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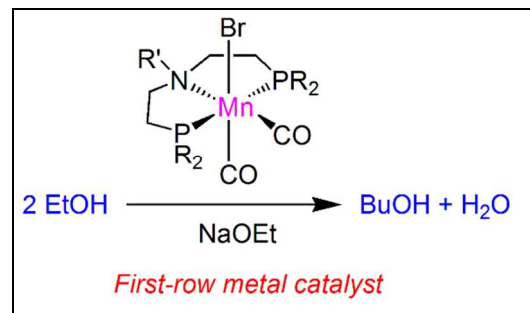
Catalytic Upgrading of Ethanol to *n*-Butanol via Manganese Mediated Guerbet Reaction

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ABSTRACT: Replacement of precious metal catalysts in the Guerbet upgrading of ethanol to *n*-butanol with first-row metal complex catalysts is highly appreciated due to the economic and environmental benign. The manganese pincer complexes of the type $[(^R\text{PNP})\text{MnBr}(\text{CO})_2]$ ($R = ^i\text{Pr}, \text{Cy}, ^t\text{Bu}, \text{Ph}$ or Ad) are found to be excellent catalysts for upgrading of ethanol to *n*-butanol. Under suitable reaction conditions and with an appropriate base about 34% yield of *n*-butanol can be obtained in higher selectivity. The detailed account on the effect of the temperature, solvent, nature and proportion of base used and the stereo-electronic effects of the ligand substituents on the catalytic activity of the catalysts as well as the plausible deactivation pathways is presented.



Keywords: Guerbet Chemistry, ethanol upgrading, manganese pincers, butanol, dehydrogenation.

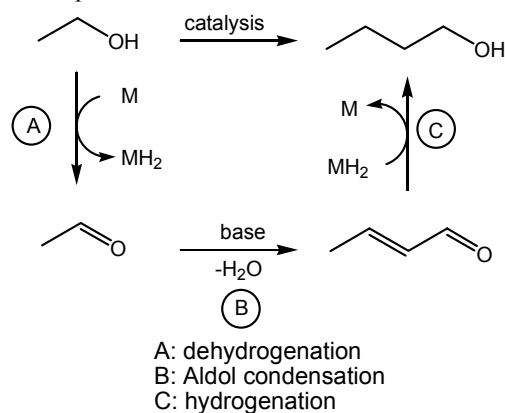
INTRODUCTION

In recent years, the search for alternative energy sources has increased significantly, mainly due to energy security and environmental protection issues.¹ Biofuels offer much promise in these frontiers and are being explored as substitutes for the diminishing fossil fuels. Biofuels are viable economically and cause low environmental damage, therefore development of efficient methods and technologies for the production of biofuels from renewable biomass sources is receiving increased attention in academic and industrial research.² Currently, bioethanol is being probed as a sustainable alternative fuel (or fuel additive) to conventional gasoline. However there are some concerns to be attended to. Ethanol has only 70% of the energy density of gasoline.³ It readily absorbs water, and causes problems in separation and transportation in existing fuel-infrastructure and can be corrosive to the current engine technology. Alternatively, butanol offers a more viable option, as it has properties similar to that of gasoline. It has an energy density closer to that of gasoline (90%), and is immiscible with water. It is noncorrosive to the engine parts and can be blended with gasoline at higher concentrations, offering twice the renewable content compared to ethanol per gallon.⁴

Although some methods are known for the synthesis of butanol, such as the ABE fermentation process⁵ and the hydroformylation/hydrogenation of propylene,⁶ these processes suffer from selectivity issues, separation problems, and low yield, making the bulk production of clean butanol still a challenge. Alternatively, the Guerbet reaction⁷ offers a great opportunity to synthesize butanol from an easily accessible feedstock, ethanol, via a metal catalyzed “borrowed hydrogen” sequence (Scheme 1). Despite the thermodynamic difficulties in the dehydrogenation of ethanol (Step A, Scheme 1) and the possibility of various side reactions of the acetaldehyde formed (Step B, Scheme 1), the Guerbet reaction has attracted interest since it provides a faster route to synthesize butanol and ena-

bles the use of distinct catalysts in the various stages of the reaction.

In pioneering studies, Ishii and co-workers reported the catalytic application of $\text{Ir}(\text{COD})(\text{acac})$ (COD: 1,5-cyclooctadiene, acac: acetylacetonate), for the conversion of ethanol to *n*-butanol. The reactions were carried out in the presence of a bidentate phosphine ligand, a base (sodium ethoxide), and a sacrificial hydrogen acceptor (1,7-octadiene). However, low conversions (about 12%) and a moderate selectivity (up to 67%) were reported.⁸



Scheme 1. Catalytic upgrading of ethanol to *n*-butanol via the Guerbet process

Wass et al. reported ruthenium-based homogeneous catalysts supported by bisphosphine and phosphine-amine ligands that promote the Guerbet reaction of ethanol. Distinct ligand influence over the activity of the catalyst was observed. With a $[\text{RuCl}(\eta^6\text{-p-cymene})(\text{dppm})]\text{Cl}$ ($\text{dppm} = 1,1\text{-bis}(\text{diphenylphosphino})\text{methane}$) based system, a 22% yield of *n*-butanol was obtained with a selectivity as high as 94%. With

a relatively stable but slower system, $\text{trans-}[\text{RuCl}_2(\text{dppm})_2]$, a higher yield of *n*-butanol (35.5%) was obtained at 85 % selectivity.⁹ A ruthenium system with a mixed donor ligand, 2-(diphenylphosphino)-3-methyl-1H-indole, performed well providing a 28% yield of *n*-butanol at 93% selectivity.¹⁰ It is worth noting that obtaining high selectivity at high ethanol conversions becomes difficult, since the amount of butanol exceeds that of ethanol.

Szymczak and co-workers reported a N,N,N-ruthenium catalyst for the upgrading of ethanol. This catalyst was found to be faster compared to other catalysts providing a 31% yield of *n*-butanol with 82% selectivity in 2 h when 10 mole % of sodium ethoxide was used. Addition of 4 equivalents of triphenylphosphine led to an increase in activity (53% conversion), however with a lower selectivity towards *n*-butanol (78%).¹¹ Recently, Milstein et al. reported a highly active, acridine-based P–N–P ruthenium pincer catalyst which exhibited very good ethanol conversion (up to 73%) with high turnover numbers. Although this high conversion is remarkable, the selectivity towards *n*-butanol was modest (38% yield at 67% ethanol conversion).¹²

Earlier, we reported a highly selective catalyst-system based on an iridium complex bearing an α -hydroxypyridine motif and transition-metal hydroxides supported by bulky organic ligands. Under optimized conditions, ethanol conversions of up to 37% with >99% selectivity towards *n*-butanol were achieved. The control experiments and mechanistic studies revealed the key role of steric and electronic features of the basic nickel and copper hydroxide complexes in defining the extent of the aldol reaction and hence controlling the total product distribution leading to the unprecedented selectivity.¹³

On the other hand, Guerbet chemistry of ethanol involving heterogeneous catalyst systems has also achieved considerable development. The basic metal oxides and transition metal catalysts supported by basic metal oxides have been used for this chemistry extensively. Despite the development of various new heterogeneous catalysts and technologies for the Guerbet reaction of ethanol, the harsh reaction conditions, low conversions, and low selectivity profile present a major downside for this area of research.¹⁴

It should be noted that all the homogeneous catalysts that have been developed to catalyze the Guerbet reaction of ethanol are based on rare metals (Ru or Ir) and their excellent performance in the catalysis also comes with the economic and environmental issues associated with them. Hence replacement of these precious metal catalysts with inexpensive and eco-friendly first-row metal catalysts would be a worthwhile goal.

There are several first-row transition metal catalysts known in the literature that can efficiently dehydrogenate a primary alcohol to produce the respective aldehyde under basic conditions in an acceptorless fashion. Some of them can also hydrogenate C=C and C=O bonds under similar reaction conditions, which indeed satisfies the requirement of a potential Guerbet catalyst. We examined several of these established catalysts (see Table S6 for summary), including the cobalt-pincer complexes developed by the Hanson group,¹⁵ iron-pincer complexes developed by our group,¹⁶ and manganese pincer complexes developed by the Beller group.¹⁷ Interestingly, the manganese complexes were found to be the better catalysts for the upgrading of ethanol under our reaction conditions. Herein, we report a manganese catalyzed Guerbet upgrading of the ethanol to *n*-

butanol with remarkably high conversions and good selectivity (Figure 1). This is the first example of the application of manganese based catalysts in ethanol upgrading.

The Guerbet Reaction

We began our investigation using the complex $[\text{HN}(\text{CH}_2\text{CH}_2\text{P}^i\text{Pr}_2)_2]\text{Mn}(\text{CO})_2\text{Br}$ (**1**) (0.5 mol% loading)^{17c} as the homogeneous catalyst for the Guerbet reaction of neat ethanol. In the presence of a base, potassium hydroxide (25 mol%), the activity of this manganese-based catalyst could be compared with the reactivity of the previously reported iridium and ruthenium systems. KOH was chosen as base since it has been the most compatible and successful base for the present manganese system in the dehydrogenation of methanol.^{17a} Catalytic reactions were performed at 150 °C for 24 h and the results are shown in Table 1 (eq 1). With KOH (entry 1) we observed a moderate conversion of ethanol (30%), in which the desired *n*-butanol was obtained in only about 11% yield and about 3% of other higher alcohols were observed. Some of the ethanol that was consumed that did not produce Guerbet alcohols is listed as “missing EtOH”, and was found to produce H₂ and NaOAc (vide infra). Altogether, this reaction was not impressive, either in terms of conversion or selectivity; hence we started looking for alternative base and reaction conditions in order to achieve better reactivity.

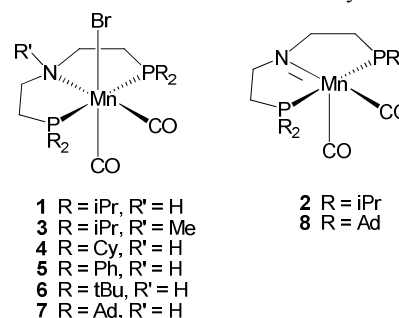


Figure 1. Manganese pincer complexes investigated in this work.

Table 1. Conversion of Ethanol to *n*-Butanol using **1 and Common Inorganic Bases.^a**

Entry	Base	EtOH left %	<i>n</i> -BuOH formed %	Higher alcohols ^b %	Missing EtOH ^c %
1	KOH	70	11	3	16
2	NaOEt	38	30	10	22
3	KO ^t Bu	30	19 ^d	2	25
4 ^e	NaOMe	61	11	1	16
5 ^f	K(N(SiMe ₃) ₂)	44	10	1	19
6 ^g	PhONa	69	5	0	11
7 ^h	NaOAc	96	0	0	4
8 ^h	-	97	0	0	3

^a All the reactions are carried out in a Schlenk bomb, loaded with 0.5 mol% of complex **1** (34.2 μmol), 25 mol% of base (1.7 mmol) and 0.4 mL (6.85 mmol) of ethanol, at 150 °C for 24h, conversions and yields are based on GC studies of at least two

reaction samples. ^b Mixture of 2-ethyl butanol, 1-hexanol, 2-ethyl hexanol and 1-octanol (See SI for the distribution). ^c Missing EtOH refers to the amount of total moles of ethanol that do not appear as BuOH or higher alcohols. ^d 24 % of ^tBuOH was observed. ^e 7 % of MeOH and 4% of *n*-propanol was observed. ^f 26% of bis(trimethylsilyl)amine and its decomposition products were observed. ^g 15% of phenol was observed. ^h 3-4% loss of ethanol due to evaporation in a typical run.

When sodium ethoxide (NaOEt) (Table 1, entry 2), which is the most commonly used base in the Guerbet reaction of ethanol, was employed in the reaction,⁹⁻¹² an excellent conversion (62%) was observed, in which 30% of ethanol was converted into the desired *n*-butanol and about 10% was converted into higher alcohols. On the other hand, a reaction with KO^tBu (Table 1, entry 3) provided only about at 19% yield of *n*-butanol, while a 24 % yield of *t*-butanol was observed due to the protonation of the KO^tBu in ethanol. NaOMe (Table 1, entry 4) gives sluggish reactivity, producing about an 11 % yield of *n*-butanol. About 7% of methanol was observed originating from the protonation of NaOMe in ethanol and about 4% of *n*-propanol was produced by the cross-Guerbet reaction of the ethanol and methanol.¹⁸ However, no traces of isobutanol were observed. A bulky base, K(N(SiMe₃)₂) did not improve conversion or selectivity (Table 1, entry 5), producing only about a 10% yield of *n*-butanol; however, several unidentified compounds and gasses were produced during the reaction, which may have originated from the decomposition of the (trimethylsilyl)amine fragment. Use of a weaker base, PhONa (Table 1, entry 6) resulted in sluggish activity; only about a 5% yield of *n*-butanol was observed, while about 10 % of the ethanol was converted into phenol due to protonation of PhONa. Sodium acetate (NaOAc) was also found to be an unsuitable base for the current studies, as it did not produce any of the expected products (Table 1, entry 7). A control experiment carried out in the absence of a base provided no detectable products (Table 1, entry 8); however a loss of about 3-4% ethanol was observed during workup.

Among the common bases employed in these studies, NaOEt stood out to be the best (Table 1, entry 2), producing the desired Guerbet products in a good quantity. However, this reaction mixture also produces about 80 to 85 cm³ of hydrogen gas (EXPLOSION HAZARD. Identified by GC). This H₂ gas actually accounts for the ‘missing’ ethanol, indicating that the dehydrogenation step is predominant over the hydrogenation step in this case. Since dehydrogenation of ethanol is uphill thermodynamically, further irreversible reaction of the acetaldehyde could lead to the high pressures of H₂ gas that is observed. NaOAc was identified as the major solid product remaining following work-up by ether extraction (Solid analysis, GC, GCMS, ESI-MS and NMR). These by-products are thought to arise due to a Cannizzaro reaction that uses the H₂O produced in the Guerbet reaction to make NaOAc (see SI for details).

We then attempted to see if the conversion of ethanol and selectivity towards *n*-butanol could be further improved by varying the catalyst:base ratio and the reaction conditions. First we increased the catalyst loading to 5 mole % and the NaOEt loading to 50 mol% (Table 2, entry 1). After heating the reaction at 150 °C for 24 h we observed a high consumption of ethanol (86%); however, the yield of *n*-butanol was only 28%, whereas the gas formation was enhanced greatly. Next, we lowered the catalyst loading to 1 mol% while keeping the base loading the same (50 mol%) (Table 2, entry 2).

These conditions had the effect of actually lowering the amount of gas formed but the yield of *n*-butanol was no better than the first reaction (Table 1, entry 2). Changing the base loading to 50 mol% for 0.5 mol% catalyst (Table 2, entry 3) resulted in a decrease in the amount of Guerbet products formed. In the next attempt we lowered the catalyst amount to 0.2 mol% and the NaOEt to 25 mol% (Table 2, entry 4), which resulted in a decrease in the reactivity. Extending the reaction period to 48 h with this combination did not improve the yield of the desired products significantly, but increased gas formation was observed (Table 2, entry 5). Further lowering the base loading to 12.5 mol%, while keeping the catalyst loading 0.5 mol%, resulted into a drop in the total reactivity (Table 2, entry 6).

From these results, a combination of 0.5 mol% catalyst and 25 mol% of NaOEt was established to be the best catalytic composition to achieve the highest conversion and selectivity in the Guerbet reaction of ethanol under our reaction conditions (150 °C, 24 h). Further extension of the reaction time to 48 h resulted in only a slight increase in the formation of *n*-butanol and higher alcohols (Table 2, entry 7). In order to see if lowering the reaction temperature could improve the selectivity toward Guerbet products and suppress gas production, a reaction was examined at 120 °C (Table 2, entry 8). Although the amount of hydrogen gas formed was reduced, the amount of Guerbet products was also significantly decreased. Interestingly, upon extending the reaction time to 48 h (Table 2, entry 9), the amount of *n*-butanol formed increased to 28% yield, while a considerably smaller amount of hydrogen was produced. On the other hand, when the reaction temperature was set to 180 °C (Table 2, entry 10), the formation of *n*-butanol and other higher alcohols decreased significantly, but a large amount of hydrogen gas was produced.

Table 2. Optimization of Manganese-Catalyzed Guerbet reaction of Ethanol ^a

Entry	Cat (mol%)	NaOEt (mol%)	Rxn time h	T °C	EtOH left %	<i>n</i> -BuOH formed %	Higher alcohols ^b %	Missing EtOH %
1	5	50	24	150	14	28	19	39
2	1	50	24	150	30	27	16	27
3	0.5	50	24	150	34	26	11	29
4	0.2	25	24	150	62	18	4	16
5	0.2	25	48	150	42	21	8	29
6	0.5	12.5	24	150	56	20	4	20
7	0.5	25	48	150	35	31	13	21
8	0.5	25	24	120	63	22	3	12
9	0.5	25	48	120	53	28	6	13
10	0.5	25	24	180	37	18	4	41
11 ^c	0.5	25	24	150	46	25	6	23
12 ^d	0.5	25	24	150	40	31	11	18

^a reactions were carried out in a Schlenk bomb at the indicated temperature and time; the conversions and yields are based on GC analysis of at least two reaction samples. ^b Mixture of 2-ethyl bu-

tanol, 1-hexanol, 2-ethyl hexanol and 1-octanol (See SI for the distribution). ^c 0.4 mL toluene was added. ^d 2.5 mol% of the ligand bis[(2-diisopropylphosphino)ethyl]amine was added.

The addition of a solvent (0.4 mL of toluene) decreases the formation of Guerbet products but the hydrogen formation was found to be almost unaffected (Table 2, entry 11). Addition of 2.5 mol% of the free ligand, bis[(2-diisopropylphosphino)ethyl]amine (Table 2, entry 12), showed only a slight improvement in the yield of *n*-butanol (31%). The excess ligand present in the reaction system was expected to bind to any free metal ion and re-form the catalyst, in case there had been any decomposition during the reaction.

In order to assess some basic information about the degree of conversion of ethanol into the Guerbet products and hydrogen gas, we carried out a series of experiments using the established catalyst-base combination (0.5 mol% [Mn], 25 mol% NaOEt) at different periods of time (Table 3). The amount of *n*-butanol and *n*-hexanol were observed to increase slowly over time, while the gas formation was faster by comparison. Interestingly, after 4 h, the amount of gas produced remained mostly unchanged over the period of reaction (as indicated by no increase in the missing ethanol). This can be clearly visualized in the graphical representation of the data in Figure 2.

Table 3. Reaction profile for the Guerbet reaction of ethanol catalyzed by complex 1^a

Entry	Time h	EtOH left %	<i>n</i> -BuOH formed %	Higher alcohols ^b %	Missing EtOH %
1	1	66	14	2	18
2	4	54	17	4	25
3	8	48	21	7	24
4	12	45	24	8	23
5	24	38	30	10	22
6	48	35	31	12	22

^a All the reactions are carried out in a Schlenk bomb, loaded with 0.5 mol% of complex 1 (34.2 μmol), 25 mol% of base (1.7 mmol) and 0.4 mL (6.85 mmol) of ethanol, at 150 °C for the noted period of time, the conversions and yields are based on the GC analysis of at least two reaction samples. ^b Mixture of 2-ethyl butanol, 1-hexanol, 2-ethyl hexanol and 1-octanol (See SI for the distribution).

The reactivity of the catalyst stops or slows down significantly after about 24 h. We suspected that water, which is a main by-product of Guerbet reaction (Scheme 1), might be the culprit in shutting down the reactivity of the catalytic system. In order to examine the role of water in the deactivation of the catalyst, two separate experiments were run under the optimized conditions with 10 and 30 mol% of added water. The catalytic mixture with 10 mol% of water (Table 4, entry 1) exhibited a decreased reactivity, converting only 24% of ethanol to *n*-butanol and 3% into *n*-hexanol. The catalytic mixture with 30 mol% of water (Table 4, entry 2) exhibits significantly lower activity providing only a 15% yield of *n*-butanol and 1% of *n*-hexanol. Even the hydrogen production was decreased notably. This clearly suggests that water plays a key role in the catalyst deactivation. To validate this further, about a gram of

3 Å molecular sieves was added at the beginning of the reaction (0.5 mol% [Mn], 25 mol% NaOEt) and the reaction examined under the established conditions (Table 4, entry 3). Although molecule sieves were not expected to be fully efficient at removing all of the water that was formed during the reaction at 150 °C, a slight increase in the formation Guerbet products was observed, with about 33% of the ethanol being converted into *n*-butanol and 6% into *n*-hexanol.

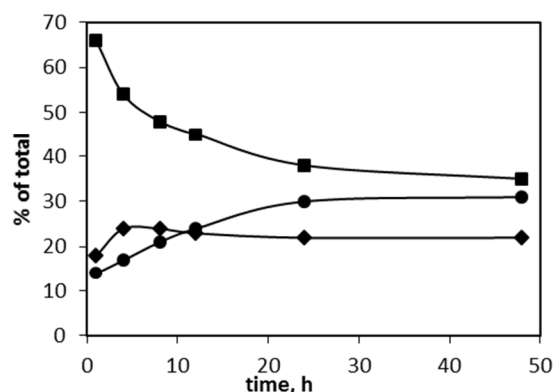


Figure 2. Graphical representation of reaction profile for the Guerbet reaction of ethanol catalyzed by complex 1. Data points from Table 3: ethanol (■), *n*-butanol (●), missing ethanol (= hydrogen gas) (◆).

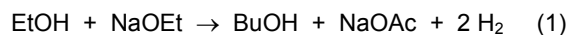
Table 4. Investigation of Guerbet reaction of Ethanol catalyzed by complex 1^a

Entry	EtOH left %	<i>n</i> -BuOH formed %	Higher alcohols ^b %	Missing EtOH %
1 ^c	48	24	6	22
2 ^d	66	15	2	17
3 ^e	23	33	13	31
4 ^f	77	9	1	13
5 ^g	77	13	1	9
6 ^h	47	23	9	21

^aAll the reactions are carried out in a Schlenk bomb with 0.4 mL (6.85 mmol) of ethanol, at 150 °C for 24 h, with 0.5 mol% 1 and 15 mol% NaOEt as base. The conversions and yields are based on the GC analysis of at least two reaction samples. ^bMixture of 2-ethyl butanol, 1-hexanol, 2-ethyl hexanol and 1-octanol (See SI for the distribution). ^c10% water w.r.t. EtOH was added. ^d30% water w.r.t. EtOH was added. ^e1 g of molecular sieves were added. ^fVolatiles evaporated after 24h, fresh EtOH (0.4 mL) was added and reaction was carried for additional 24h at 150 °C. ^gVolatiles evaporated after 24h, fresh EtOH (0.4 mL), 0.5 mole% of ligand were added and the reaction was carried for additional 24h at 150 °C. ^hVolatiles evaporated after 24h and fresh NaOEt (25 mol%), EtOH (0.4 mL) were added and the reaction was carried for additional 24h at 150 °C.

After witnessing the effect of water on the catalytic reaction, we were interested to know if its effect was to deactivate the manganese catalyst or to interfere with the base, NaOEt, or both. To investigate these possibilities, the catalytic reaction was run under optimized conditions (0.5 mol% [Mn], 25

mol% NaOEt, 150 °C, 24h) and after the completion of reaction all the volatiles were evaporated under vacuum for several days to give a dry powder. To this dry mixture was added fresh ethanol and the reaction was heated for 24h at 150 °C (Table 4, entry 4). Analysis of the sample showed only about 9% of the ethanol was converted into *n*-butanol (along with some traces of higher alcohols), indicating the deterioration of the catalytic species during the first run (24 h). In a second experiment, 1 equivalent of the ligand bis[(2-diisopropylphosphino)ethyl] amine was added to the catalyst mixture along with fresh ethanol (Table 4, entry 5), to see if reformation of the complex was possible. This resulted into a slight improvement in the *n*-BuOH formation (13%). However, to our surprise, when a fresh batch of NaOEt (25 mol%) was loaded along with fresh EtOH (Table 4, entry 6), a boost in catalytic activity was observed providing 23% of *n*-butanol and other higher alcohols. These observations indicate that it is the base, NaOEt, which likely decomposes during the reaction and hence causes a decrease in catalytic activity. Upon careful analysis of the solid products of the optimized catalytic reaction (0.5 mol% [Mn], 25 mol% NaOEt, 150 °C, 24h) (as in Table 3, entry 5), we found that about 32% of the NaOEt was converted into NaOAc, via Cannizzaro routes, promoted by the free water formed during the reaction.¹⁰ The water produced in the Guerbet process reacts with NaOEt to make NaOH, which enables the Cannizzaro reaction to make NaOAc. No ethyl acetate is observed by GC. This loss of base affects the catalytic performance (Table 1, entry 7). Thus, the net reaction is shown in equation 1. The observed stoichiometry is slightly less than this equation predicts, however, probably because the Cannizzaro reaction is not 100% efficient. Some EtOH loss due to evaporation during handling of the sample (3-4%) was unavoidable (see control in Table 1, entry 8).



In a catalytic cycle developed for the dehydrogenation of alcohols involving the current manganese system Beller^{17a} proposed the formation of an amido complex upon treatment of the complex **1** with the base, which actually serves as the active-form of the catalyst. In order to validate the formation of the same catalytic species under our reaction conditions, we prepared the amido complex, $[\text{N}(\text{CH}_2\text{CH}_2\text{P}^i\text{Pr}_2)]\text{Mn}(\text{CO})_2$ (**2**) independently¹⁹ and employed it in the catalytic reaction under the optimized conditions (Table 5, entry 2). This species exhibited a slight lower catalytic activity than complex **1**, which may be correlated to the relatively lower stability of the compound. This is in line with the observations made from Gauvin et al. in the related dehydrogenative coupling reactions.²⁰

In the present catalytic reactions the high base loading (25 mol%, 50 equiv) is essential in order to achieve a better reactivity. However, we see that the amido complex **2**, which is a proposed active species, can be prepared by treating the complex **1** with only 1.5 equivalent of NaOEt. This indicates that the high concentration of base are actually not needed to generate the active species but may perhaps be required to maintain the catalytically active species during the course of the reaction. The low conversions observed in the catalytic reactions performed with the independently prepared active-species (complex **2**) and 12.5 mol% of NaOEt (Table 5, entry 3) further supports this notion.

In order to investigate the influence of the amino proton on the PNP framework of the ligand, and the cooperativity be-

tween the metal and ligand, the N-methylated analog of complex **1** ($[\text{MeN}(\text{CH}_2\text{CH}_2\text{P}^i\text{Pr}_2)]\text{Mn}(\text{CO})_2\text{Br}$ (**3**))²¹ was prepared and employed it in the Guerbet reaction (Table 5, entry 4). Interestingly, this complex exhibited significantly lower activity with respect to complex **1**, giving only 6% of *n*-butanol. This result indicates a strong influence of the metal–ligand cooperativity over the catalytic activity in the case of the N–H analogs. The lower catalytic activity exhibited by this N-methylated complex suggests the presence of a minor alternative path in the catalytic reaction as suggested by Pub and Gordon in related chemistry.²² On the other hand, a negative mercury drop test indicated that neither of the catalysts **1** or **3** produces products via a heterogeneous pathway.²³

Table 5. Guerbet reaction of Ethanol catalyzed by Complexes 1 - 8^a

Entry	Cat. (Mol%)	Base Mol%	EtOH left %	<i>n</i> -BuOH formed %	Higher alcohols formed ^b %	Missing EtOH %
1	1 (0.5)	25	38	30	10	22
2	2 (0.5)	25	45	26	8	21
3	2 (0.5)	12.5	57	19	4	20
4	3 (0.5)	25	73	6	1	20
5	4 (0.5)	25	38	27	8	27
6	5 (0.5)	25	28	34	16	22
7	6 (0.5)	25	67	10	2	21
8	7 (0.5)	25	51	10	2	37
9	8 (0.5)	25	55	9	2	34

^aAll the reactions are carried out in a Schlenk bomb with 0.4 mL (6.85 mmol) of ethanol, at the said temperature for the noted period of time. The conversions and yields are based on the GC analysis of at least two reaction samples. ^bMixture of 2-ethyl butanol, 1-hexanol, 2-ethyl hexanol and 1-octanol (See SI for the distribution).

In order to study the steric and electronic influence of ligand substituents on the catalytic activity of the manganese pincer catalyst, a series of complexes bearing different substituents on the phosphorus atoms of the PNP ligand were prepared and subsequently employed in the catalysis under the established reaction conditions. Complex **5**, which bears slightly bulkier but flexible cyclohexyl substituents $[\text{HN}(\text{CH}_2\text{CH}_2\text{PCy}_2)]\text{Mn}(\text{CO})_2\text{Br}$ (**5**)^{17c} showed a slightly lower activity providing about a 27% yield of *n*-butanol (Table 5, entry 5). Complex, $[\text{HN}(\text{CH}_2\text{CH}_2\text{PPh}_2)]\text{Mn}(\text{CO})_2\text{Br}$ (**6**)²¹ turned out to be the best, providing about a 34% yield of *n*-butanol and 8% of *n*-hexanol (Table 5, entry 6). Complex, $[\text{HN}(\text{CH}_2\text{CH}_2\text{P}^i\text{Bu})_2]\text{Mn}(\text{CO})_2\text{Br}$ (**4**)²⁴ bearing bulky *t*-butyl groups was found to be catalytically poor under the given conditions, providing only about 10% of the desired *n*-butanol (Table 5, entry 7). The complex, $[\text{HN}(\text{CH}_2\text{CH}_2\text{PAD}_2)]\text{Mn}(\text{CO})_2\text{Br}$ (**7**) bearing super bulky adamantyl groups was also found to be poorly reactive converting only about 10% of ethanol into *n*-BuOH (Table 5, entry 8). Its deprotonated version, $[\text{N}(\text{CH}_2\text{CH}_2\text{PAD}_2)]\text{Mn}(\text{CO})_2$ (**8**) also shows similar reactivity under the established conditions (Table 5, entry 9).

Although lower activities of the complexes bearing bulky substituents clearly indicates the profound steric influence of the phosphorus substituents on the catalysis, the electronic effect might also be playing a key role. Superior activity of the phenyl substituted complex over cyclohexyl or isopropyl versions gives hints in this direction.

In conclusion, we have developed an efficient manganese pincer-catalyzed Guerbet process for the production of biofuel from ethanol with a high conversion rate and selectivity. The phosphorus substituent and the cooperativity between the metal and ligand N-H moiety were found to play a key role in the catalytic activity. High loading of base (25 mol %) is required to maintain the catalytic activity and the water which formed during the reaction was found to promote the major deactivation pathway. Detailed experiments aimed at further mechanistic insight and improvements are in progress in our lab. Since this is the first example of a manganese catalyst being successfully employed in the Guerbet reaction of ethanol, this finding promotes the development of new advanced early transition metal based catalysts for this process.

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ASSOCIATED CONTENT

Supporting Information. The SI for this article includes full experimental procedures with additional data on the products described in Tables S1-S5. Table S6 summarizes results with Fe and Co PNP catalysts. X-ray tables for the structure of complexes **7** and **8**, deposited in the Cambridge Crystallographic Database (CCDC# 1580557-8). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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