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SYNTHESIS OF A DIRHODIUM TETRAPHOSPHINE CATALYST AND THE EFFECT OF VARIOUS H2/CO RATIOS ON THE CATALYST

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SYNTHESIS OF A DIRHODIUM TETRAPHOSPHINE CATALYST AND THE EFFECT OF VARIOUS H_2/CO RATIOS ON THE CATALYST

Honors Thesis
The Department of Chemistry
by
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Dedication

I dedicate this work to my Mom, Yvonne Saltzman, and Dad, Terry Sweeney. I wouldn't have had the opportunity to do this research if it wasn't for them constantly pushing me to do my best. Thank you for your support and love throughout the years. Love you both very much.

Acknowledgements

I hope that I have not forgotten anyone who has supported me throughout my trials and tribulations in seeking my undergraduate degree and this honors thesis. I am also thankful for the people who put up with me being stressed out and being in the lab all summer.

Katie Scoggin, Kristi Richey, and Christina Boeke: Thank you for being my support and comfort during my years at LSU. Thank you for putting up with me when I was stressed out, tired, or aggravated because of my research. Thank you for encouraging me to finish my honors thesis and to always work hard. Also thank you for not pressuring me with distractions that could have prevented me from finishing my research or honors thesis.

Dr. Ward and Dr. Oey: Thanks for encouraging my love for science and helping me to realize my passion for chemistry. If it wasn't for you two I may have given up after my first chemistry test at LSMSA. I will never forget the help you gave me that started my journey which led to the completion of this document.

Professor George Stanley: Thank you for your patience with me. Thank you for guiding me in my research. Thank you for having the confidence in my ability and allowing me to work on projects with minimal supervision and to have the ability to guide some of my peers. Thank you for allowing me to present at regional and national meetings. Thank you for helping me get into graduate school and have the experience needed to do well.

Catherine Thomas: Thank you for guiding me and supervising me these four years. Thank you for also giving me advice on research, classes, and personal areas. Thank you for having the patience and confidence in me when I messed up or took a little longer to catch onto something.

The Stanley Group: Thanks for allowing me to have room in the lab and to share the chemicals and glove box. Thanks you respecting me and treating me like another researcher and not like an undergraduate.

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Abstract

The first part of this honors thesis concerns the synthesis and testing of a bimetallic homogenous catalytic system based on a tetraphosphine ligand system. The procedure involves four different aspects: ligand synthesis, separation of *racemic*- and *meso*-et, ph-P4 ligand, preparation of the dirhodium catalyst, and hydroformylation catalysis. The research introduced me to air-sensitive organometallic synthetic procedures, organophosphine and transition metal chemistry, and catalysis concepts of which I had no prior knowledge of. I became proficient in the inert atmosphere synthetic techniques, a variety of laboratory equipment, and was able to complete most of the project with minimal assistance. I successfully synthesized the binucleating tetraphosphine ligand, dirhodium catalyst precursor, and studied bimetallic cooperativity in hydroformylation catalysis. For future research, we hope to perform additional catalytic runs, compare the catalyst to other monometallic rhodium catalysts, and to determine better reaction conditions for the hydrogen producing aldehyde-water shift catalysis.

The second part of this honors thesis concerns the study of modern monometallic and bimetallic rhodium bisphosphine catalysts and the effect of various H_2/CO ratios. The catalysts and their effects were initially studied by graduate student Bobby Barker at Louisiana State University under Dr. George Stanley. After reviewing his research there were some experimental issues that may have caused his data to be inaccurate. I built an autoclave system and created new procedures that should eliminate the inaccuracies found in Dr. Barker's research.

Since it is believed that the H_2/CO ratios were not properly used experimentally, it is very possible that the turnover rates of 1,000 equivalents and linear to branched ratios Dr. Barker found are also incorrect. I plan on testing these rates with the new autoclave system and procedures. I assume that the turnover rates should be similar to the ones Dr. Barker found, since they follow the theoretical expectations. I also plan on testing the maximum efficiency of the catalysts. This will be accomplished by using 10,000 equivalents of alkene in a standard hydroformylation run. I am hoping to get the catalyst to reach a turnover number of 10,000 equivalents of alkene converted to aldehyde.

Chapter 1. Introduction

1.1. Homogenous and Heterogeneous Catalysis

Heterogeneous catalysis is where the catalyst is in a different phase (solid, liquid, and gas) relative to the reactants and products. Solid heterogeneous catalysts provide a surface for the chemical reaction to take place on. Homogeneous catalysis is where the catalyst is a discrete molecular species in the same phase as the reactants, typically in solution. Good homogeneous catalytic systems have several advantages relative to heterogeneous catalytic systems. These include: far more selective for a single product; far more active; more easily studied from chemical and mechanical aspects due to the solution phase; and more easily modified for optimizing selectivity and activity. The main disadvantages of homogeneous systems are that they are far more sensitive to permanent deactivation and the engineering problems related to product/catalyst separation. Despite the advantages of homogeneous systems in relation to heterogeneous systems, approximately 95% of chemical and petrochemical industries use heterogeneous catalytic systems.[2]

In determining the efficiency of a homogeneous or heterogeneous catalyst, there are a few factors that chemists look at: the turnover frequency (TOF), the total number of turnovers (TON) performed before catalyst deactivation, selectivity for products, and the reaction conditions. The higher the number of turnovers the better the catalyst. The turnover frequency (TOF) represents the number of passes through the catalytic cycle per unit time (typically sec, min, or hrs). This number is usually determined by taking the number of moles of product produced, dividing that by the number of moles of catalyst

used in the reaction, and then dividing that by the time to produce the given amount of product.[2] The units, therefore, are usually just *time*$^{-1}$.

1.2. Hydroformylation

Hydroformylation, or oxo, is one of the most important homogeneous industrial processes in use today. The reaction involves the reaction of alkenes, carbon monoxide, and hydrogen to produce aldehyde products.[3]

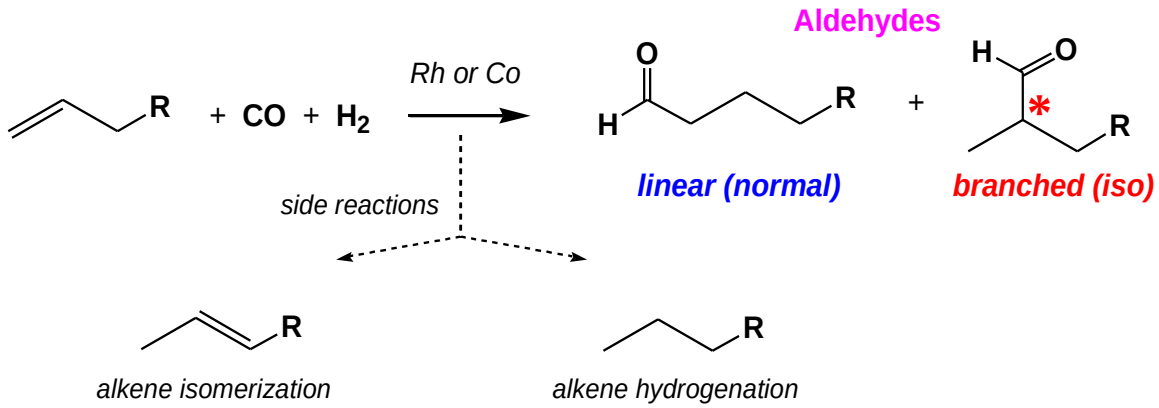


Figure 1.2: Standard Example of a Hydroformylation Reaction

As can be seen above in Figure 1, hydroformylation can give two aldehyde products. The products will be either a linear (normal) or branched (iso) aldehyde, however the linear is generally preferred by industry for bulk commodity chemicals.[3]

1.3. Rhodium Catalysis

The proposed $[Rh_2H_2(\mu\text{-}CO)_2(rac\text{-et,ph-P4})]^{2+}$ homogeneous catalyst system discovered in Prof. Stanley's laboratory can be resolved into pure enantiomers and has been shown to be a very good asymmetric hydroformylation catalyst for vinyl esters with 85% enantiomeric excess (ee) and 4:1 branched to linear

regioselectivity for vinyl acetate. This bimetallic catalyst is based on a binucleating tetraphosphine ligand (*racemic*- and *meso*-et,ph-P4) that is designed to both bridge and chelate two transition metal centers, producing bimetallic complexes that only have a single, conformationally flexible bridging group.

The research that will be presented in this paper is concerning the synthesis and testing of the catalytic system. The research involves four different aspects: ligand synthesis, separation of racemic- and meso-et, ph-P4 ligand, preparation of the dirhodium catalyst precursor, and hydroformylation catalysis. Although asymmetric hydroformylation was the initial goal of this research, I focused my actual work on the "regular" (non-chiral) ligand and catalyst to gain experience with air-sensitive synthetic methods and the use of the catalytic autoclaves. I intend to continue this project during the school year with chiral asymmetric hydroformylation as my ultimate goal.

The synthesis of the tetraphosphine ligand that is the foundation for the dirhodium catalyst system is a fairly long and complicated process involving air-sensitive synthetic techniques. My first goal was to become proficient with it and to be able to complete it without any assistance. The future resolution of *racemic*-et, ph-P4 ligand into pure *R,R*- and *S,S*- enantiomers will use a chiral preparatory HPLC column and an automatic collection HPLC system to isolate the two enantiomers of the tetraphosphine ligand. Prof. Stanley intends to purchase this system within the next year.

The dirhodium catalyst preparation step is relatively simple as it only involves reacting the *racemic*-et,ph-P4 ligand with two equivalents of $[Rh(nbd)_2](BF_4)$ (nbd = norbornadiene) to make the catalyst precursor, $[Rh_2(nbd)_2(rac\text{-et,ph-P4})](BF_4)_2$. This reaction usually occurs with close to quantitative yields. The last step is the catalytic testing – the hydroformylation of 1-alkenes to produce aldehyde products. GC/MS (and sometimes NMR) is used to determine the product distributions. Previous runs were done using pure acetone solvent, but Prof. Stanley's group has discovered that an acetone/water solvent mixture (30% water by volume) is far more effective at dramatically reducing catalyst degradation reactions and, increasing both the rate and overall selectivity of the hydroformylation catalysis.

1.4. Asymmetric Bimetallic Hydroformylation

Hydroformylation produces two isomeric products: the linear aldehyde and the branched aldehyde (Figure 1.2). In the case of asymmetric hydroformylation the branched products have a new chiral center alpha to the carbonyl of the aldehyde for most alkenes. For most industrial applications, the linear aldehyde product is the desirable form of the aldehyde. However, branched aldehydes and related compounds are desirable in pharmaceutical and fine chemical markets, assuming that one can control the chirality.[1] One example of this is the pain reliever naproxen (also known as Aleve). *(R)*-naproxen is a deadly liver toxin, while *(S)*-naproxen has the desired anti-inflammatory characteristics. Asymmetric hydroformylation (Figure 2) is one way in which *(S)*-naproxen could be selectively synthesized.

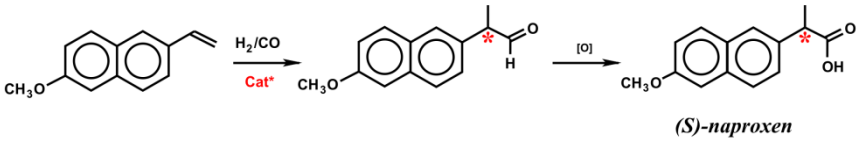


Figure 1.4: Hydroformylation Reaction for *(S)*-naproxen

A desirable asymmetric hydroformylation catalyst would produce high-branched regioselectivity along with enantioselectivity (ee). The ee is defined as:

$$ee = \frac{|R - S|}{R + S} \times 100\%$$

A catalyst that makes an equal amount of *R* and *S* enantiomers has 0% ee. 85% or higher is generally considered a good ee, depending on what the best known catalyst can do relative to that being reported.

1.5. References

[1] Barker, Bobby L. "Separation and in Situ Catalytic Testing of a Dirhodium Tetraphosphine Catalyst." Asymmetric Hydroformylation and Tetraphosphine Ligand Separations: Introduction, pg. 16 (2005).

[2] Stanley, George. "Organometallic Chemistry: Lecture Notes." Catalysis Intro, pgs. 4 8 (2005).

[3] Stanley, George. "Organometallic Chemistry: Lecture Notes." Hydroformylation, pg. 1 and 21 (2005).

Chapter 2. Asymmetric Hydroformylation and Tetraphosphine Ligand Separations Procedures

2.1 Introduction

The entire process of making the catalyst is actually a four-step process. It involves the synthesis of the ligand (shown in figure 3 below), separation of racemic and meso-et, ph-P4 ligand, dirhodium catalyst precursor preparation, and hydroformylation catalysis. Each step will be discussed in detail concerning the actual reactions and techniques used.

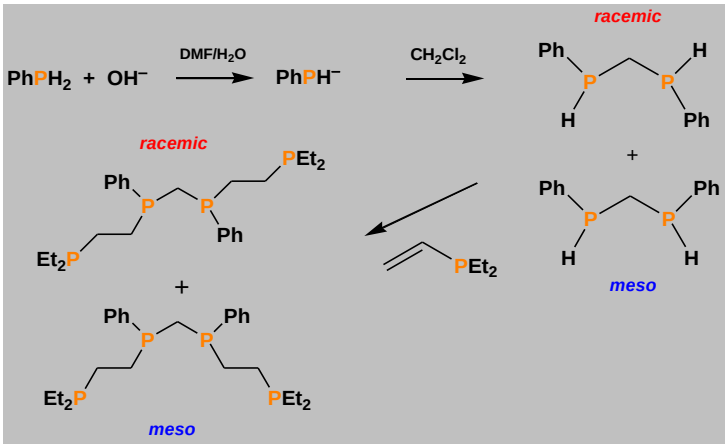
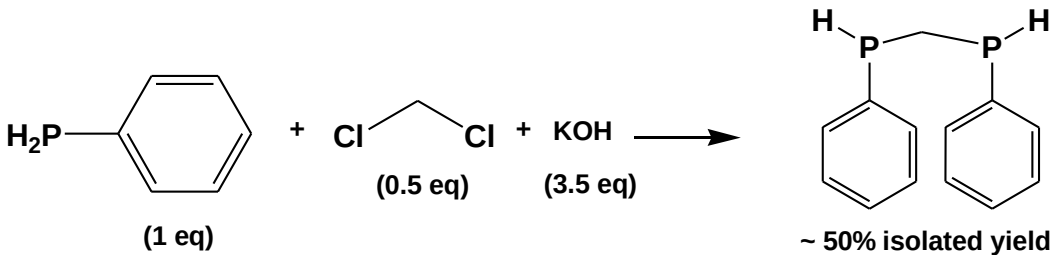


Figure 2.1: The overall reaction for the synthesis of the *racemic* and *meso*-et, ph-P4 ligand

Ligand Synthesis:

The ligand is made from "bridge", $Ph(H)PCH_2P(H)Ph$, and vinyldiethylphosphine, which both have to be made in separate steps. The bridge is made in one step, while the vinyldiethylphosphine requires a two-step synthesis.

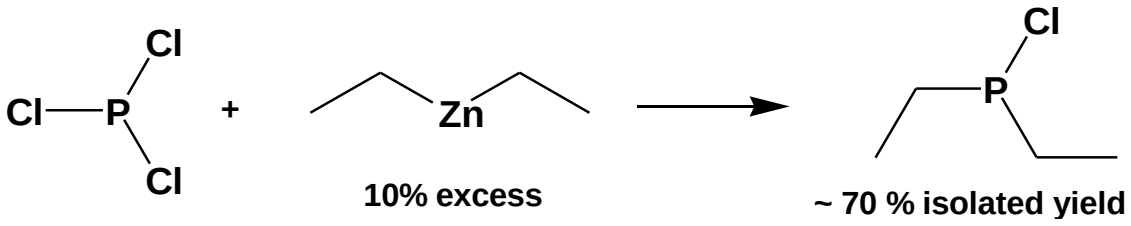
2.2 Ph(H)PCH$_2$P(H)Ph, "Bridge" synthesis:[4]



1. Weigh a 500 mL Schlenk flask for the reaction and product collection and a 250 mL Schlenk flask for the KOH solution.
2. In a drybox, weigh out CH_2Cl_2 (0.5 eq) and $PhPH_2$ (1 eq). Add both to a Schlenk flask with a stirbar, close with septum, and remove from box.
3. Degas DMF via N_2 sparging (100 mL for 20g $PhPH_2$) and transfer to prepared Schlenk flask via canula. Cool flask in ice bath.
4. Prepare saturated KOH (aq) solution in degassed deionized H_2O (3.5 eq KOH). Add drop wise via canula after cooling solution in ice bath for 30 minutes. While flasks are in ice bath, add KOH to the stirred DMF solution.
5. Remove ice baths and allow reaction to warm to reaction temperature with stirring. Should stir at least two hours under N_2, however can stir overnight.
6. After solution turns completely colorless with white precipitate, add approximately 100 mL degassed deionized H_2O to react with any remaining $PhPH_2$ and dissolve solid KCl.
7. Remove bridge via degassed pentane extraction (canula transfers) into the preweighed Schlenk flask.

8. Remove solvent via vacuum and warm bridge to 80^{o} C for approximately one hour in a hot water bath with vacuum to remove any impurities. Do no heat above 85^{o} C.
9. Add hexane to bridge and filter through a Schlenk frit to remove oxidized bridge, and then remove hexane via vacuum.

2.3 Diethylchlorophosphine:[5]



1. In glove box, charge a Schlenk flask with PCl_3, a stir bar, and an equal volume of t-glyme. Use a large graduated cylinder to make pouring and measuring easier and use the same graduated cylinder for t-glyme as for PCl_3 to rinse out remaining PCl_3. Close flask with septum.
2. In glove box, charge a second Schlenk flask with t-glyme from a different graduated cylinder (equal volume as intended for $ZnEt_2$). Then quickly and carefully measure and add $ZnEt_2$ using same graduated cylinder. Close flask with septum. ($ZnEt_2$ is highly air sensitive and may smoke slightly).
3. Remove flasks from glove box and cool in ice bath for at least 30 minutes. With vigorous stirring in PCl_3 flask, add $ZnEt_2$ drop-wise via cannula at the rate of approximately 2 drops per second. Keep ice baths cold.

4. After addition is complete, use trap-to-trap distillation to collect product (shown in Figure 4 below).

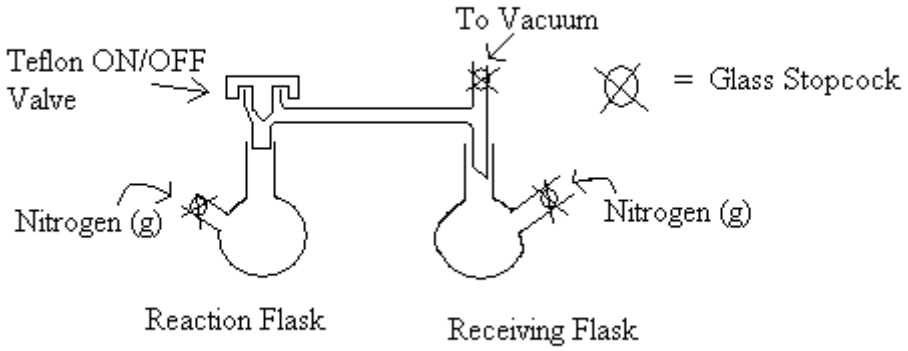
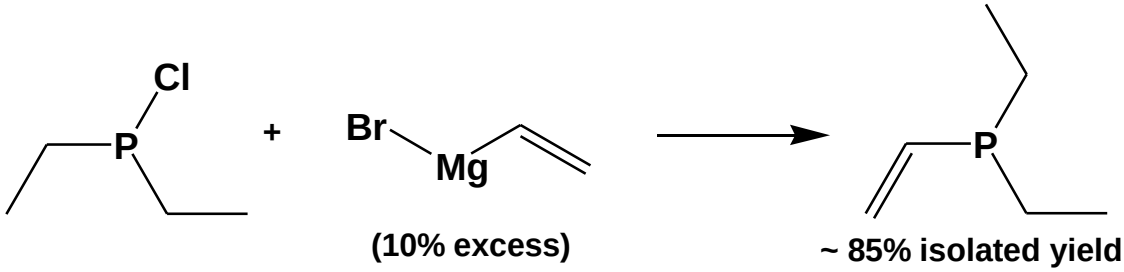


Figure 2.3: Trap-to-trap distillation setup

5. Flush N_2 through reaction flask while quickly adding the trap-to-trap apparatus with the Teflon valve open (to allow N_2 flow) and then quickly close the Teflon valve. Attach a clean pre-weighed Schlenk flask to receiving end. Keeping the Teflon valve closed, attach trap-to-trap stopcock to vacuum and evacuate receiving flask. Cool receiving flask in liquid N_2 bath.
6. With both N_2 stopcocks closed, open the Teflon valve. Slowly and carefully open vacuum stopcock to bring reaction flask to boiling. Do not allow reaction to 'bump" into the trap-to-trap apparatus. Heat reaction flack to approximately 80^o C in a warm water bath to get the entire product to distill over. Continue heating until solution stops boiling.

7. After distillation is complete, fill system with N_2 and allow receiving flask to thaw. After thawed, flush N_2 through receiving flask while you disconnect it and put a septum in place. Store in freezer.

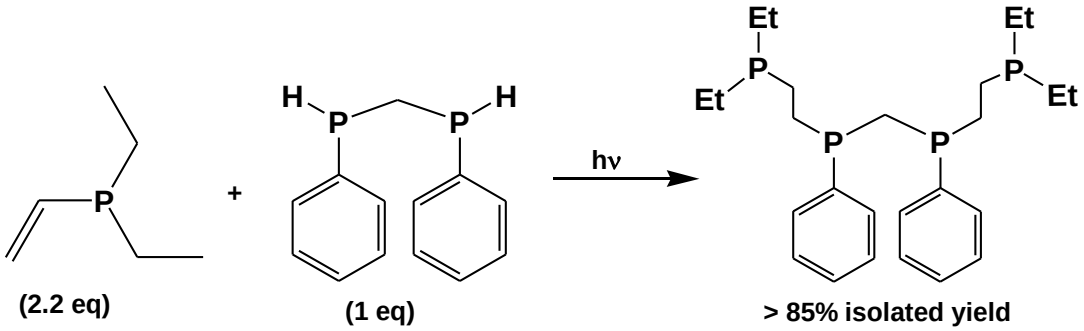
2.4 Vinyldiethylphosphine:[6]



1. In the glove box put 100 mL 1M VinylMgBr in THF (clear brown liquid) into a 500 mL two-necked Schlenk flask. Add 100 mL t-glyme and a stir bar into the 500 mL schlenk flask. It is very important that the vinylMgBr solution (in THF) is clear of any precipitate. Add a trap-to-trap to the middle neck flask and a septum to the side neck. Be sure the Teflon valve is closed.
2. In the glove box charge a 250 mL Schlenk flask with $ClPEt_2$ (12 mL $\rightarrow$ 0.09 mol) and then put 100 mL of t-glyme. Close the flask with a septum.
3. Remove both flasks from the glove box.
4. To the receiving end of the trap-to-trap apparatus, attach a tiny flask simply to close off the system. Apply vacuum to the vinylMgBr solution via the vacuum stopcock and remove the THF and collect it in the line trap. Weigh the THF to determine the volume of THF removed. Must remove at least 95 mL. Heat the vinylMgBr solution to approximately 80^oC with a warm water bath and open the Teflon valve.

5. After solvent exchange is complete, fill the vinylMgBr flask with N_2 and close Teflon valve. Cool both the vinylMgBr and the $ClPEt_2$ solutions in ice baths for approximately 30 minutes. Then, add the $ClPEt_2$ via canula drop-wise in the stirring reaction flask.
6. Collect the vinyldiethylphosphine via a trap-to-trap distillation into a clean preweighed Schlenk flask. Keep the reaction below 85°C, because t-glyme may distill over at 90°C.

2.5 *rac*- and *meso*-et,ph-p4 Ligand:[7]



1. Under nitrogen atmosphere, combine one equivalent of bridge to 2.2 equivalents of vinyldiethylphosphine in a small (less than 50 mL) Schlenk flask with a stir bar.
2. Expose to the Xenon arc lamp while stirring for at least 8 hours, but longer exposure times may ensure complete reaction. Test for complete reaction via ^{31}P NMR (solution in hexanes). All bridge must have reacted!
3. If unreacted bridge remains, continue UV exposure until all bridge has reacted. The addition of more vinyldiethylphosphine is okay, but should not be necessary if excess was originally used.

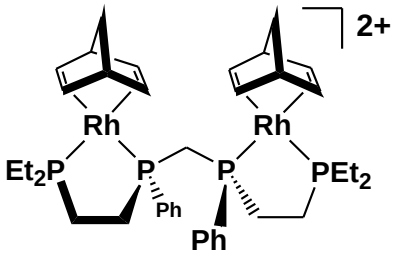
4. After all of bridge has reacted, remove excess vinyldiethylphosphine by applying vacuum to the reaction flasks for approximately one hour, while heating the flask to about 75^{o}C by a warm water bath. Save the collected vinyldiethylphosphine for future reactions (it should be pure).

2.6 Partial Separation of racemic and meso et,ph-P4:

1. Separate the racemic and meso mixture by adding hexane to the solution and placing it in the freezer overnight.
2. Once the meso ligand forms white precipitate, remove the racemic ligand from the meso ligand via canula and place in another flask.
3. Remove excess hexane under reduced pressure; add more hexane to the solution and place in freezer.
4. Process is continued until mixture is >80% racemic.

2.7 Catalyst Precursor:

The ligand is part of the catalyst precursor, which will be combined with other compounds to make what we believe is the active catalyst system $[Rh_2H_2(\mu\text{-}CO)_2(rac\text{-}et,ph\text{-}P4)]^{2+}$. The catalyst precursor is shown below.



[rac-Rh_2(nbd)$_2$(et, ph-P4)]
(catalyst precursor)

Figure 2.7. The molecular structure of the catalyst precursor.

2.8 Synthesis of Rh(nbd)(acac):[1]

1. Add $Rh(CO)_2(acac)$ and norbornadiene to a 250 mL schlenk flask. Attach a reflux condenser to the flask and heat while stirring in an oil bath at 90^oC for three hours.
2. After reaction is complete, cool, filter, and remove the unreacted norbornadiene by vacuum. Use 10 mL of THF and the heat gun to dissolve the powder and then add 3 or 4 seconds of hexane.
3. Filter using a fritted funnel, cap funnel, and place crystals in the glove bow freezer overnight.

2.9 Synthesis of $[Rh(nbd)_2](BF_4)$:[2]

1. Dissolve Rh(nbd)(acac) in 30 mL of THF in the glove box. Cool solution to -20^oC by placing in freezer. After solution is cooled, add $HBF_4 \bullet OEt_2$ drop wise.
2. Add norbornadiene via a cannula into the reaction flask. Place flask in freezer to cool to -20^oC for two hours. Collect the precipitate by filtration.

2.10. Synthesis of $[Rh_2(nbd)_2$(*rac*-et,ph-P4)$](BF_4)_2$:[3]

1. Dissolve the $[Rh(nbd)_2](BF_4)$ in 10 mL of CH_2Cl_2 in a 250 mL flask. Dissolve the *rac*-et,ph-P4 in 5 mL of CH_2Cl_2.
2. Add the *rac*-et,ph-P4 drop wise to the $[Rh(nbd)_2](BF_4)$ with the solution stirring for 30 minutes. Remove the CH_2Cl_2 under vacuum.

3. Heat the red-orange solid slightly and add acetone drop wise (be careful the pressure might pop off the septum). Put in freezer overnight and allow the solid to crystallize.

2.11. Hydroformylation Runs:

The two diastereotopic forms of the et,ph-P4 ligand, *racemic* and *meso*, are produced from the synthesis of the ligand and are shown below.

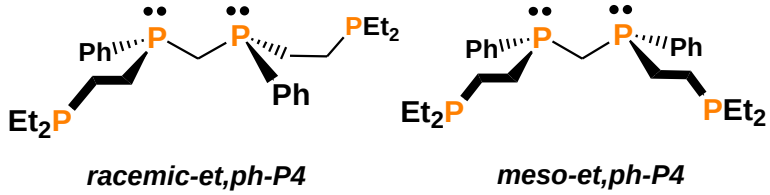


Figure 2.11. The diasteromeric et,ph-P4 ligands

1. 1mM [*rac*-$Rh_2(nbd)_2$(et,ph-P4)]$^{2+}$ in 80 mL 30% water/acetone is placed in an autoclave.
2. The autoclave is heated to 90°C and the catalyst solution soaks under H_2/CO gas (90 psig) for 20 min with stirring (1000 rpm).
3. 1-hexene (1000 equivalents) is added from an external stainless steel reservoir and data is collected until olefin is consumed.
4. Samples are collected during and at the end of runs for GC analysis.

2.12. Results

In the synthesis of the bridge, we used 15.093 grams $PhPH_2$, 5.832 grams CH_2Cl_2 (DCM), and 26.27 grams KOH. When making the bridge there is a color and state change

during the addition of the KOH to the DMF solution, the reaction will turn bright yellow and from a solid precipitate. The oxidized bridge will be present as a solid, but the desired $Ph(H)PCH_2P(H)Ph$ bridge will be a clear colorless liquid after the hexane is removed. The molecular weights for the compounds in the reaction are as follows: CH_2Cl_2 is 89.83 g/mol, KOH is 56.11 g/mol, and the $Ph(H)PCH_2P(H)Ph$ bridge is 232.20 g/mol. The expected chemical shifts for the ^{31}P NMR of the *rac*- and *meso*-$Ph(H)PCH_2P(H)Ph$ bridge are -53 ppm and -54 ppm and Figure 2.12a shows that there are indeed chemical shifts at -53.1 ppm and -54.1 ppm. The typical percent yield is approximately 40-50%, however we got a slightly better with a 52% percent yield.

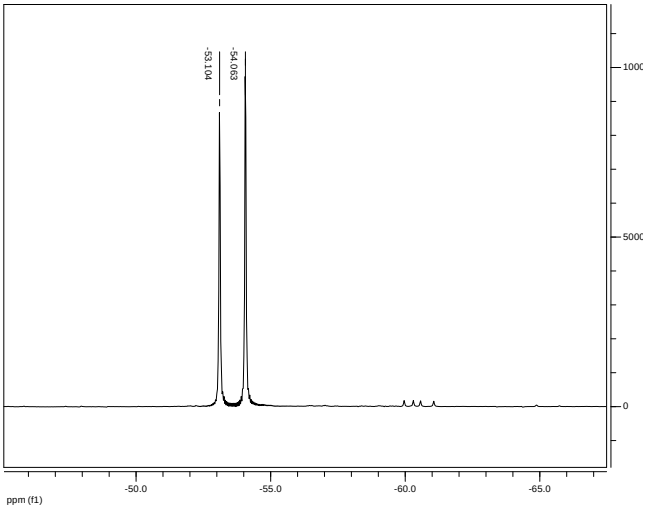


Figure 2.12a The ^{31}P NMR of the $Ph(H)PCH_2P(H)Ph$ bridge shows chemical shifts at -53.1 ppm and -54.1 ppm for the *racemic* and *meso* diastereomers.

In the synthesis of the diethylchlorophosphine, we used 21.0 grams PCl_3 in 30mL of t-glyme and 20.071 grams $ZnEt_2$ in 35mL of t-glyme. The $ClPEt_2$ is a clear colorless liquid, which should be stored in the freezer. The molecular weights for the compounds in the reaction are as follows: PCl_3 is 137.5 g/mol, $ZnEt_2$ is 123.5 g/mol, and $ClPEt_2$ is

124.55 g/mol. The expected chemical shift for the ^{31}P NMR is 112 ppm, however small amounts of the unknown impurity with a 66 ppm chemical shift is considered okay. The expected percent yield for this reaction is approximately 70% and we got an isolated yield of 83%.

In the synthesis of the vinyldiethylphosphine, we used 15.758 grams $ClPEt_2$ and 140.0 mL of vinylmagnesium bromide, $H_2C{=}CHMgBr$. When the t-glyme is added to the vinylMgBr, a white precipitate forms in the flask. When the t-glyme is added to the 250 mL $ClPEt_2$ charged Schlenk flask the solution becomes clear and colorless. When the $ClPEt_2$ is added to the reaction flask there is a color change to light yellow and a white precipitate forms. The vinyldiethylphosphine is a clear colorless liquid with a molecular weight of 116.14 g/mol. The expected chemical shift for the ^{31}P NMR is –18 ppm and Figure 8 shows a chemical shift at -17.8 ppm. The expected percent yield for the reaction is 85+%, however it will contain some THF that cannot be easily separated. We got an isolated yield of 75%.

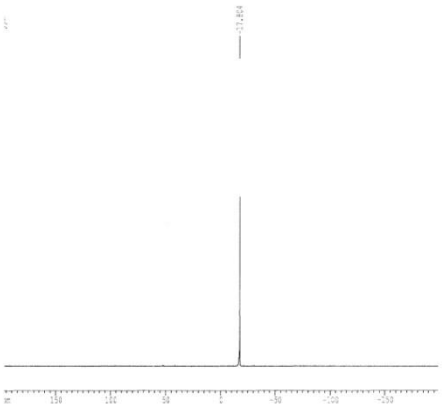


Figure 2.12b: The ^{31}P NMR of the vinyldiethylphosphine sample shows a chemical shift at -17.8 ppm.

When photolyzing the vinyldiethylphosphine and the bridge to prepare the final et,ph-p4 ligand, the reaction mixture becomes more viscous as the reaction proceeds. When testing to determine if all of the bridge has reacted, the expected chemical shift for the bridge in the ^{31}P NMR is –53 ppm and –54 ppm and vinyldiethylphosphine at –18 ppm. The mixed *meso* and *racemic* et,ph-p4 ligand is a colorless oil with a molecular weight of 464.49 g/mol. The expected chemical shifts for the ^{31}P NMR are as follows: the external phosphine arms are around –17 ppm, the internal methylene-bridged *racemic* phosphine resonances are at –25 ppm, and the *meso* bridge phosphines are at –26 ppm. Figure 2.12c below shows that the external phosphines are at -15.8 ppm and -16.7, the *racemic* bridge is at -24.2 ppm, -24.5 ppm, and -24.9 ppm, and the *meso* bridge is at -25.1. These chemical shifts are very close to the expected results.

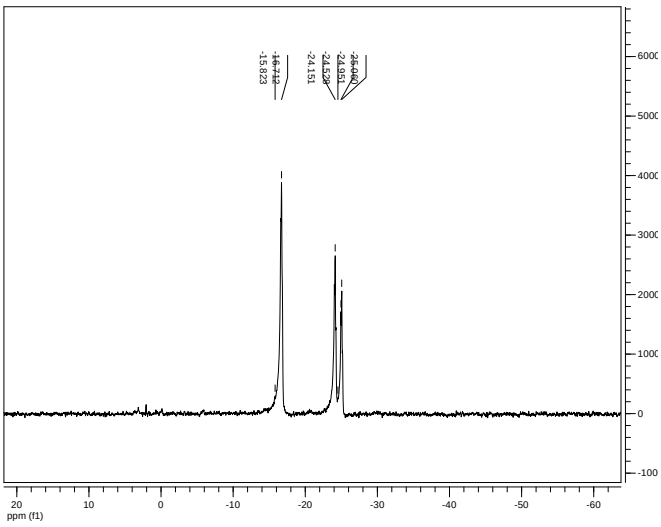


Figure 2.12c: The ^{31}P NMR of the *racemic*- and *meso*-et,ph-p4 ligand sample shows chemical shifts at -25.1 ppm, -24.9 ppm, -24.5 ppm, -24.2 ppm, -16.7 ppm and -15.8 ppm.

When making Rh(nbd)(acac), the solution will turn from dark green to bright yellow. After removing any unreacted norbornadiene, the solution will solidify into a

yellow powder, which crystallized to form yellow crystals. The expected yield for the reaction is 90-95%. The expected chemical shifts for the ^{1}H NMR ($CDCl_3$) are as follows: 1.2–2.0 (m, CH_2 of nbd and CH_3 of acac), 3.8-4.0 (m, CH of nbd), 5.3 (s, CO-CH-CO of acac), 6.2 and 6.7 (br s, and br m, olefinic CH of nbd).

In the making of $[Rh(nbd)_2](BF_4)$, $HBF_4 \bullet OEt_2$ is added drop-wise which causes a color change from yellow to dark red. The addition of norbornadiene caused an orange-red precipitate to form. The expected percent yield for the reaction is 90-95%. The expected chemical shifts for the ^{1}H NMR (CD_2Cl_2) are as follows: 1.7 (br s, CH_2 of nbd), 4.3 (br s, CH of nbd), 5.3 and 5.6 (br m, and br s, olefinic CH of nbd).

In the final step in the dirhodium catalyst precursor synthesis, the red-orange solid will crystallize to yield orange crystals. In the synthesis of the catalyst, we used 2.075 grams $[Rh(nbd)_2](BF_4)$ and 1.287 grams of the racemic-et,ph-p4 ligand. The expected percent yield for the reaction is 88-95%. The expected chemical shifts for the ^{31}P NMR (CD_2Cl_2) are as follows: 47.5 (dm, $J_{P\text{-}Rh}$ = 156 Hz, internal phosphorus atoms) and 58.0 (dd, $J_{P\text{-}P}$ = 23 Hz and $J_{P\text{-}Rh}$ = 150 Hz, external phosphorus atoms). The expected chemical shifts for the ^{1}H NMR (CD_2Cl_2) are as follows: 0.8-1.4 (m, PCH_2CH_3), 1.5-2.1 (m, PCH_2CH_3 and m, PCH_2CH_2P and s, CH_2 of nbd), 2.9 (t, PCH_2P), 3.6-4.2 (br d, CH of nbd), and 4.8 and 5.3 (br s, olefinic CH of nbd).

The last thing I was supposed to do this summer was a hydroformylation run, however I was unable to complete this due to an improperly working glove box. The glove box was needed to make a sample for the NMR and to also prepare the catalyst for the hydroformylation run. Theoretically the catalyst should run very well, since the

NMRs of all the compounds used in the catalyst were at the expected chemical shifts and percent yields.

2.13 Discussion

The purpose of the research was to introduce me to air-sensitive organometallic synthetic procedures, organophosphine and transition metal chemistry, and catalysis concepts that I had no prior knowledge. Due to the research, I became proficient in the inert atmosphere synthetic techniques, and a variety of laboratory equipment and was able to complete most of the project with minimal assistance. I successfully synthesized the binucleating tetraphosphine ligand and dirhodium catalyst precursor and studied bimetallic cooperativity in hydroformylation catalysis. This is supported by the data I collected and presented in this paper. Also, the purity of the ligand and catalyst precursor sample and its components shows that the synthesizing of the compounds was successful.

2.14 Conclusions

1. Successfully synthesized binucleating tetraphosphine ligand and catalyst precursor.
2. Ready to study bimetallic cooperativity in hydroformylation catalysis and to tackle the asymmetric project.

2.15 References:

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Chapter 3. The Effect of Various H_2/CO Ratios on Monometallic and Dirhodium Hydroformylation Catalysis

3.1. Dr. Barker's Research on H_2/CO ratio

Little research has been reported concerning the effect of varying H_2:CO gas ratios on the effect of activity and selectivity of hydroformylation. The only data reported on modern bisphoshine catalysts and the effect of increased H_2/CO ratios was by Dr. Bobby Barker at Louisiana State University.

Anthony *et al* reported that Henry's law constants for H_2 and CO are 1878 and 3382, respectively, in acetone. CO being roughly twice as soluble as H_2 holds true across a broad range of organic solvents, and there is no reason to believe the same would not hold true for the acetone/water solution. The higher solubility of CO in most solvents means that the usual 1:1 ratio of H_2/CO used in academic hydroformylation reactions effectively gives a 1:2 ratio of H_2/CO in solution. Most industrial hydroformylation reactions are run with H_2/CO ratios around 1.2-1.5:1 (Barker, 2005).

Dr. Barker believed that the higher effective concentrations of CO in solution when running with 1:1 H_2/CO (the ratio he used in almost all his studies) could be detrimental to the stability of the dirhodium catalyst discussed above in the Rhodium Catalysis Section. From *in situ* NMR spectroscopic studies it was found that CO is a key played in the fragmentation and deactivation of the catalyst.

Dr. Barker found the importance of hydrogen and CO partial pressures on the selectivity of final products is dramatic. His dirhodium catalyst under a 4:1 H_2/CO ratio increased the aldehyde linear to branched (l:b) regioselectivity from 33:1 (97.1% linear product) to 152:1 (~99.3% linear). This was by far the highest selectivity ever observed,

which put the dirhodium-P4 catalyst in the same league as some of the most selective monometallic hydroformylation catalysts known.

Dr. Barker's research found that CO, H_2, and H_2O have different roles in the fragmentation of his catalyst. The CO concentration (partial pressure) is inversely proportional to selectivity meaning that higher CO partial pressures will favor a lower l:b aldehyde regioselectivity.

When the CO/H_2 ratio was increased to 2:1 and the same standard conditions were used, there was no observed hydroformylation activity. This occurs because either the deactivation equilibrium is favored too much or the saturated 18 e^- complex is formed, which are both inactive for hydroformylation catalysis. Too much CO has long been known to inhibit activity of transition metal complexes toward hydroformylation, however, the lack of any significant catalysis was surprising. The effect of increased hydrogen pressure on the rates hydroformylation has been a mainly positive one. The catalysts had a moderate to dramatic rate and selectivity increase with increasing hydrogen pressure.

Dr. Bobby Barker found that the increase in CO leads to CO induced deactivation of the catalyst systems which eventually leads to no catalytic activity in the dirhodium system. Higher CO pressures in the monometallic systems eventually lead to Rh induced fragmentation pathways. An increase in the hydrogen partial pressure also caused an increase in the reaction rate. However, the increase of CO partial pressure caused a decrease in the effect of any phosphine ligands. The phosphine ligands are sterically directing and they cause an increase in selectivity. However, after reviewing this research there were some experimental issues that may have caused this data to be inaccurate. To

determine the accuracy of the data an autoclave system and new procedures were created to test these results.

3.2 H_2/CO Ratio Set-up and Procedure:

The following are the procedures Dr. Barker used in his hydroformylation runs to determine the effects of the H_2/CO ratios. He used an insulated 300 mL stainless steel reservoir cylinder equipped with an electronic pressure transducer. The stainless steel reservoir is used to store an excess of H_2/CO (usually 800-1200 psig). A thermocouple is located next to the external reservoir (and covered by the insulation) to keep track of its temperature. This cylinder is connected to a Parr model 4560 autoclave (160 mL volume) via an Air Products straight-line dual stage regulator (250 psig maximum deliverable pressure, but can replace this regulator with a 2000 psig regulator for high pressure runs). The regulator allows performance of constant pressure autoclave runs. There is a 50 mL stainless steel cylinder connected via a bypass loop to the gas/liquid inlet for the autoclave. This container is used to store liquid alkenes for addition under H_2/CO pressure to the catalyst solution in the autoclave.

The autoclave is equipped with an electronic pressure transducer, packless magnetic stirrer (maximum stirring speed of 1100 rpm), and thermocouple. The Parr autoclave introduces the gas into the solution via a dip tube. This same dip tube allows solution samples to be taken during runs. A Parr model 4850 electronic controller is used that has data collection channels for the two pressure transducers, thermocouple, elapsed time, stirring rate, and can operate two independent autoclaves. The addition of a modern

4870 controller allows for control and real time monitoring of data from four separate autoclaves on a PC.

Experimental conditions for a typical catalytic run: the catalyst precursor (0.090 g, 0.0875 mmol) is dissolved in 80 mL of 70% acetone 30% water under inert atmosphere conditions in a 150 mL capacity Parr autoclave under inert atmosphere in the glove box. 1-hexene (10 mL, 6.73g, 80 mmol) is added under inert atmosphere conditions to the external addition cylinder connected to the autoclave. The autoclave is flushed with H_2/CO for approximately one minute, then heated to 90^{o}C and stirred at 1000 rpm with approximately half the desired operating pressure (~45 psig) of a 1:1 H_2/CO gas mixture. When the autoclave stabilizes at 90^{o}C (~65 psig), the alkene addition cylinder is pressurized with 90 psig H_2/CO and the olefin is transferred into the autoclave. A typical soaking time at 90^{o}C for the catalyst is 20 minutes prior to alkene addition. An initial sample is taken and the data collection begins. All runs are done at constant autoclave pressure. 1-2 mL samples from the autoclave are taken at regular intervals and analyzed by GC (with secondary confirmation by ^{1}H NMR) for product distributions.

When testing the effect of H_2/CO ratios, the procedure was changed only a small amount. The gas was fed into the autoclave under the ratio pressure. For example if a 3:1 ratio was wanted, there would be three times as much hydrogen gas fed into the autoclave system as there was CO. However, because hydroformylation only consumes a 1:1 ratio of H_2/CO, feeding in 3:1 H_2/CO causes the hydrogen gas concentration to gradually increase during a run and eventually causing a lack of CO to support the hydroformylation. Because Dr. Barker only ran 1000 equivalents of 1-hexene in his catalytic runs, he didn't run into CO-starvation problems until he got to a 4:1 H_2/CO

ratio. But when my graduate student mentor, Catherine Thomas, attempted 10,000 turnovers very poor hydroformylation results were obtained. This is when Prof. Stanley figured out the gas ratio problem.

3.3. New Set-up and Procedure

To fix this issue in H_2/CO ratio for hydroformylation runs, Dr. Stanley, Catherine Thomas, and I built a new autoclave system and created new procedures that should allow studies to correctly observe the effects of difference H_2/CO ratios on hydroformylation.

The new system is similar to the previous one; however the gas intake system is the main difference. The autoclave itself has different input sections so that the catalyst precursor (0.090 g, 0.0875 mmol) can be added to the 80 mL of 70% acetone 30% water without having to be in the glove box. Also, the 1-hexene (10 mL, 6.73g, 80 mmol) can be added to the external addition cylinder connected to the autoclave without being in the glove box.

The biggest change is the use of quick connects and tubing to allow easier disassembly and cleaning after each catalytic run. Three differenct 300 mL stainless steel reservoir cylinders are now shared between two autoclave systems and can be used to store an excess of H_2/CO (usually 800-1200 psig) and with different ratios for use in two separate catalytic runs. A thermocouple is attached to the autoclave to monitor the temperature of the reaction mixture. A second thermocouple is attached to the gas reservoir to monitor the temperature of the gases used. The regulators are attached to the

top of the system and control the pressure for each autoclave and reservoir at the same time. The regulators allow delivery of constant gas pressure to the autoclaves during runs. The 50 mL stainless steel cylinder is still connected to the autoclave via quick connects, so that the alkene can be added to the autoclave using syringes instead of having to be added in the glove box. This cylinder is also under the same H_2/CO pressure ratio as the catalyst solution in the autoclave. The new system is shown in Figure 3.31.

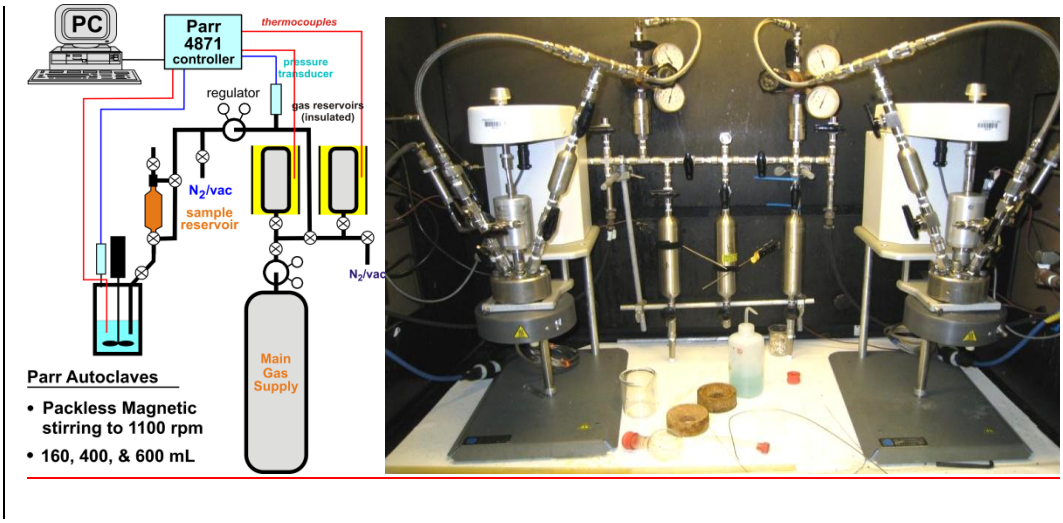

Figure 3.31. *Left*: Schematic of autoclave system. *Right*: photograph of redesigned autoclaves.

The main change in procedure is the H_2/CO ratio for the hydroformylation reaction. Hydroformylation reactions consume a 1:1 H_2/CO ratio, so that needs to be the gas ratio that we feed into the autoclave once the catalysis begins. To study the effect of different H_2/CO ratios we need to initially load that ratio of gas into the autoclave before the reaction starts. The catalyst will be soaked in the appropriate H_2/CO ratio for approximately 20 minutes. This will allow for the ratio to affect the activity and selectivity for the reaction before the hydroformylation reaction begins. Once the alkene

is added the gas feed is 1:1 H_2/CO, but the initial H_2/CO ratio present in the autoclave will remain, thus giving us a constant ratio during catalysis.

3.4. Turnover Number and Rate

Dr. Barker found in his hydroformylation runs a turnover number of 1000 for five of his seven runs using the rac-dirhodium-P4 catalyst. The five runs had either a 1:1 ratio or a higher H_2 ratio. The other two runs had higher CO partial pressures and produced zero turnovers. His conditions for his reactions were as follows: 90^{o}C, 1-hexene (1000 equivalents), 1 mM Rh catalyst, solvent = 30% H_2O (by volume) in acetone, constant pressure conditions, and 1000 rpm stirring. The turnover number is the total amount of alkene reactant converted to products. Dr. Barker also observed a considerable increase in the initial turnover frequency as the H_2/CO ratio was increased (keeping the CO partial pressure fairly low at 22.5 psig).

Since it is believed that the H_2/CO ratios actually changed during his runs, it is very possible that the turnover rates are also incorrect. I plan on testing these rates with the new autoclave system and procedures. I believe that the turnover rates should still be close to the ones Dr. Barker found. I also plan on testing the maximum efficiency of the dirhodium catalyst in comparison to the monometallic catalysts. I am hoping to test each experiment using 10,000 equivalents of alkene. Percent and rate of conversion of the 10,000 equivalents of alkene will illustrate the efficiency of each system.

Although Catherine Thomas and I have collected preliminary data using different H_2/CO gas ratios, we are still experimenting with the best conditions for initiating the

catalysis in order to get consistent results. I intend to continue these studies in Spring, 2009.

3.5 References

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