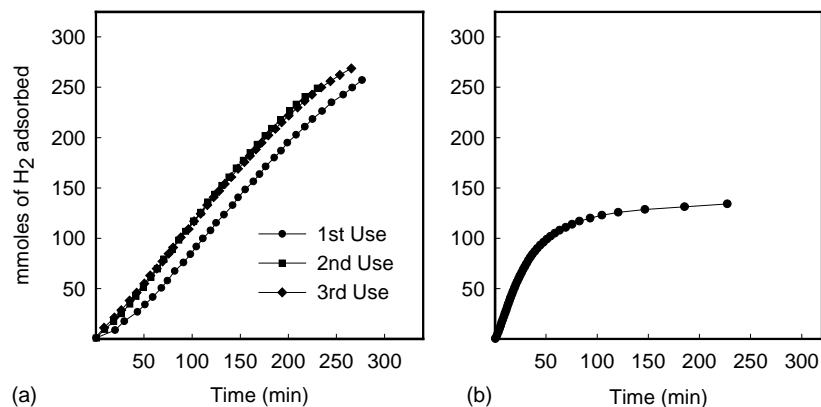
Fig. 4. Hydrogen uptake curves for the hydrogenations of 260 mmol of cyclohexene (13 000 TON) run at 35 °C and 50 psig in 18 ml of 10% toluene in EtOH over: (a) alumina anchored Wilkinson's catalyst containing 20 μmol of active complex; (b) 20 μmol of homogeneous Wilkinson's catalyst.
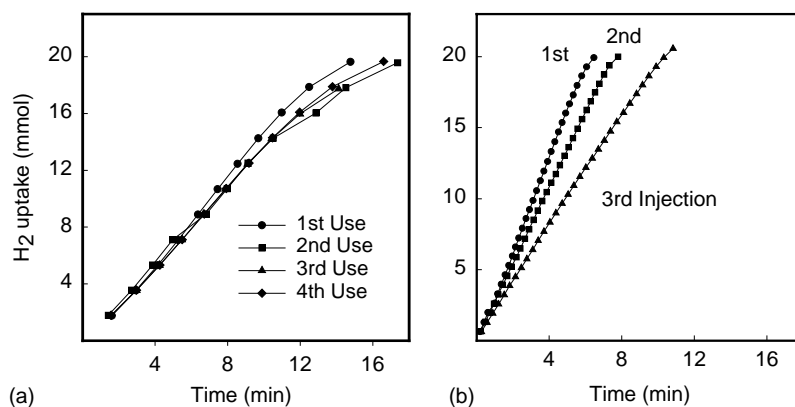

Fig. 5. Hydrogen uptake curves for the hydrogenations of 20 mmol of dmit (1000 TON) run at room temperature and 50 psig in 15 ml of EtOH over: (a) the anchored Skewphos catalyst, **3**, containing 20 μmol of the active complex; (b) 20 μmol of $Rh(COD)(Skewphos)^+BF_4^-$ with additional 20 mmol of dmit added sequentially after the previous batch had been hydrogenated.

are shown the hydrogen uptake data for the hydrogenation of neat dmit (9000 TON per run). The homogeneous catalyst is completely deactivated after the first injection while the anchored catalyst, **3**, is consistently active through three

re-use cycles (27 000 TON). Table 2 shows the reaction rates and product ee's for these reactions. It is interesting to note that with the homogeneous Skewphos catalyst the product ee decreases substantially with increase in reaction TON going
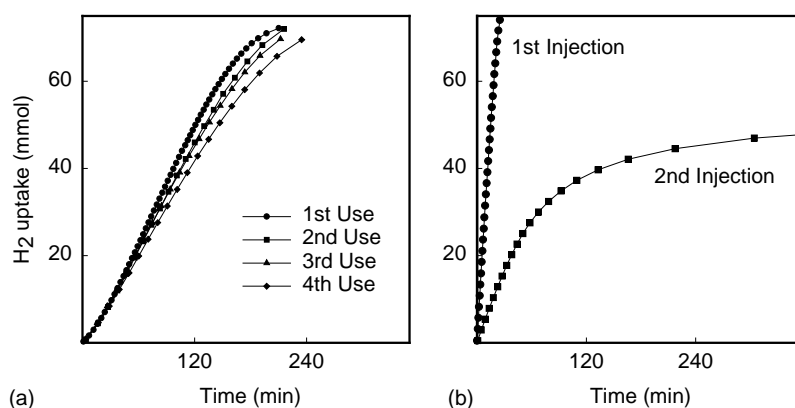

Fig. 6. Hydrogen uptake curves for the hydrogenations of 70 mmol of dmit (3500 TON) run at room temperature and 50 psig in 15 ml of EtOH over: (a) the anchored Skewphos catalyst, **3**, containing 20 μmol of the active complex; (b) 20 μmol of $Rh(COD)(Skewphos)^+BF_4^-$ with additional 70 mmol of dmit added sequentially after the previous batch had been hydrogenated.
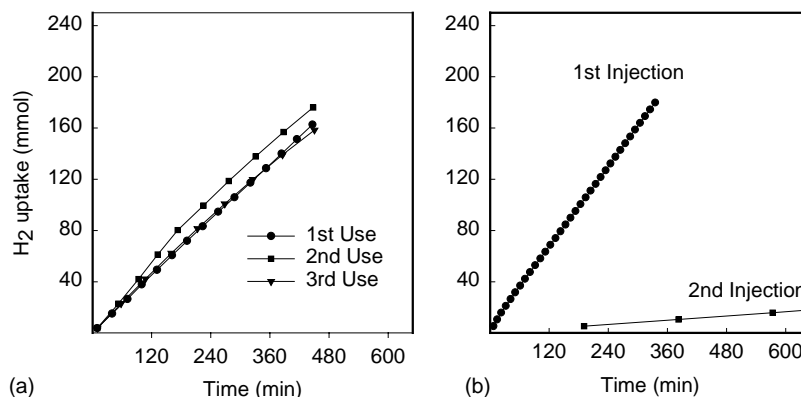
Fig. 7. Hydrogen uptake curves for the hydrogenations of 180 mmol of neat dmit (9000 TON) run at room temperature and 50 psig over: (a) the anchored Skewphos catalyst, **3**, containing 20 μmol of the active complex; (b) 20 μmol of Rh(COD)(Skewphos)$^+$BF$_4$$^-$ with additional 180 mmol of dmit added sequentially after the previous batch had been hydrogenated.

from 70% at 1000 TON to 62% at 9000 TON. With the anchored catalyst, though, the product ee is higher than that obtained from the homogeneously catalyzed reaction and is consistent at 79–81% regardless of the reaction TON.

One of the more obvious reasons for the slower reaction rates observed with the anchored catalysts as compared with the homogeneous analogs is the fact that hydrogen and substrate diffusion will certainly be more important in a heterogeneously catalyzed reaction than in one promoted by a homogeneous catalyst. Fig. 8 depicts the relationship between the stirring speed and reaction TOF for the hydrogenation of dmit over catalyst **1**. All hydrogenations were run at a 5000 TON and each catalyst re-used three times. Even though the catalysts were pre-hydrogenated the rate increased with successive use but the ee's, on the other hand, remained constant at 95–97% for all of the hydrogenations. It is obvious from these data that the agitation was still not sufficient to over-

come diffusion control of these reactions. Fig. 9 shows the relationship between the reaction TOF and stirring speed for the anchored Rh(Shewphos), **3**, run at 1000 TON. These data indicate that there is probably some degree of kinetic control in reactions run at 2000 rpm but that complete elimination of diffusion control was not attained, even at 2400 rpm. In all of these reactions the product ee was 79–80%.

It has been reported that homogeneous catalysts containing the diene, norbornadiene (NBD), are generally significantly more active than those containing cyclooctadiene (COD) [34,35]. In a preliminary report, we have shown that with the anchored homogeneous catalyst, Rh(Diene)(DiPamp)/PTA/Al$_2$O$_3$, the NBD containing material was only slightly more active than that containing COD [29]. With other anchored homogeneous catalysts the material containing COD is usually more active than that with NBD. Table 3 lists the TOFs and product ee's for the catalysts, Rh(Diene)(BoPhoz)/PTA/Al$_2$O$_3$, in which the diene is either NBD or COD. Here the COD containing

Table 2

Comparison of reaction rate and product ee with the use of Rh(COD)-(Skewphos)/PTA/Al$_2$O$_3$ (**3**) and homogeneous Rh(COD)(Skewphos)$^+$ BF$_4$$^-$ with respect to reaction TON and dmit concentration[a]

TON	[dmit] (M)	Use no.	Anchored catalyst **1**		Homogeneous	
			TOF (h^{-1})	ee (%)	TOF (h^{-1})	ee (%)
1000	1.1	1	4750	79	9900	70
		2	4100	78	8100	70
		3	4400	78	6100	69
		4	4400	77		
3500	2.8	1	1200	79	10000	65
		2	1250	80		66
		3	1200	79		
		4	1100	79		
9000	7.2[b]	1	1150	81	1550	62
		2	1400	82		
			1200	80		

[a] Reactions run at room temperature and 50 psig of H$_2$ with catalysts containing 20 μmol of Rh complex.
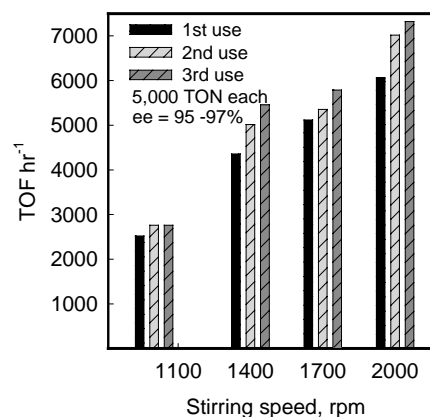
[b] Reactions run on neat dmit (no solvent).

Fig. 8. Effect of stirring speed on the reaction rate in the 5000 TON hydrogenations of dmit over catalyst **1** containing 10 μmol of active complex. Hydrogenations run at 50 °C and 50 psig with 50 mmol of dmit in 15 ml of MeOH.
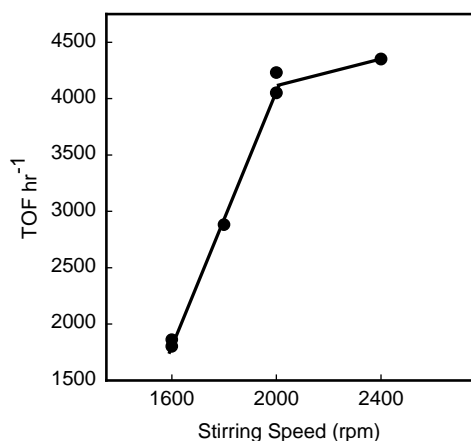
Fig. 9. Effect of stirring speed on the reaction rate in the 1000 TON hydrogenations of dmit over catalyst **3** containing 20 μmol of active complex. Hydrogenations run at room temperature and 50 psig with 20 mmol of dmit in 15 ml of EtOH.

species was more active that having the NBD diene but the NBD containing species gave more reproducible reaction rates on re-use of the catalyst. Analysis of the combined reaction mixtures for each of these series of reactions found that they contained rhodium in only 2 ppm. The reaction rates for this catalyst were even independent of the TON of the reaction but, this was not the case with the COD containing material. With this later catalyst, the rates dropped off slightly with re-use and were quite different between those reactions run at 1000 and 3000 TONs. The product ee's observed with these catalysts were essentially the same as those obtained with the homogeneous catalyst.

It was found with these NBD containing alumina supported catalysts that 10–15% toluene in the ethanol solvent was needed to stabilize the catalyst, but even this was not sufficient for the COD containing material. The presence of toluene in the reaction mixture, especially at this level, re-

Table 3
Comparison of reaction rate and product ee with multiple uses of Rh(NBD)(BoPhoz)/PTA/Al$_2$O$_3$ and Rh(COD)(BoPhoz)/PTA/Al$_2$O$_3$ in the hydrogenation of dmit at TONs of 1000 and 3000[a]

TON	Use no.	NBD[b]		COD[b]	
		TOF (h^{-1})	ee (%)	TOF (h^{-1})	ee (%)
1000	1	1140	91	3300	91
	2	1260	91	2850	91
	3	1200	92	2730	91
	4	1140	92	2550	91
	5	1080	92	2460	92
	6			2340	92
3000	7	1050[c]	92	1590	91
	8	1050[d]	92	1440	92

[a] Reaction run at room temperature and 50 psig, 1400 rpm in 10–15% toluene in EtOH.
[b] 2 ppm of Rh found in combined reaction mixtures.
[c] Use 6 for the NBD catalyst.
[d] Use 7 for the NBD catalyst.

Table 4
Reaction rates and product ee's obtained on the multiple hydrogenations of dmit over Rh(COD)(Me-BoPhoz)/C at 10 000 TON per run[a]

Use no.	TOF (h^{-1})	ee (%)
1	10400	92
2	10500	92
3	10500	92
4	10600	91
5	9200	92

[a] Reaction run at room temperature and 75 psig at 1700 rpm, 100 mmol of dmit in 5% toluene in MeOH, catalyst contained 10 μmol Rh(Me-BoPhoz).

sulted in a lowering of the reaction rates for these catalysts. Attempts at using these alumina supported Rh(BoPhoz) catalysts at higher TONs has proven unsuccessful so far, even in the presence of toluene.

However, since the carbon supported Rh(DuPhos) catalyst was apparently more active than the alumina supported material (Fig. 2), the Rh(COD)(BoPhoz)/PTA/C was prepared and used to promote the hydrogenation of dmit. In Table 4 are listed the TOFs and product ee's for five successive uses of this catalyst with a 10 000 TON for each reaction. The first four hydrogenations had nearly identical rates while the fifth showed about a 10% decrease, probably because the catalyst was exposed to hydrogen too long after run number four was completed. These reactions were all run using only 3% toluene in methanol, a considerable difference with the amount of toluene required for the alumina supported catalysts.

In some previous work it was reported that immobilized Rh(DuPhos) catalysts did not give consistent results in the hydrogenation of methyl 2-acetamidoacrylate over several cycles, even at TONs of only 100 [36]. Because of this observation it has been suggested that for large scale use, the homogeneous Rh(COD)(DuPhos)$^+$BF$_4^-$ be used. This was substantiated by the use of this homogeneous catalyst in a 50 000 TON hydrogenation of dmit [37]. This reaction was run at 20 °C and 75 psig and was completed in 10 h. While the data shown in Fig. 2 illustrate the viability of both alumina and carbon supported Rh(DuPhos) catalysts for the multiple 10 000 TON hydrogenations of dmit, we have now used the carbon supported catalyst, Rh(COD)(DuPhos)/PTA/C, in multiple 50 000 TON hydrogenations of dmit with the hydrogen uptake data shown in Fig. 10. The first use of this catalyst proceeded at a TOF of 7000 h^{-1} and a product ee of 96% and, after that was completed, the reaction mixture was removed from the catalyst and a second 50 000 TON use of this same portion of the catalyst was run. This second run was slower than the first but still proceeded at an appreciable TOF of 5500 h^{-1} with a product ee of 96%. A third run of 50 000 TON was also accomplished with this catalyst. This proceeded at a TOF of 4000 h^{-1} with a product ee of 96%. Thus, this anchored catalyst was used for a total TON of 150 000.
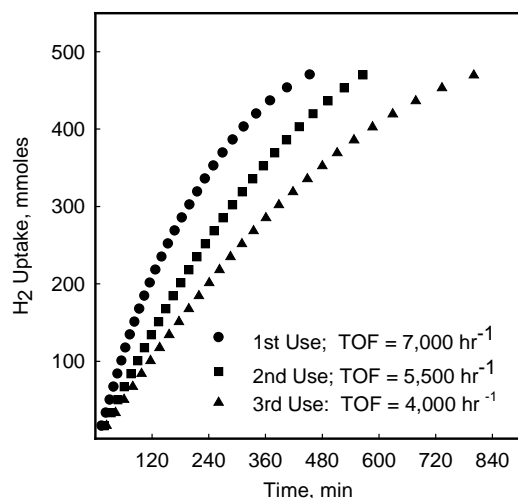
Fig. 10. Hydrogen uptake curves for the hydrogenation of successive batches of 500 mmol of dmit (50 000 TON) in 30 ml of MeOH over catalyst **1** containing 10 μmol of active complex, hydrogenations run at 50 °C and 75 psig at a stirring rate of 1700 rpm.

4. Conclusions

While, in general, homogeneous catalysts may be more active than the corresponding anchored homogeneous catalysts (AHC) in, at least, moderately high TON reactions, the anchored species are still quite active and, in addition, have several advantages over the homogeneous materials. For example, homogeneous catalysts appear to be more susceptible to deactivation or reduction by hydrogen once all of the substrate has been hydrogenated. Thus, these materials cannot be used to hydrogenate additional material, at least at the rate of the initial reaction. This is not the case with the AHCs which can be re-used several times, even at high substrate/catalyst ratios with little, if any, loss of activity or selectivity. This factor can be of importance when the size of the reactor available determines the amount of substrate which can be hydrogenated in a single batch. Secondly, metal leaching is insignificant with the AHCs so removal of the catalyst by filtration can give a product mixture more easily purified than that obtained from a homogeneously catalyzed reaction. In addition, AHCs, in some cases give results significantly better than those obtained with the homogeneous analog. As illustrated with the data obtained from the Rh(Skewphos) catalyzed hydrogenations, the product ee's obtained on hydrogenation of dmit using an anchored catalyst were considerably higher than those found with the homogeneously catalyzed reactions, particularly at the higher TONs. The ability of the anchored Wilkinson to hydrogenate cyclohexene to very high TON without the deactivation seen with the homogeneous catalyst is another example. Finally, these AHCs can readily be used in continuous reactions, a feature which will be presented in a future publication.

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