# Selectivity, Activity and Stability

# of

# Ruthenium-Carbene Based Olefin Metathesis Initiators

Thesis by

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*In Partial Fulfillment*
*of the Requirements for the Degree of*
*Doctor of Philosophy*

California Institute of Technology
Pasadena, California

2000

(Submitted February 24, 2000)

To the Fiat Freaks…

## Acknowledgement

I would first and foremost like to thank Prof. Bob Grubbs. His hands off management style has allowed me to pursue different research interests in the lab, some more productive than others, and has trained me to better approach and solve problems on my own. For this I am eternally grateful to him. I would like to thank Prof. Abhijit Mitra for giving me the opportunity to work in his lab when I was in high school and for opening the world of chemistry to me. It is his fault, I mean his doing that I chose to study chemistry. I would also like to thank Prof. Mits Kubota for exposing me to organometallic chemistry and sending me on the path to Caltech.

Over the years at Caltech I worked with and around many great people. When I just got started, Eric Dias and Tomás Belderrain got me started in the lab and helped me learn proper lab techniques. Tomas also taught me the difference between Guiness and Budweiser, helped me swap the motor in my car and has been a great friend throughout. Melanie Sanford has been a tremendous help in sorting my research results and plans. She is an amazing chemist and a good friend (oh, heart!), not to mention a very meticulous glovebox maintainer. Eric Connor and John Morgan have been a lot of fun to chat and joke around with, discuss chemistry with and to share a lab with, even if our musical tastes did not always overlap (oddly, John's definition of 80's music differs from my definition)! They have been great friends. Since I'm always eager to talk about politics, Jason Henderson, Tom Kirkland and Marcus Weck have been a lot of fun to be around, especially Marcus since our views are totally opposite (clearly he's misguided!). I'd also like to thank Delwin Elder, with whom I've shared a lab bay for 4 years. Delwin

was always very helpful, always willing to share glassware (*most* of which I returned!) and solvents and he was always smiling. Its been a pleasure working around him.

I would like to thank the rest of the Grubbs group. Everyone has helped me with something at some point. Bob Maughon is a good chemist and helped critique my early work in the group. Shojiro Kaita was a visiting student from Japan, a cool guy and an awesome guitar player. His acoustic renditions of Judas Priest songs were awesome! Tom Wilhelm was very helpful in suggesting ways to synthesize ruthenium carbenes and is always eager to show off pictures if his dogs, which I am always eager to look at! Adam Matzger is a walking encyclopedia of all knowledge. I always took advantage of his knowledge of computers and of NMR analysis and for this I am grateful. Todd Younkin is a fun-lovin' fella, always entertaining to be around and was very helpful in getting the GX-400 running when I would've taken a sledge hammer to it. Matt Scholl was always a pleasure to chat with and to discuss European micro Fiats with. Dave Lynn, Helen Blackwell, Heather Maynard, Erika Bellmann, Arnab Chatterjee, Sheldon Okada, Andrew Moorehead, Tina Trnka, Chris Bielawski, Janis Louie, Diego Benitez, Choon-Woo Lee, Mike Koscho, Amy Giardello, and Bill Ward at some point either proofread something for me, helped me resolve some research dilemma or were otherwise helpful. A special thanks goes to Bill Ward for being named after Black Sabbath's drummer.

From Caltech as a whole, I'd like to thank Antek Wong-Foy and Fenton Harvey from Chem 5 TAing. J.P. "Jimbo" Johnson and Dr. Francisco Miguel Guerra Martinez (a.k.a. Paco) from the Carreira group for hours of stimulating discussion. Rick Gerhart from the glass shop has helped me many times with repairs to my vac line. Steve Gould

has been essential to obtaining chemicals and supplies. Dian Buchness was invaluable in getting the grad students in, through and out of Caltech and I am very grateful to her for all her hard work. I'd also like to thank Linda Clark, Bob's secretary, for helping me schedule meetings, submit manuscripts and track down The Boss. Finally, I'd like to thank my committee members, John Bercaw, Dennis Dougherty and Harry Gray for taking the time to read my candidacy report, proposals and thesis and for coming to my exams.

I would like to thank my parents for instilling in me the importance of higher education and for encouraging me to pursue a Ph. D. Finally, I have to thank my girlfriend, Janet Leiben, for being wonderful and caring and loving and for helping motivate me to finish my degree faster!

When I graduated from college, I decided to expand my horizons and progress from motorcycles to cars. I "invested" in a '74 Fiat 124 Spider. Two Spiders and one 124 Sedan later, I am totally addicted to those little Italian cars. I think if I didn't find time to "tinker" with the cars I would have lost my sanity long ago (though some say I lost my sanity *when* I got into the Fiats). Having said that, I am very grateful to Wayne "Randy" Mangum for helping me learn about building/rebuilding/fixing Fiats. His generosity with his time and his spare parts stash has been invaluable to me. I am also grateful to his wife Malia for allowing Randy to come out and play on Saturday afternoons! Having met a lot of Fiat Freaks, guys and gals who buy basket case Fiats and restore them to full grandeur, I am in awe of their dedication and tenacity to this time consuming and financially draining activity. I dedicate this thesis to them. May their dual Webers sing the sweet songs of Italian engineering for decades to come!

## Abstract

The olefin metathesis reaction has found many applications in polymer synthesis and more recently in organic synthesis. The use of single component late metal olefin metathesis catalysts has expanded the scope of the reaction to many new applications and has allowed for detailed study of the catalytic species.

The metathesis of terminal olefins of different steric bulk, different geometry as well as electronically different *para*-substituted styrenes was studied with the ruthenium based metathesis initiators, *trans*-$(PCy_3)_2Cl_2Ru$=CHR, of different carbene substituents. Increasing olefin bulk was found to slow the rate of reaction and *trans* internal olefins were found to be slower to react than *cis* internal olefins. The kinetic product of all reactions was found to be the alkylidene, rather than the methylidene, suggesting the intermediacy of a 2,4-metallacycle. The observed effects were used to explain the mechanism of ring opening cross metathesis and acyclic diene metathesis polymerization. No linear electronic effects were observed.

In studying the different carbene ligands, a series of ester-carbene complexes was synthesized. These complexes were found to be highly active for the metathesis of olefinic substrates, including acrylates and trisubstituted olefins. In addition, the ester-carbene moiety is thermodynamically high in energy. As a result, these complexes react to ring-open cyclohexene by metathesis to alleviate the thermodynamic strain of the ester-carbene ligand. However, ester-carbene complexes were found to be thermolytically unstable in solution.

Thermolytic decomposition pathways were studied for several ruthenium-carbene based olefin metathesis catalysts. Substituted carbenes were found to decompose through

bimolecular pathways while the unsubstituted carbene (the methylidene) was found to decompose unimolecularly. The stability of several derivatives of the bis-phosphine ruthenium based catalysts was studied for its implications to ring-closing metathesis. The reasons for the activity and stability of the different ruthenium-based catalysts is discussed.

The difference in catalyst activity and initiation is discussed for the bis-phosphine based and mixed N-heterocyclic carbene/phosphine based ruthenium olefin metathesis catalysts. The mixed ligand catalysts initiate far slower than the bis-phosphine catalysts but are far more metathesis active. A scheme is proposed to explain the difference in reactivity between the two types of catalysts.

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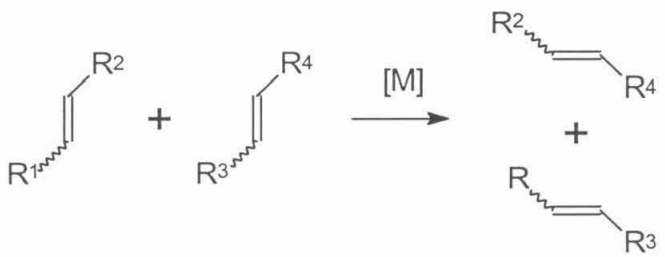
# Chapter 1

## Introduction, Background and History

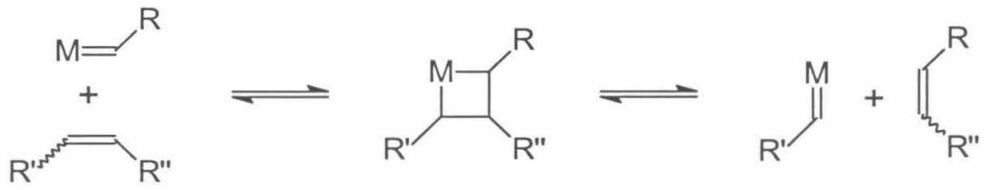
The detailed study of organic chemistry has been conducted for over a century, such that the chemistry of carbon compounds is considered a mature science. The variation of uncatalyzed organic reactions is very diverse, but the prospects of using transition metal-based catalysts to carry out new transformations seem almost limitless. When no viable kinetic pathway exists for converting certain organic reactants into desired organic products, the transition metal catalyst provides a means for accommodating the reaction through organometallic intermediates. The goal of the organometallic catalyst chemist is to devise new metal-substrate reactions, to implement them with the right metal and ligand sphere and finally to study their mechanisms and selectivity. The work in this thesis is concerned with the latter aspects of organometallic chemistry in studying the selectivity, reactivity and stability of ruthenium-based olefin metathesis catalysts.




**Scheme 1** – The olefin metathesis reaction.

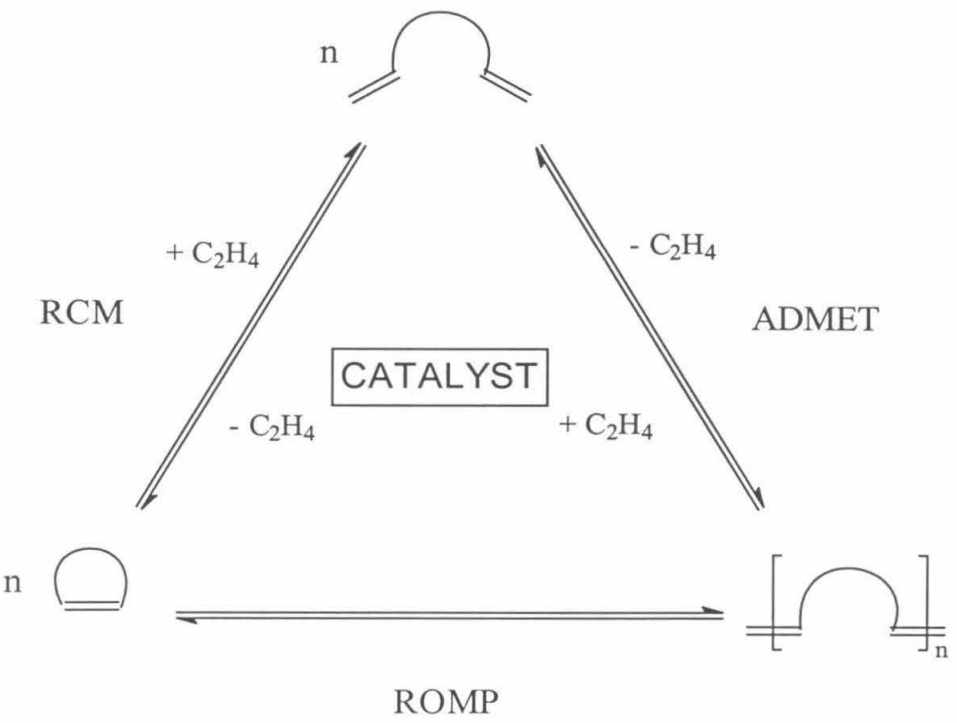
Olefin metathesis is a metal catalyzed reaction between olefins such that the alkenes are effectively cut in half and recombined to form new C-C double bonds (Scheme 1). The reaction was originally discovered in 1957 when metal oxides/salts activated by cocatalysts were able to polymerize cyclopentene and norbornenes.[1] The detailed history of the evolution of olefin metathesis is documented in the literature.[2] The currently accepted, but long disputed, mechanism for this reaction, first proposed by Chauvin in 1970,[3] involves a metal carbene complex reacting with an olefin in a formal

2+2 cycloaddition to form a metallacyclobutane intermediate. This metallacycle can productively cleave into a new carbene and olefin or unproductively revert back to the original species (Scheme 2). The reaction is under equilibrating conditions and the final products are determined by thermodynamic control.




**Scheme 2** – Chauvin's mechanism for olefin metathesis.

Olefin metathesis has a variety of applications, as shown in Scheme 3. In addition to the cross-metathesis of acyclic olefins (Scheme 1), cyclic olefins can undergo Ring Opening Metathesis Polymerization (ROMP)[4] while α,ω-dienes can undergo Ring Closing Metathesis (RCM)[5] or Acyclic Diene Metathesis Polymerization (ADMET).[6] These three processes form a series of equilibria which can be forced towards either of the three products under the appropriate reaction conditions (Scheme 3).




**Scheme 3** – Three equilibrating processes of metathesis.

The evolution of metathesis catalysts from the early ill defined metal salts to the early-metal single component systems[7] lent solid proof for the metallacycle-based reaction mechanism because these early catalysts, such as Grubbs' titanacycle[7a-d] and Schrock's tantalacycle,[7e-f] were, in fact, isolated as the respective metallacycles, not as carbenes (Figure 1). The first widely applicable single component systems were Schrock's tungsten and molybdenum neopentylidenes.[8] However, the disadvantage of all those early-metal catalysts,[9] including the tungsten and molybdenum based systems, was that they were very sensitive to air and water and typically reacted with polar functional groups, such as alcohols and carbonyls, more readily than with olefins. It was noted that in considering the different catalysts, based on different metals, the further to the right of the Periodic Table the metal lay, the more selective the catalyst was for olefins over other

functional groups.[10] The objective set out in the Grubbs group during the late 1980's was to develop catalysts based on group VIII transition metals which are less oxyphilic and were expected to result in catalysts with the greatest functional group tolerance.

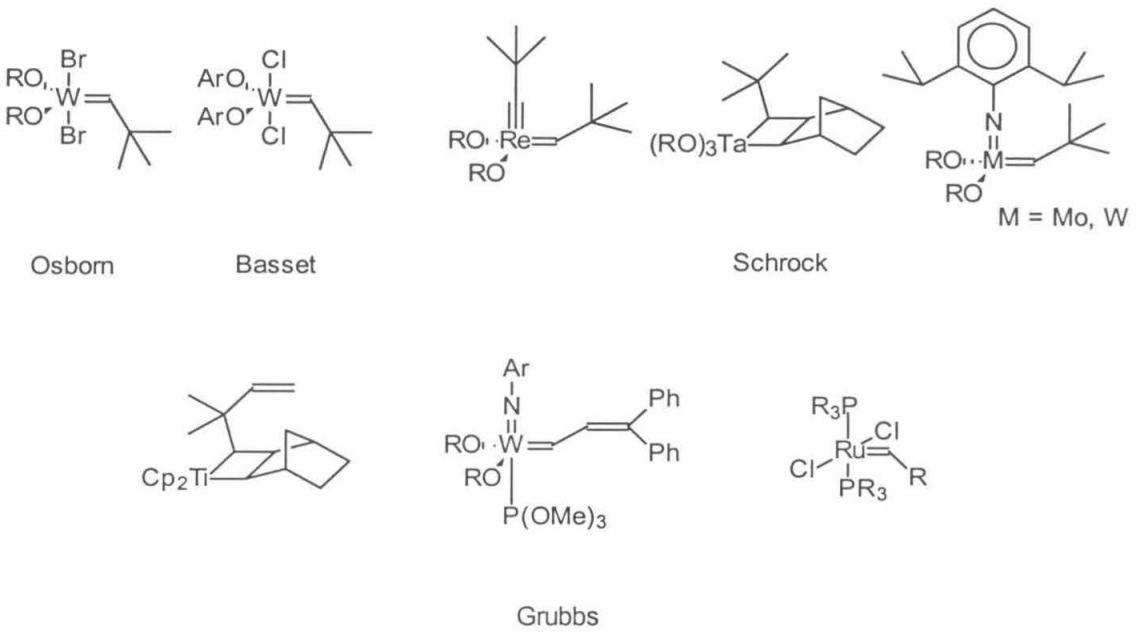
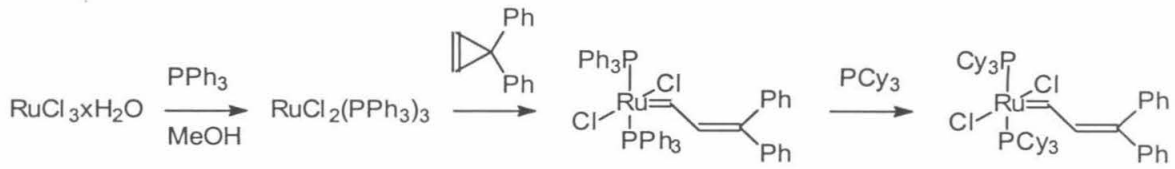



**Figure 1** – Select group of single component olefin metathesis initiators.[9]

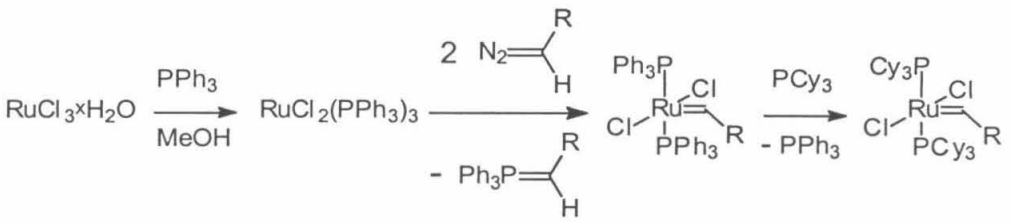
Since the early days of metal salt catalyzed metathesis reactions, it was known that salts such as $RuCl_3$, $OsCl_3$ and $IrCl_3$ were active initiators for the ring opening metathesis polymerization of norbornene.[9] As a result, research efforts were concentrated on developing single component catalysts based particularly on these late metals. The observation that $Ru(H_2O)_6(tos)_2$ (tos = *p*-toluenesulfonate) was faster at initiating metathesis than $Ru(III)_{(aq)}$ species and that reaction mixtures of each initiator showed the same NMR carbene resonances suggested that Ru(II) was the active metal center for olefin metathesis[11] and was presumably formed in $RuCl_3$ initiated reactions by the disproportionation of Ru(III).[9] This helped focus on developing a Ru(II) based catalyst.




**Scheme 4** – Synthesis of Sonbinh's Catalyst.

Work by Lynda Johnson on the synthesis of tungsten based catalysts using cyclopropenes as carbene sources,[12] inspired the synthesis, by SonBinh Nguyen, of the first isolated metathesis active ruthenium carbene, $(Ph_3P)_2Cl_2Ru{=}CH\text{-}CH{=}CPh_2$ (Scheme 4).[13] However, this species only polymerized very strained olefins, such as norbornene, but not cyclooctene or acyclic olefins. Upon replacement of the triphenyl phosphine with tricyclohexyl phosphine, the revised catalyst was active for the metathesis of less strained cyclic olefins as well as acyclic olefins. The complex $(Cy_3P)_2Cl_2Ru{=}CH\text{-}CH{=}CPh_2$ was thereafter known as "SonBinh's Catalyst."

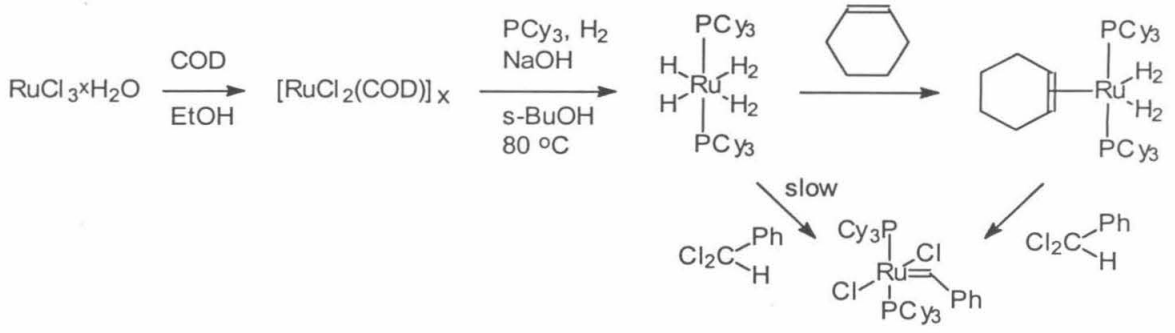
While the diphenyl vinyl carbene complex was applicable to many different olefin metathesis substrates, it did have some drawbacks. First, the catalyst suffered from a difficult synthesis, as the preparation of diphenylcyclopropene is a multistep process and the product is not stable for long periods of time. Second, vinyl carbene based catalysts have slow rates of initiation, though upon initiation the resultant alkylidenes are highly active for reaction propagation. Finally, these ruthenium catalysts were highly active for metathesis but not as active as molybdenum based species which could readily react with tetrasubstituted olefins. A new way to make a different carbene ligand was sought.




**Scheme 5** – Synthesis of Peter's Catalyst.

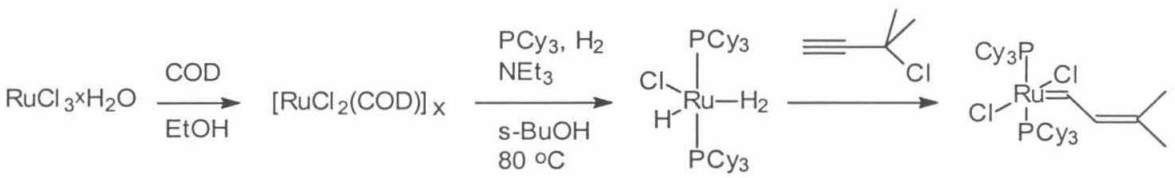
An alternate approach to carbene synthesis was being developed by Marsha France whereby $(PPh_3)_3RuCl_2$ was treated with two equivalents of a diazo compound to form, upon release of nitrogen, the ruthenium carbene and a phosphine ylide.[14] This approach was optimized by Peter Schwab and the benzylidene complex which he made, $(Cy_3P)_2Cl_2Ru{=}CHPh$, became known as "Peter's Catalyst" (Scheme 5).

The advantage of the benzylidene species is the higher rate of initiation relative to the vinyl carbene. However, the preparation and handling of the diazo species is dangerous, especially on a large scale, and the required phosphine exchange is wasteful of triphenyl phosphine. An alternate synthesis of the benzylidene was developed by Tomás Belderrain (Scheme 6).[15] He found that the reaction of α,α-dichlorotoluene with a Ru(0) precursor, such as $Ru(H)_4(H_2)(PCy_3)_2$, or with what is believed to be $(H_2)_2Ru(cyclohexene)(PCy_3)_2$, resulted in a double oxidative addition of the halides to very cleanly form a carbene species. While this approach avoided the hazardous diazo compounds and the wasteful phosphine exchange reaction, the synthesis of the ruthenium precursor was not trivial and therefore the method was still not ideal.




**Scheme 6** – Revised synthesis of Peter's Catalyst.

In an effort to design an inexpensive synthesis of ruthenium carbene complexes, Thomas Wilhelm, Seth Brown and Tomás Belderrain discovered that $[RuCl_2(COD)]_x$ was readily converted to $(PCy_3)_2(H_2)Ru(H)(Cl)$. When this ruthenium hydride was treated with propargylic halide compounds, the acetylene inserted into the ruthenium hydride bond and the vinyl complex rearranged to form a vinyl carbene (Scheme 7).[16] This metathesis initiator was simple to make on a large scale but still suffered from poor initiation rates. However, for most applications the rates of initiation are not significant, making this catalyst the ruthenium based initiator of choice.

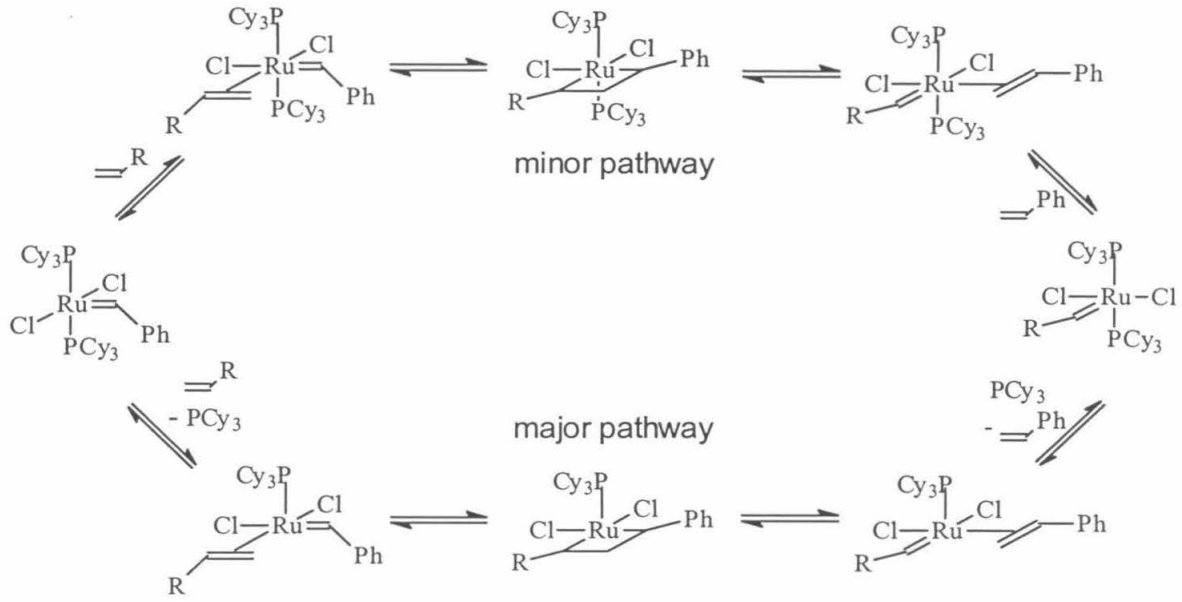



**Scheme 7** – Highly efficient synthesis of vinyl carbene species.

The latest breakthrough in ruthenium based olefin metathesis catalysts evolved from the use of N-heterocyclic carbenes as phosphine mimics. Herrmann has been very successful in improving many phosphine based catalytic systems, such as hydroformylation and Heck coupling, by substituting in these ligands for phosphines.[17]

The application of ligands of this general type to ruthenium based olefin metathesis, as discussed in Chapters 4 and 5 of this thesis, has drastically improved the activity of these catalysts such that they now rival Schrock's molybdenum based catalysts.

The effect of the ligand sphere of the ruthenium catalyst was studied by Eric Dias.[18] He showed that phosphine dissociation is vital for the major active pathway of the catalyst (Scheme 8) and therefore larger phosphines make better catalysts due to better phosphine dissociation. Furthermore, phosphines which are more basic have a stronger trans influence and help dissociate the phosphine located *trans* to them, thereby increasing catalyst activity. As a result, it turned out that the tricyclohexyl phosphine initially used to increase the activity of the triphenyl phosphine version of Sonbinh's Catalyst was the ideal phosphine ligand for these systems. Dias also found that the more electron withdrawing halogen ligands, with smaller trans influence, make the better catalysts. This was rationalized by the hypothesis that the two *trans* halogens rearrange into a *cis* orientation and allow the incoming olefin to coordinate *trans* to one halogen and *cis* to the carbene (Scheme 8). As a result, halogens of lower trans influence, such as chloride or pseudo-halogens like trifluoroacetate, promote better coordination of the incoming olefin and make the better catalysts.




**Scheme 8** – Major and minor pathways in the mechanisms for ruthenium carbene catalyzed olefin metathesis.

Many ligand derivatives of these complexes have been made which all differ in their catalytic activity. Water soluble ligands[19] can support metathesis in water/methanol mixtures; chelated ligands produce more oxygen stable catalysts;[20,21] chiral ligands produce enantioselective induction;[22a] and N-heterocyclic carbene substituted ligands[22] are highly active for the metathesis of hindered and otherwise unreactive substrates.

Ruthenium based olefin metathesis catalysts has been extensively studied for application to RCM and ene-yne-ene metathesis by William Zuercher[23] and Thomas Kirkland.[24] The study of ROMP control was carried out by Zhe Wu,[25] Marc Hillmyer,[26] Bob Maughon[27] and Christopher Bielawski.[28] Cross metathesis was studied by Helen Blackwell, Dan O'Leary,[29] Arnab Chatterjee[30] and John Morgan.[22b] Marcus Weck[31] examined applications of the ruthenium catalysts to material and surface science. Metathesis of polypeptides was also studied by Helen Blackwell[32] and by Scott Miller.[33]

The synthesis of other biopolymers via metathesis was developed by Heather Maynard[34] and Sheldon Okada.[35]

The objective of the work in this thesis was to study the selectivity and activity of the ruthenium metathesis catalysts. While some observations had been previously made, based on the utilization of the catalyst for ring opening cross metathesis, regarding the catalysts' selectivity for different olefins,[36] a detailed study was needed to examine how the metal carbene reacts with an incoming olefin and to examine the orientation of substituents in metallacycle formation. By varying the carbene substituents and reacting the complexes with different olefins, a better understanding of these goals was achieved.

The variance of the carbene substituents was an extention of the work that Eric Dias conducted in studying the effect of the ligand sphere on catalyst activity. In considering different carbene ligands, ester-carbene complexes, [Ru]=CHC(O)-OR, were discovered to produce catalysts which were extremely active for metathesis and reacted with olefins which are otherwise unreactive. However, these complexes were also thermally unstable and readily decomposed in solution at room temperature over the course of several hours.

The observation that the ester carbene complexes underwent facile decomposition led to a study of the modes of catalyst decomposition. It was previously known that the catalysts decomposed by the dimerization of the carbene species. Upon a selective study of the decomposition of different carbene complexes, it was discovered that not all carbenes decompose by a bimolecular pathway and that the ancilliary ligands have a strong influence on the rate and mode of decomposition.

Several concluding remarks are made at the end of this thesis speculating about the activity of the newest derivatives of the ruthenium based olefin metathesis catalysts supported by N-heterocyclic carbene ligands. The rates of initiation, propagation, activity and decomposition of these systems vary dramatically from the earlier bis-phosphine catalysts and some ideas are proposed to explain the notable differences.

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# Chapter 2

## Relative Reaction Rates of Olefin Substrates with Ruthenium (II) Carbene Metathesis Initiators

## Abstract

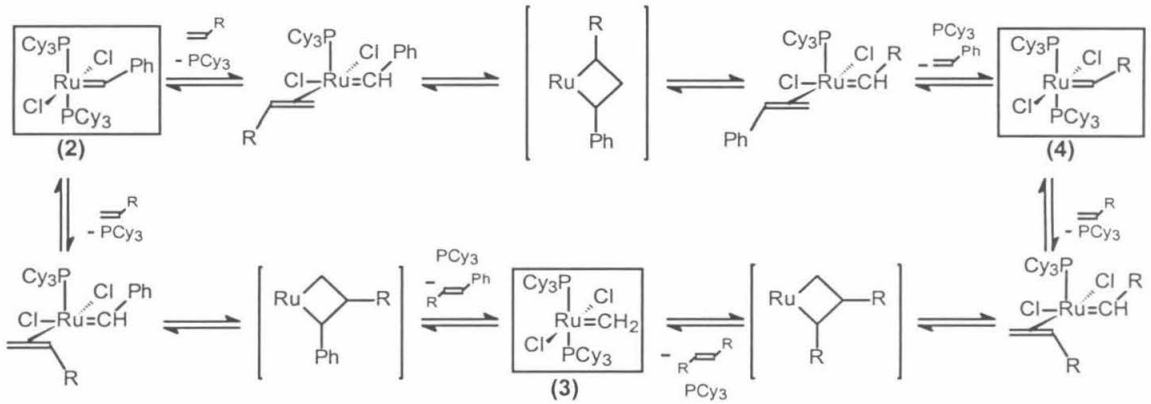
The metathesis of terminal olefins of different steric bulk, different geometry as well as with electronically different *para*-substituted styrenes was studied with the ruthenium based metathesis initiators, *trans*-$(PCy_3)_2Cl_2Ru$=CHR. Increasing olefin bulk was found to slow the rate of reaction and *trans* internal olefins were found to be slower to react than *cis* internal olefins. The kinetic product of all reactions was found to be the alkylidene, rather than the methylidene, suggesting the intermediacy of a 2,4-metallacycle. The observed effects were used to explain the mechanism of ring opening cross metathesis and ADMET. No linear electronic effects were observed.

## Introduction

Over the past several years, extensive effort has been expended to design and isolate single component late transition metal[1] olefin metathesis catalysts to be used for Ring Opening Metathesis Polymerization (ROMP),[2] Ring Closing Metathesis (RCM)[3] and Acyclic Diene Metathesis (ADMET) processes.[4] Among the first of such well defined catalysts coming from the Grubbs laboratory was the ruthenium (II) carbene, *trans*-$(PPh_3)_2Cl_2Ru$=CH-CH=$CPh_2$ **(1)**, active only for the living polymerization of highly strained cyclic olefins.[5] The replacement of the triphenyl phosphine ligands with bulkier and more basic tricyclohexyl phosphine or triisopropyl phosphine ligands extended the activity to the metathesis of less strained cyclic olefins and acyclic olefins.[6] The next generation catalyst developed in the Grubbs laboratory was the benzylidene, *trans*-$(PCy_3)_2Cl_2Ru$=CHPh **(2)**, which exhibited faster initiation than its predecessors for ROMP, RCM and ADMET processes.[7] It was observed that the benzylidene catalyst reacted with terminal acyclic olefins to produce the new substituted alkylidenes in high

yield. This observation provided the opportunity to examine the details of metathesis with these catalysts and to explore the factors that control the rates of product formation and the relative thermodynamic stability of the intermediates. Information of this nature is required to understand the growing number of applications of these catalysts in organic and polymer syntheses.

The accepted mechanism for olefin metathesis proceeds as a series of equilibria: the coordination of the olefin to the metal adjacent to the carbene followed by reversible formation of a metallacycle to form either the original or the metathesized carbene and olefin.[8] Scheme 1 outlines these steps using the proposed intermediates for the ruthenium catalysts.




**Scheme 1** – Metathesis of terminal olefins initiated by the ruthenium benzylidene.

Previous work from the Grubbs laboratory[7] has shown that when the benzylidene initiator **(2)** reacted with terminal acyclic olefins, such as 1-hexene, the initial organometallic product observed by $^1$H NMR was the alkylidene[9] **(4)** (Scheme 1). After approximately 10 minutes, at room temperature, the complete disappearance of **(2)** was observed along with the formation of **(3)**. After 2 hours, the only organometallic product

observed was **(3)**. The present work examines the relative reaction rates of metathesis active carbenes with acyclic olefins of different bulk, geometry and electronic properties to study selectivity in alkylidene formation and explores the factors that effect the rate of metathesis.

## Results and Discussion

### *Relative Steric Effects of Substrates and Metallacycle Formation*

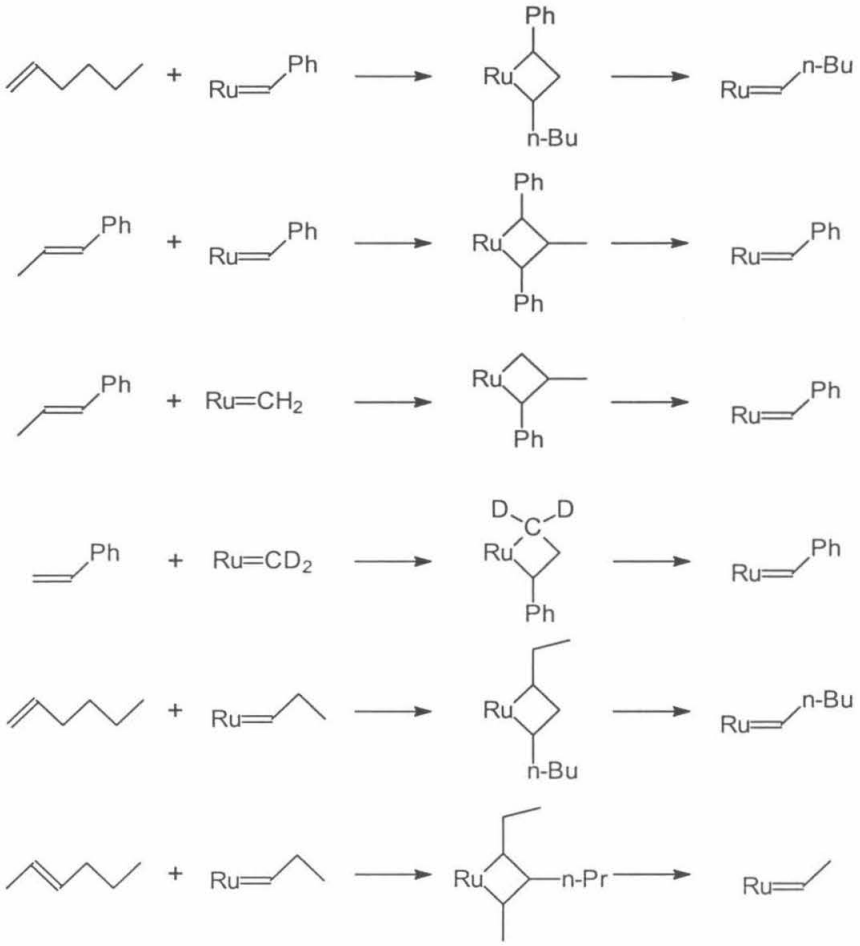
When the benzylidene catalyst **(2)** was reacted with sterically unhindered terminal olefins, the initial carbene product observed by $^1$H NMR was the alkylidene **(4).** When the steric bulk of the olefin was gradually increased, there was a decrease in the reaction rate, as shown by reactions 4 and 6 in Table 1. For even bulkier terminal olefins (Table 1, reactions 7 and 8, compared with reaction 5), metathesis was even slower and surprisingly led directly to the methylidene **(3)**. A 2,2-disubstituted olefin (Table 1, reaction 9) showed no activity under present conditions. These results were puzzling because they implied that bulky olefins alter the selectivity in metallacycle formation between a 2,4 and a 2,3-metallacycle.

The selectivity of metallacycle formation was examined more systematically (Scheme 2). The reaction of the benzylidene **(2)** with 1-hexene led to the formation of the pentylidene, suggesting that the reaction proceeded through a 2,4-metallacycle, placing the incoming alkyl substituent adjacent to the metal. When β-methylstyrene was reacted with the benzylidene **(2)** or the methylidene **(3)**, the phenyl group, not the methyl group, was oriented next to the metal in the intermediate as evidenced by the benzylidene product in both cases. The reaction between the methylidene **(3)** and 1-hexene (examples 13 and 14) produced the pentylidene, and the reaction of deuterated methylidene with

styrene produced the benzylidene, not the proteomethylidene. Consequently, the favored reaction of the methylidene appears to be the productive pathway, again placing the substituent of the olefin in the 2 position of the metallacycle. Finally, the reaction of an alkylidene, such as the propylidene, with 1-hexene led to the formation of the pentylidene, again proceeding through a 2,4-metallacycle. However, when the propylidene was reacted with 2-hexene, the ethylidene was formed, not the butylidene.

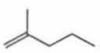
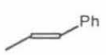
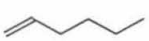
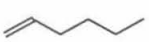
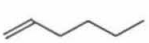
These observations imply that the most kinetically preferred substituent adjacent to the metal in the metallacycle is a phenyl group. The second most preferred would be an alkyl group, though smaller alkyl groups are preferred over larger ones. The proton would then be the least preferred substituent next to the metal.

While a clear explanation of these observations is not known, the kinetic stability of the phenyl in the 2 position of the metallacycle can be rationalized based on presumed conjugation between the phenyl and the metal's d-orbital electrons. The preference of the alkyl group in the 2 position can be fathomed if the $\sigma+$ Hammet parameter in final section of this chapter is true. The formation of a positive charge on the ruthenium in the formation of the metallacycle would be stabilized by an electron donating alkyl group. However, clearly the sterics of bulky alkyl groups would interact with the bound phosphine ligand such that smaller alkyl groups, having comparable electronic properties, would be better suited to the 2-position than larger substituents.




**Scheme 2** – Inferred selectivity in metallacycle formation.

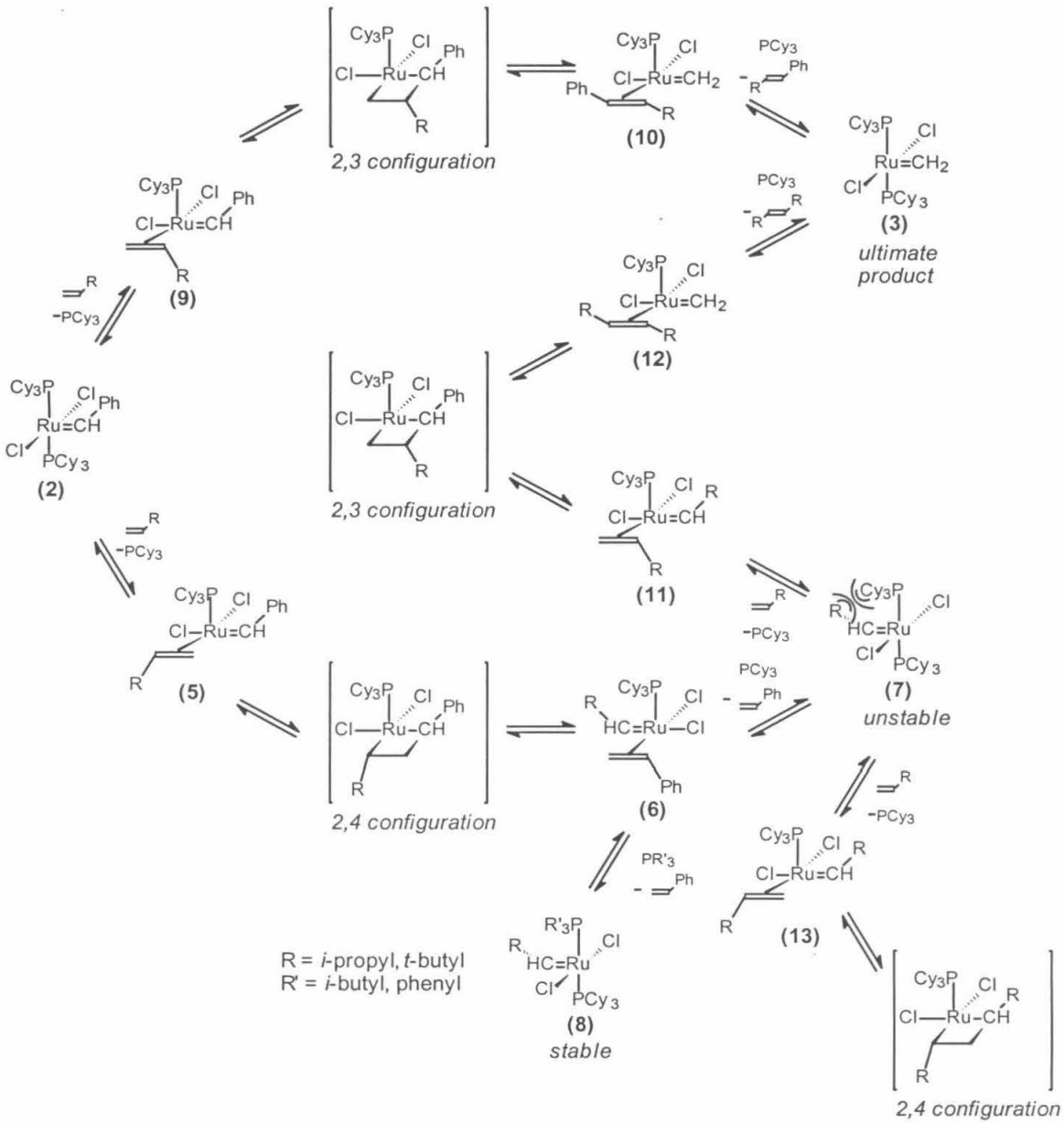
**Table 1** – Second order rate constants (k) for metathesis reactions in $C_6D_6$ at 0.018 M carbene with 31 equivalents of olefin.

| | olefin | initiator | product | Temp / °C | k ± SDOM[a] / L/mole•sec |
|---|---|---|---|---|---|
| **1** | styrene-d 8 | Ru=CH(Ph) | Ru=CD(Ph-d5) | 7 | $1.3 \pm 0.4 \times 10^{-3}$ |
| **2** | styrene-d8 | Ru=CH(Ph) | Ru=CH(Ph-d5) | 7 | $2.15 \pm 0.01 \times 10^{-3}$ |
| **3** | styrene | Ru=CH(C4H7) | Ru=CH(Ph) | 7 | $7.6 \pm 0.2 \times 10^{-3}$ |
| **4** |  | Ru=CH(Ph) | Ru=CH(C4H7) | 7 | $1.48 \pm 0.04 \times 10^{-3}$ |
| **5** |  | Ru=CH(Ph) | Ru=CH(C4H7) | 35 | $\sim 10^{-2}$ |
| **6** |  | Ru=CH(Ph) | Ru=CH(CH(CH3)2) | 7 | $1.02 \pm 0.06 \times 10^{-3}$ |
| **7** |  | Ru=CH(Ph) | Ru=CH2 | 35 | $2.5 \pm 0.2 \times 10^{-4}$ |
| **8** |  | Ru=CH(Ph) | Ru=CH2 | 35 | minor in 4 days |
| **9** |  | Ru=CH(Ph) | | 35 | no rxn. |
| **10** |  | Ru=CH(Ph) | | 35 | no obs. rxn. |
| **11** |  | Ru=CH(Ph) | Ru=CH(C2H5) | 35 | $3.0 \pm 0.4 \times 10^{-4}$ |
| **12** |  | Ru=CH(Ph) | Ru=CH(C2H5) | 35 | $7.6 \pm 0.8 \times 10^{-4}$ |
| **13** |  | Ru=CH2 | Ru=CH(C4H7) | 25 | $1.64 \pm 0.1 \times 10^{-4}$ (6000) |
| **14** |  | Ru=CH2 | Ru=CH(C4H7) | 35 | $6.10 \pm 0.04 \times 10^{-4}$ (1000) |
| **15** |  | Ru=CH(C2H5) | Ru=CH(C4H7) | 7 | $\sim 7 \times 10^{-3}$ |

[a] SDOM = Standard Deviation of the Mean

The preferred formation of the methylidene, rather than an alkylidene, from **(2)** upon reaction with bulky olefins can be explained by a closer examination of the proposed mechanism for metathesis by the ruthenium carbenes.[10] It was proposed that the key first step is the dissociation of one phosphine and the coordination of an incoming olefin, as a pre-equilibrium step. The olefin can bind in one of two orientations, **(5)** and **(9)** (Scheme 3). The next step would be the formation and breakup of the metallacycle.

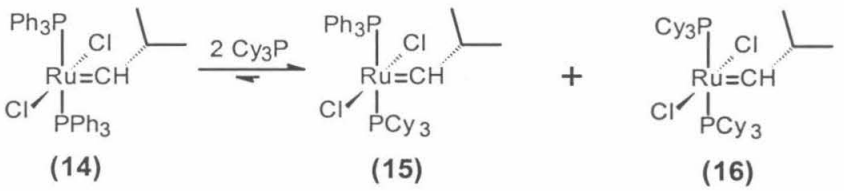
Although the data from Scheme 2 suggest that the alkyl substituent of a terminal olefin prefers to be next to the metal (2,4 configuration) in the kinetically favored metallacycle formed through **(5)**, steric bulk near the olefin *appears* to shift the path through **(9)** to the 2,3-substituted metallacycle and leads directly to **(3)**. However, an alternate pathway is possible where the formation of **(7)** as a reactive intermediate is involved. It is proposed that after the initial metathesis step, the olefin complex **(6)** loses the olefin and free phosphine coordinates to form **(7)**. If the alkyl group on the carbene ligand of **(7)** is too large to readily accommodate two bulky phosphines, one of those phosphines would be especially labile. As a result, **(7)** would be very ready to reinitiate metathesis. A new olefin would react with **(7)** to form **(11)** which could undergo metathesis to form **(12)** and on to the methylidene **(3)** as the stable product. Alternatively, an olefin can react with **(7)** to form **(13)**, but that reaction would be degenerate and unproductive. The pathway through **(11)** is the only way that **(7)** can react to result in a stable bis-phosphine species.




**Scheme 3** – Proposed mechanism of "direct" formation of methylidene with bulky olefins.

To test this explanation for methylidene formation, 3-methyl-1-butene was allowed to react with **(2)** while a smaller phosphine was present in solution to trap the proposed intermediate **(6)**. When the phosphine was triphenyl phosphine or triisobutyl

phosphine,[11] the smaller ligand was able to bind in place of the bulky phosphine and form the observed stable complex **(8)** which, in contrast to **(7)**, could sterically accommodate the bulky carbene. The formation of such a mixed phosphine complex was confirmed by an AB spectrum in the $^{31}P$ NMR. An alternate synthesis of the bis(triphenylphosphine) isobutylidene complex **(14)**[12] was carried out by the standard diazoalkane procedure[7] and a partial phosphine exchange with tricyclohexyl phosphine confirmed the resonances observed in the metathesis reaction (Scheme 4). Furthermore, while the bis(triphenylphosphine) benzylidene complex reacted with a slight excess of tricyclohexyl phosphine to undergo complete phosphine exchange, **(14)** reacted to form both **(15)** and **(16)**, supporting the steric argument that bulky carbenes result in the lability of bulky phosphines as the more basic tricyclohexyl phosphine did not completely displace the triphenyl phosphine on the isobutylidene complex. However, it must be pointed out that the possibility that bulky olefins also have an inherently greater tendency to form 2,3 metallacycles cannot be ruled out as a contributor to the observed methylidene formation.



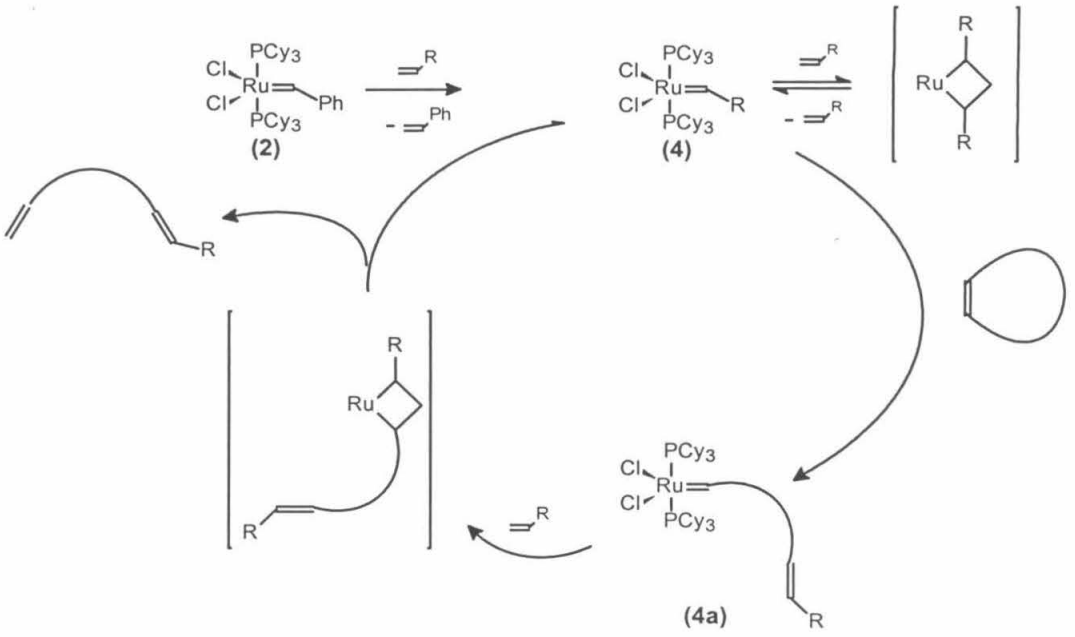

**(14)** **(15)** **(16)**

**Scheme 4** – Phosphine exchange on isobutylidene complex.

### *Ring-Opening Cross Metathesis*

Given the generally observed 2,4 metallacycle formation, the reactions of ring opening cross metathesis[13] with the ruthenium initiators can be explained, such as the

observation of Randall, *et al.* that bicyclic cyclobutenes react with 1.5 equivalents of a terminal olefin to produce almost exclusively a single product such that the terminal olefin is effectively added across the cyclobutene double bond.[13a] The proposed pathway for this process is shown in Scheme 5. The benzylidene **(2)** is quickly lost to the terminal olefin forming styrene and an alkylidene **(4)**, which then reacts rapidly with additional terminal olefin, though almost always degeneratively, regenerating the alkylidene complex rather than a methylidene. Meanwhile, though the reaction with the cyclic olefin is slower, once the ring is metathesized, the newly formed long chain alkylidene **(4a)** quickly reacts with a terminal olefin and the long chain olefin is end-capped with a methylene, again regenerating the alkylidene complex **(4)**. Of course the relative rates of reaction of the carbene with cyclic and terminal olefins depend on the nature of the cyclic olefin. However, the fact that Randall, *et al.* did not observe poly-cyclobutene formed by ROMP, and did in fact obtain a ring-opened cross-metathesis product further supports the proposed mechanism, namely that the reactions with terminal olefins are predominant and oligomerization of the monomer is slower than cross-metathesis.[14]




**Scheme 5** – Selective Ring-Opening Cross Metathesis by ruthenium carbene metathesis catalysts.

### *Effect of Carbene Structure on Initiation*

The activity of different carbene ligands can be compared from the data in Table 1. For instance, reactions 5 and 14 demonstrate the surprisingly greater activity of the benzylidene over the methylidene. Clearly, there are other factors that more strongly effect the rate of metathesis than the size of the carbene and the steric interaction between the carbene and olefin. Further, reaction 4 and reaction 15 demonstrate the greater activity of alkylidenes over the benzylidene. These relative rates can be significant when one plans to use a catalytic amount of the carbene for a synthesis. Once the benzylidene is initiated, if the newly formed carbene is a methylidene, it will proceed slower in the next step. However, if the newly formed species is an alkylidene it will propagate much more readily.

The observed relative activity of the carbenes can be rationalized as a function of their electronic and steric properties. The most active carbenes are the alkylidenes. Their electron donating properties and their relative size help to dissociate the phosphine and speed up metathesis initiation. The least active carbene is the methylidene, which lacks both the size and the electron donating ability of the alkylidenes. The benzylidene is an intermediate case where the resonance of the phenyl ring is somewhat electron withdrawing while the size of the ring helps to dissociate a phosphine. The effect of carbene and olefin electronic properties will be addressed in the last section of this chapter.

### *Cis/Trans Substrates*

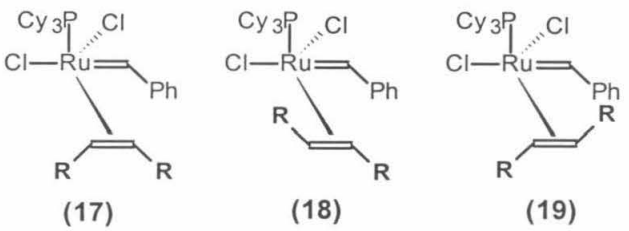
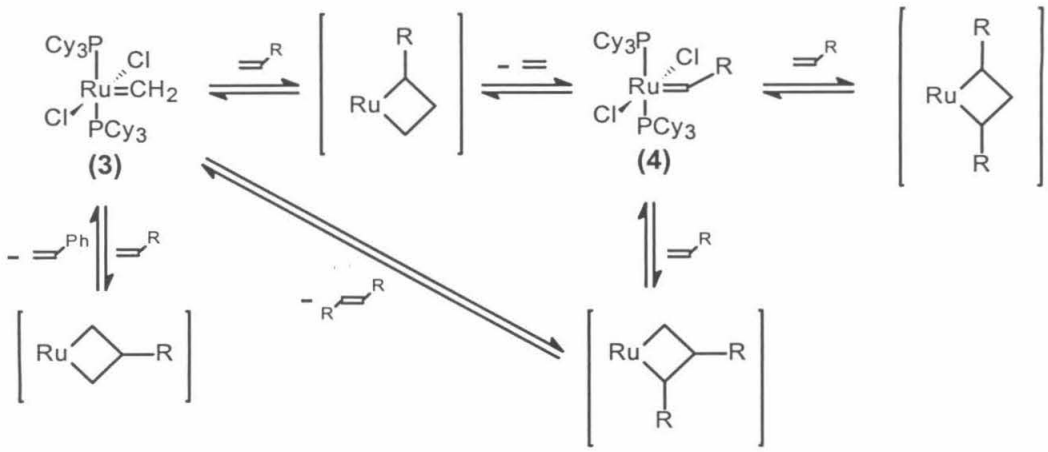



**Figure 1** – Olefin complex formation affecting the rates of metathesis of *cis* and *trans* olefins.

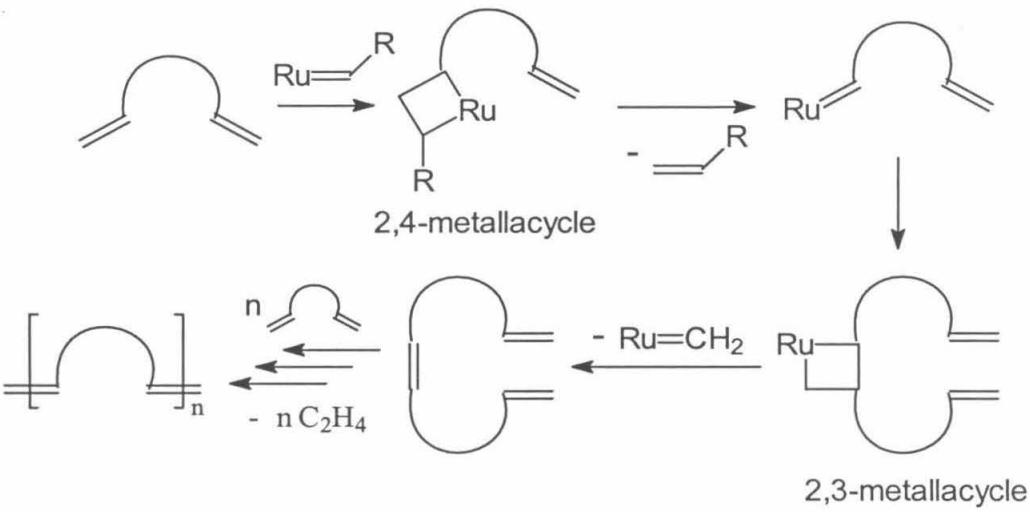
When examining the relative rates of *cis* and *trans* olefins, the benzylidene reacts approximately twice as fast with *cis*-3-hexene as with *trans*-3-hexene. This can be explained by considering the binding of the olefin to the complex (Figure 1). When the *cis* olefin binds to the metal **(17)**, the substituents can point away from the bulky phosphine. The *trans* olefin can bind either as **(18)** or as **(19)**; in either case there is an adverse steric interaction with the phosphine, which results in a slower rate of initial olefin binding.

***Methylidene***




**Scheme 6** – Reactivity of the methylidene with terminal olefins.

In studying the reactivity of the methylidene, we examined the reaction with 1-hexene (Scheme 6). The metathesis exhibited pseudo-first order kinetics up to 40% conversion, at 25 °C, before the concentration of the newly formed pentylidene became sufficient so that its productive (non-degenerate) metathesis of 1-hexene became significant and the methylidene concentration started to again rise. At 35 °C, this same reaction was pseudo-first order only to 27% conversion before the methylidene concentration started to increase again. From this we can conclude that the selectivity of the metallacycle formation is temperature sensitive. Thus, at elevated temperatures the formation of **(3)** can be as likely as the formation of **(4)** in the metathesis of terminal olefins by **(2)** (Scheme 1). This explains how the ruthenium catalysts are active for ADMET at elevated temperatures (Scheme 7). Since ADMET required both 2,3 and 2,4-metallacycles, at elevated temperatures catalyst selectivity is decreased and the same ruthenium catalyst can form both metallacycle configurations.



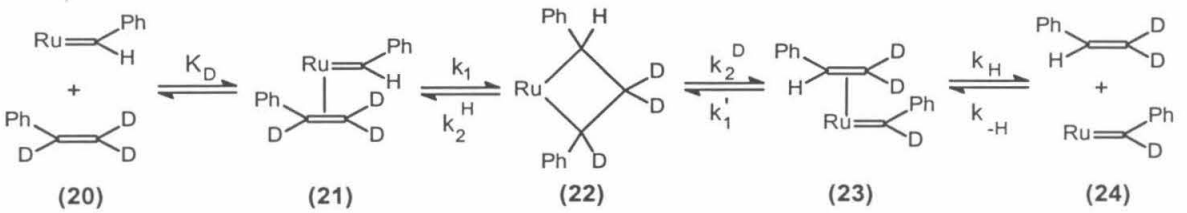

**Scheme 7** – ADMET with ruthenium carbene complexes.

### *Kinetic Isotope Effects*

An examination of the secondary kinetic isotope effect for metathesis, obtained from reactions 1 and 2 in Table 1, reveals that $k_H/k_D = 1.7$. Scheme 8 depicts the mechanistic pathways for the metathesis of deuterated styrene. The derived initial rate expression for the process, assuming a pre-equilibrium for **(21)**, a steady-state for **(22)** and **(23)** and that the equilibrium between **(23)** and **(24)** is a lot faster than that between **(22)** and **(23),** is:

$$\frac{d[Ru = CDPh]}{dt} = \frac{K_D k_1 [Ru = CHPh][PhDC = CD2]}{1 + {k_2}^H / {k_2}^D}$$

The positive secondary isotope effect results from the $sp^3$ to $sp^2$ hybridization change of the metallacycle carbons during breakup.[15] As a result, the denominator for the rate equation should increase when styrene-$d_8$ is metathesized and lead to a slower rate relative to styrene-$d_5$. This effect is similar to that observed for the breakup of titanium based metallacycles where $k_H/k_D = 2.2$.[16]

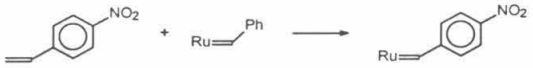
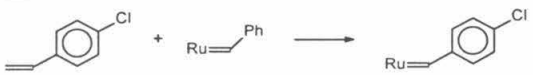
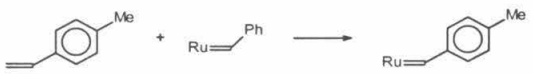
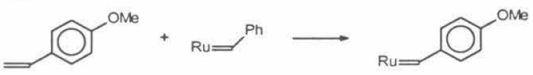
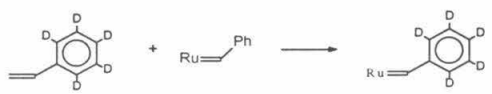



**Scheme 8** – Mechanistic pathway to explain the secondary kinetic isotope effect.

## Electronic Effects of the Substrates

The study of the electronic effects of the metathesis substrate was undertaken by metathesizing *para*-substituted styrenes with **(2)** (Table 2). The exclusive product of each reaction was the *para*-substituted benzylidene. A Linear Free Energy Relationship (LFER) with the $\sigma^+$ electronic parameter[17] was found, LOG $(^{k}/_{k'})$ = $\rho\sigma^+$ ($R^2 = 0.991$), $\rho$ = -0.84 (Figure 2). However, when the rate for styrene-$d_5$ was added to the plot, no fit was found. The expected rate for styrene, interpolated from the Hammet plot, is 0.18 times the observed rate for styrene-$d_5$. Although there is precedent for $\beta$ secondary isotope effects acting through a conjugated linkage,[18] the observed styrene-$d_5$ rate is too great to be justified by effects of the styrene ring deuterium. Thus, no definite conclusion can be drawn regarding the substrate electronic effects. An earlier study of the effect of the *para*-substituent on benzylidene complexes reacting with 1-hexene showed only small and non-linear electronic effects.[7] However, it is clear that electron rich olefins, such as *p*-methoxystyrene, react faster than electron poor olefins, such as *p*-nitrostyrene, presumably due to a better ability to coordinate to the metal center.

**Table 2** – Kinetic Data for Hammet Plot using 0.018 M complex with 31 equivalents of olefin in $C_6D_6$.

| $\sigma_p^+$ | Reaction | Temp / $^oC$ | k ± SDOM[a] / L/mole•sec |
|---|---|---|---|
| **0.740** |  | 7 | $9.6 \pm 0.9 \times 10^{-5}$ |
| **0.035** |  | 7 | $3.71 \pm 0.04 \times 10^{-4}$ |
| **-0.256** |  | 7 | $5.5 \pm 0.2 \times 10^{-4}$ |
| **-0.648** |  | 7 | $1.5 \pm 0.4 \times 10^{-3}$ |
| **0** |  | 7 | $2.15 \pm 0.01 \times 10^{-3}$ |

[a] SDOM = Standard Deviation of the Mean

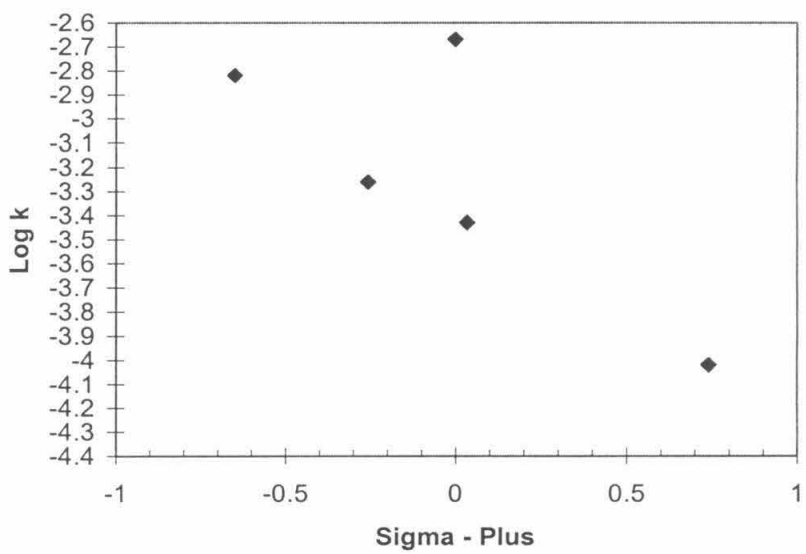



**Figure 2** – LFER for the reaction of benzylidene **(2)** with para-substituted styrenes in $C_6D_6$ at 7 °C.

## Conclusion

The relative rates of metathesis of various olefinic substrates by the ruthenium-based olefin metathesis catalysts have been studied and this work provides guidelines for the utilization of the catalyst for organic syntheses in terms of the relative reactivities of various double bonds in a molecule. In general, increased substituent bulk on the olefin, as well as electron withdrawing substituents, slow down the rate of metathesis reaction. It has been empirically shown that the kinetically preferred metallacycle has the alkyl substituent on the olefin placed adjacent to the metal. If there are two alkyl substituents available, the smaller of the two is placed near the metal in the metallacycle. The selectivity for 2,4 over 2,3-metallacycle formation decreases with increased temperature and therefore cross metathesis reactions need to be run at a slightly elevated temperature, such as refluxing methylene chloride. We have used our results to explain the behavior of the ruthenium catalysts for ring-opening cross metathesis and ADMET processes.

A study of the secondary isotope effect of the incoming olefin showed that a positive effect exists due to the carbon hybridization change in the breakup of the metallacycle, consistent with earlier metallacycle formation studies in other systems.

## Experimental Section

### General Considerations

All kinetics were performed on a GE QE-300 Plus NMR spectrometer (300.1 MHz $^{1}H$) in benzene-$d_6$. Characterization spectra were taken on a JEOL GX-400 (399.1 MHz $^{1}H$; 161.0 MHz $^{31}P$). The deuterated solvent was purchased from Cambridge Isotope Labs and purified by passing through a column of LaRoche A-2 alumina and

Engelhard Q-5 reactant (supported copper oxide).[19] The carbene complexes were all synthesized according to the published procedures.[8] The olefins were all purchased from Aldrich, except for *p*-nitrostyrene which was purchased from TCI America and *cis*-3-hexene and 4-methyl-1-pentene which were purchased from Wiley Organics. Before use, all olefins were passed through a column of activated alumina and purged with argon.

## Reaction Rate Measurements

For the kinetics, stock solutions of 0.018 M carbene complexes were used containing an internal standard of anthracene and stored in the freezer of a nitrogen filled dry box at -32 $^{o}$C. Each sample contained 0.50 mL of carbene solution at the appropriate temperature to which was added 0.285 mmol of olefin (31 equiv.) and data collection was immediately started. Data was collected over 1.5 half-lives of the initial carbene, integrating the carbene proton or the *ortho* protons of the benzylidenes relative to the anthracene internal standard. First order fits were obtained for all experiments under these pseudo-first-order conditions. Second order rate constants were calculated from the pseudo-first order rate constants for a series of olefins reacting with carbene complexes, as listed in Table 1. Clean conversions were observed unless noted otherwise. A representative plot is shown in Figure 3.

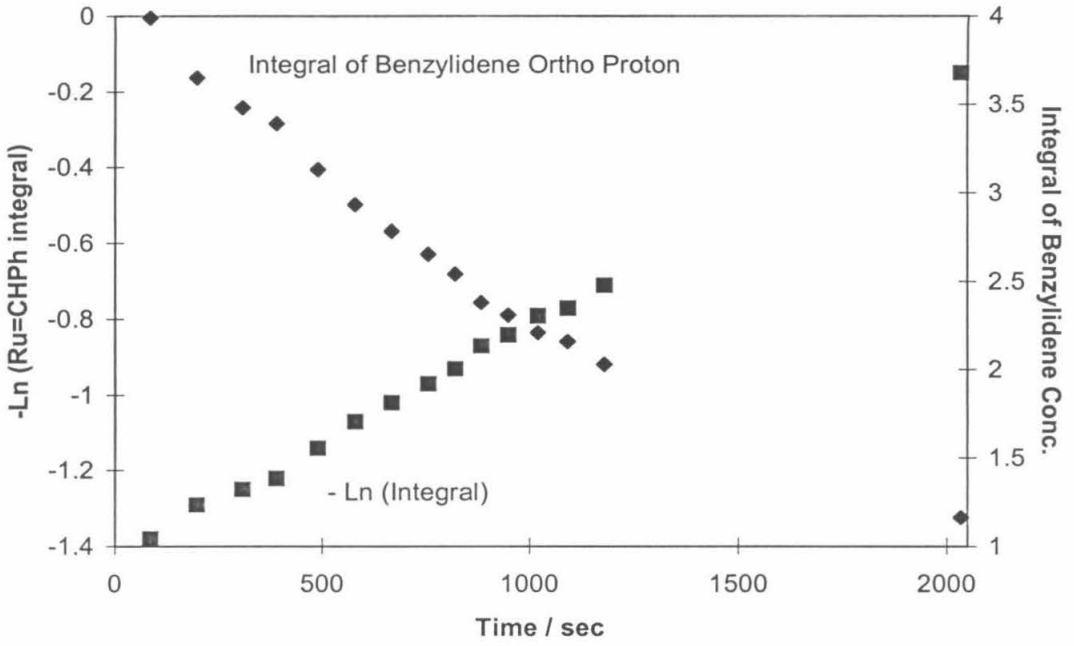



**Figure 3** – Representative kinetic plot for the metathesis of styrene-$d_8$ with benzylidene **(2)** at 7 °C in $C_6D_6$.

## References and Notes


[1] Late transition metals offer greater functional group tolerance. See: Grubbs, R. H. *J. M. S.-Pure Appl. Chem.*, **1994**, A31, 1829.

[2] For several reviews see: a) Grubbs, R. H.; Tumas, W. *Science*, **1989**, 243, 907. b) Schrock, R. R. *Acc. Chem. Res.* **1990**, 23, 158. c) Stelzer, F. *J. M. S. - Pure Appl. Chem.*, **1996**, A33, 941.

[3] a) Grubbs, R. H.; Miller, S. J.; Fu, G. C.; *Acc. Chem. Res.* **1995**, 28, 446. b) Kirkland, T. A.; Grubbs, R. H. *J. Org. Chem.* **1997**, 62, 7310 and references cited therein.

[4] Wagener, K. B.; Boncella, J. M.; Nel, J. G. *Macromolecules* **1991**, 24, 2649.

[5] Nguyen, S. T.; Johnson, L. K.; Grubbs, R. H. *J. Am. Chem. Soc.* **1992**, 114, 3974.

[6] Nguyen, S. T.; Grubbs, R. H. *J. Am. Chem. Soc.* **1993**, 115, 9858.

[7] Schwab, P.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, 118, 100.

[8] Herrison, J. L.; Chauvin, Y. *Makromol. Chem.* **1970**, 141, 161.

[9] For our purposes, we will apply the term alkylidene to signify carbene complexes other than methylidene, $Ru{=}CH_2$, or benzylidene, Ru=CHPh.

[10] Dias, E. L.; Nguyen, S.T.; Grubbs, R. H. *J. Am. Chem. Soc.* **1997**, 119, 3887.

[11] These two phosphines are sterically similar but electronically different. Their similar activity in quenching the intermediate which bulkier phosphines could not stabilize supports steric factors as being more significant than electronic effects. For a review of the steric and electronic properties of phosphines see: Tolman, C. A. *Chem. Rev.* **1977**, 77, 313.

[12] $^{31}P$ NMR ($C_6D_6$): 30.67 ppm (s); $^{1}H$ NMR: 17.70 ppm (doublet of triplets, $J_{PH}$ = 10.3 Hz, $J_{HH}$ = 8.0 Hz).

[13] a) Randall, M. L.; Tallarico, J. A.; Snapper, M. L. *J. Am. Chem. Soc.* **1995**, 117, 9610. b) Schneider, M. F.; Blechert, S. *Angew. Chem. Int. Ed. Engl.* **1996**, 35, 411. c) Snapper, M. L.; Tallarico, J. A..; Randall, M. L. *J. Am. Chem. Soc.* **1997**, 119, 1478. d) Tallarico, J. A.; Bonitatebus, P. J.; Snapper, M. L. *J. Am. Chem. Soc.*, **1997**, 119, 7157.

[14] Reference 13a addressed the potential mechanism for this process where poly-cyclobutene is first formed by ROMP and subsequently depolymerized and metathesized with the terminal olefin to form the ring-opened cross metathesis product. However, when those authors treated poly-cyclobutene with the carbene and terminal olefin, they only obtained 15% of the expected product while treating the cyclobutene with carbene and terminal olefin produced 80% yields by GC. Thus it is very unlikely that

polymerization is a significant pathway towards the products of ring opening cross-metathesis while the mechanism in Scheme 4 is consistent with the results.

[15] For a brief discussion of secondary kinetic isotope effects, see for example: Lowry, T. H. and Richardson, K. S. *Mechanism and Theory in Organic Chemistry*, 3rd ed.; Harper and Row; New York, 1987; pp238-240.

[16] Lee, J. B.; Ott, K. C.; Grubbs, R. H. *J. Am. Chem. Soc.* **1982**, 104, 7491.

[17] Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, 80, 4979.

[18] Shiner Jr., V. S.; Verbanic, C. J. *J. Am. Chem. Soc.* **1957**, 79, 373.

[19] Pangborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, 15, 1518.

# Chapter 3

## A Series of Ruthenium(II) Ester-Carbene Complexes As Olefin Metathesis Initiators: Metathesis of Acrylates

## Abstract

A series of ester-carbene complexes was synthesized. These complexes were found to be highly active for the metathesis of olefinic substrates, including acrylates and trisubstituted olefins. In addition, the ester-carbene moiety is thermodynamically high in energy. As a result, these complexes react to ring-open cyclohexene by metathesis to alleviate the thermodynamic strain of the ester-carbene ligand.

## Introduction

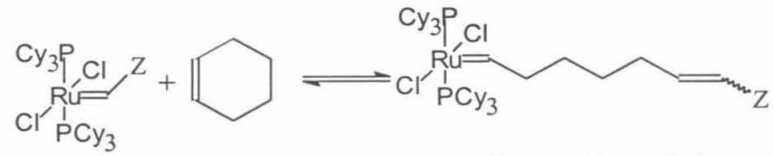
Over the past several years the use of ruthenium based olefin metathesis catalysts, of the general formula $L_2X_2Ru{=}CHR$, has become common in organic synthesis.[1] Previous work has examined the effects of the ligand sphere on catalyst activity, including the effect of L-type ligands,[2] X-type ligands,[2a] chelating ligands,[3] and the effect of carbene derivatives on catalyst initiation.[4] With the development of a novel way to make ruthenium carbenes through a double oxidative addition of an $\alpha,\alpha$-dichloroalkane to a Ru(0) precursor,[5] a new way became available for the straightforward synthesis of a variety of new carbene complexes for further studies of catalyst initiation. This chapter describes the synthesis and activity of ester-carbenes of the general formula: $Cl_2(PCy_3)_2Ru{=}CHCO_2R$.

## Results and Discussion

The first ruthenium-based metathesis-active ester-carbene, $Cl_2(PPh_3)_2Ru{=}CHCO_2Et$ **(1)**, was synthesized by the addition of ethyl diazoacetate to $RuCl_2(PPh_3)_3$.[6,7] However, this complex **(1)** was found to be very thermally unstable in solution, even at low temperature, making isolation of the pure product difficult.

Subsequent work led to the isolation of the methyl ester-carbene complex **(2a)** by the addition of methyl dichloroacetate to ruthenium bis(hydrido) (cyclohexene) bis(tricyclohexyl phosphine) in pentane such that the resulting carbene complex precipitated and decomposition was avoided.[5a]

The methyl ester carbene **(2a)** was thermally unstable at room temperature in solution, decomposing over several hours, but proved to be very active for the initiation of metathesis. A remarkable property of this initiator was that it reacted with cyclohexene to form the ring-opened metathesis product (Scheme 1). This was unexpected because metathesis reactions are thermodynamically driven and stable six-membered rings are thermodynamically stable such that the reaction equilibrium typically lies exclusively on the cyclohexene side, within NMR detection limits, as is the case for the benzylidene $Cl_2(PCy_3)_2Ru{=}CHPh$, **(3)**. The fact that the ester-carbene reacts with cyclohexene suggests that there is enough stabilization achieved by converting the less stable ester carbene into an alkyl-carbene to drive the equilibrium towards the ring-opened product. In an effort to study the activity and stability of the ester-carbene complexes, a series was prepared with different ester groups **(2)**. These complexes vary in stability but all exhibit very high rates of initiation for olefin metathesis and all are capable of the ring-opening of cyclohexene.



**2a** Z = $CO_2$-methyl
**2b** Z = $CO_2$-*p*-tolyl
**2c** Z = $CO_2$-*t*-butyl
**2d** Z = $CO_2$-*i*-propyl
**2e** Z = $CO_2$-cyclohexyl
**2f** Z = $CO_2$-1-adamantyl
**3** Z = phenyl

**5a** Z = $CO_2$-methyl
**5b** Z = $CO_2$-*p*-tolyl
**5c** Z = $CO_2$-*t*-butyl
**5d** Z = $CO_2$-*i*-propyl
**5e** Z = $CO_2$-cyclohexyl
**5f** Z = $CO_2$-1-adamantyl
**6** Z = phenyl

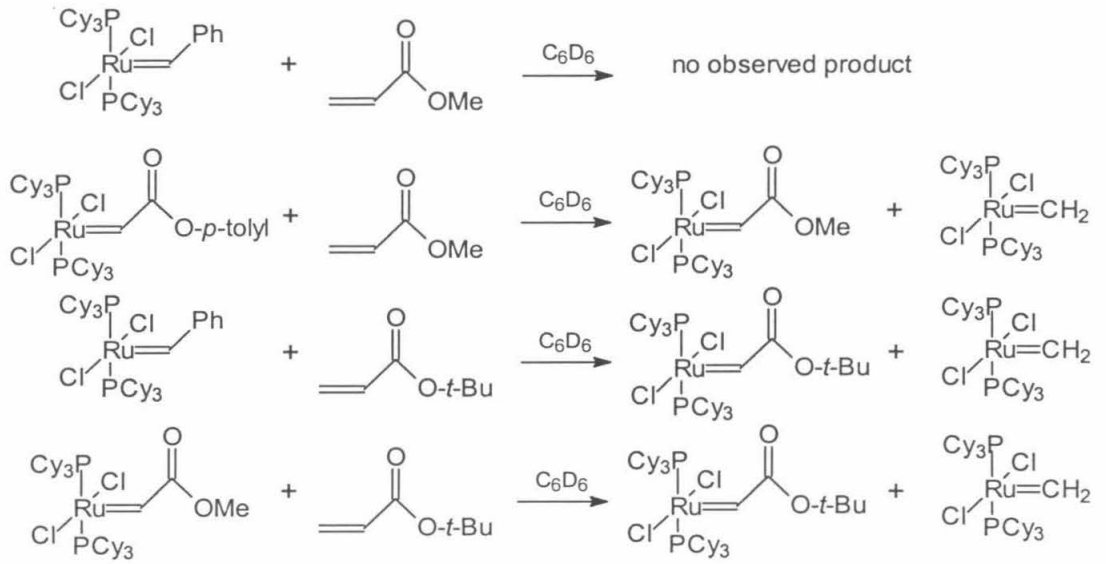
**Scheme 1** – Ring opening of cyclohexene by metathesis with ruthenium carbene complexes.

The order of increasing decomposition rate at room temperature (proceeding through the same bimolecular mechanism observed for the alkyl-carbenes[8]), for the series of ester carbenes is 1-adamantyl ≅ cyclohexyl < isopropyl < *t*-butyl < *p*-tolyl < methyl. The second order rate constants for the decomposition are shown in Table 1. Decomposition data collection was started 20 minutes after dissolving the samples in benzene (0.016 M) at room temperature and data collection was ceased at 400 minutes after dissolution.[9] It is interesting to note that the amide carbene **(4)** is stable indefinitely. It is also notable that the *t*-butyl ester carbene is significantly less stable than expected based on its bulk. In the other cases the stability was increased by increasing the ester group size to inhibit bimolecular decomposition. An attempt was made to examine the electronic effects of the ester by making the tri-, hexa- and nanofluorinated *t*-butyl esters. However, all attempts at isolating these carbene products failed as the rates of decomposition rival the rate of formation. Similarly, *p*-nitrophenyl dichloroacetate reacted with the cyclohexene ruthenium precursor with no observed ester carbene formation, suggesting that electron-poor esters are particularly unstable. All the isolated esters were found to be active for metathesis and readily ring-opened cyclohexene, while the amide-carbene **(4)** was active for acyclic metathesis but did not ring-open cyclohexene.

**Table 1** – Spectral analysis of ruthenium ester/amide-carbene complexes, $Cl_2(PCy_3)_2Ru{=}CHC(O)\text{-}Y\text{-}R$ and the rate constants for their decomposition.

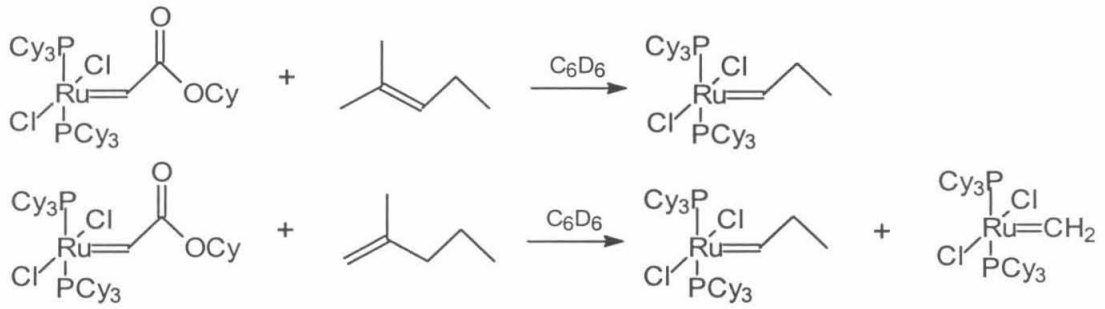
| | -Y-R | $^1H$ ($C_6D_6$) | $^{31}P$ ($C_6D_6$) | $^{13}C$ ($CD_2Cl_2$) | $k_{dec}$ (L/molar·min) |
|---|---|---|---|---|---|
| **2a** | -O-Me | 20.15 s | 38.66 s | 276.37 t | 0.6 |
| **2b** | -O-p-tolyl | 20.33 s | 38.43 s | 273.68 t | 0.5 |
| **2c** | -O-t-Bu | 20.13 s | 37.05 s | 281.67 t | 0.4 |
| **2d** | -O-i-Pr | 20.18 s | 37.75 s | 278.90 t | 0.3 |
| **2e** | -O-cyclohexyl | 20.21 s | 37.70 s | 279.38 t | 0.2 |
| **2f** | -O-(1-adamantyl) | 20.19 s | 37.33 s | 282.47 t ($C_6D_6$) | 0.2 |
| **4** | $-NH_2$ | 20.35 s | 40.29 s | 291.87 t | 0 |

To further examine the relative thermodynamic stability of ester-carbenes **(2)** and the benzylidene **(3)**, the ruthenium benzylidene was reacted with excess methyl acrylate (Scheme 2) in $C_6D_6$ but no new product was observed, though the benzylidene **(3)** was consumed over the course of 12 hours. Presumably this is because the rate of product decomposition rivals the slow rate of product formation. Meanwhile, the reaction of the *p*-tolyl ester-carbene **(2b)** with excess methyl acrylate rapidly produced the methyl ester-carbene **(2a)** and a minute amount of methylidene,[4] along with significant decomposition. However, both the benzylidene **(3)** and the methyl ester-carbene **(2a)** react with excess *t*-butyl acrylate to form a mixture of the *t*-butyl ester carbene **(2c)** and the methylidene, though the benzylidene reacted far slower and to a smaller extent. These observations imply that both the benzylidene and the ester carbenes react with excess acrylates but the ester-carbenes undergo reaction more readily.




**Scheme 2** – Metathesis of acrylates.

Having established that the ester carbenes are more active towards olefin metathesis than any ruthenium bis-L-type ligand carbene isolated to date,[10] an attempt was made to take advantage of this high activity and test its limits by reacting the carbenes with olefins which are ordinarily resistant towards ruthenium catalyzed metathesis. We first attempted to react dicyclohexyl maleate with the *t*-butyl ester-carbene, hoping that the two of the more stable ester-carbenes would yield the highest chance of observing the product. However, no reaction was observed. The experiment was repeated with the methyl ester-carbene to try to minimize the steric interaction of the carbene and substrate, but again no reaction was observed. An attempt was then made to metathesized 2-methyl-2-pentene and 2-methyl-1-pentene, both of which do not react with the ruthenium benzylidene. Reaction of the cyclohexyl ester-carbene with the former olefin produced the propylidene. The latter olefin produced both the propylidene and the methylidene. The propylidene must have been formed from the metathesis of the internal olefin produced from the isomerization of the terminal olefin by ruthenium decomposition products.[8]



**Scheme 3** – Ester-carbene metathesis of challenging substrates.

## Conclusion

In conclusion, a new series of ruthenium (II) carbenes have been synthesized which exhibit remarkable olefin metathesis activity but suffer from poor solution stability. If used for ring opening metathesis polymerization (ROMP), these complexes hold promise for the synthesis of telechelic ester terminated polymers. These complexes also show promise in other systems where rapid initiation is required. Once initiated, the reaction is identical to that of the well studied ruthenium benzylidene initiator.

## Experimental

### General Considerations

All stability studies were performed on a GE QE-300 Plus NMR spectrometer (300.1 MHz $^{1}H$) in benzene-$d_6$. Characterization spectra were taken on a JEOL GX-400 (399.1 MHz $^{1}H$; 161.0 MHz $^{31}P$). The deuterated solvent was purchased from Cambridge Isotope Labs. Deuterated benzene was purified by passing through a column of LaRoche A-2 alumina and Engelhard Q-5 reactant (supported copper oxide)[11] while deuterated methylene chloride was stirred over $CaH_2$ for 48 hours, degassed by three freeze-pump-thaw cycles and vacuum transferred into a Kontes valve Schlenk. The olefins and

dichloroacetamide were all purchased from Aldrich. Before use, all olefins were passed through a column of activated alumina and purged with argon.

**$(Cy_3P)_2(H_2)_2Ru$(cyclohexene)**

2.3 g $[RuCl_2(COD)]_x$, 4.6 g tricyclohexyl phosphine and 4.5 g sodium hydroxide were combined inside the glovebox in a 300 mL Fischer-Porter bottle. On the vacuum line, 150 mL hydrogen-purged *sec*-butanol was added to suspend the reagents. The bottle was pressurized to 2 atm hydrogen and allowed to stir for 8 hours at 85 °C with periodic repressurizing. The reaction was cooled to room temperature and all further manipulations were done under a hydrogen atmosphere. 100 mL water was added and the mixture was filtered through a medium glass frit. The beige $(Cy_3P)_2RuH_6$ solid was washed with water, twice with methanol and once with pentane. It was dried under a slow hydrogen flow through the frit.

The $(Cy_3P)_2RuH_6$ was transferred to a Schlenk in the glove box and on the vacuum line 20 mL degassed cyclohexene was added under an argon atmosphere. The exothermic reaction was stirred for 1 hour and the color turned black. The olefin was removed under vacuum and the solid washed repeatedly with pentane until it was pale yellow. $^1H$ –5.73 ppm, $^{13}P$ 59.36 ppm in $C_6D_6$.

**Dichloroester compounds**

Each alcohol was used as commercially available, without further purification. 0.9 molar equivalents of the alcohol was placed in 20 mL methylene chloride along with 0.6 mL dry pyridine. The reaction was cooled to 0 °C and 1 mL dichloroacetic anhydride was added. The mixture was allowed to stir overnight, coming to room temperature as the ice

melted. Water and ether were added and upon phase separation the organic phase was washed with sodium carbonate, ammonium chloride and brine. After drying the solution over sodium sulfate the product was concentrated to a yellow oil and Kugelrohr distilled.

*p*-Tolyl dichloroacetate: $^1$H 1.883 ppm (s, 3 H), 5.422 ppm (s, 1 H), 6.7 ppm (mult., 4 H) in $C_6D_6$.

*t*-Butyl dichloroacetate: $^1$H 1.139 ppm (s, 9 H), 5.304 ppm (s, 1 H) in $C_6D_6$.

*i*-Propyl dichloroacetate: $^1$H 0.80 ppm (d, 1 H), 4.701 ppm (sept., 6 H), 5.305 ppm (s, 1 H) in $C_6D_6$.

Cyclohexyl dichloroacetate: $^1$H 4.6 ppm (mult. 1 H), 5.395 ppm (s, 1 H) in $C_6D_6$.

1-Adamantyl dichloroacetate: $^1$H 1.3 ppm (6 H), 1.8 ppm (3 H), 2.0 ppm (6 H), 5.34 ppm (s, 1 H) in $C_6D_6$.

**Ester Carbenes**

$(Cy_3P)_2(H_2)_2Ru$(cyclohexene) was placed in a 10 mL Schlenk in the glove box. On the vacuum line, 5 mL benzene was added along with 1.2 equivalents of the dichloroester compound. The reaction was stirred for 10 minutes as the reaction changed from a pale yellow suspension to a red/brown solution. The solvent was removed, the residue was washed 3 times with pentane and vacuum dried overnight.

## References and Notes

[1] For recent reviews see: a) Grubbs, R. H.; Chang, S. *Tetrahedron* **1998**, 54, 4413; b) Armstrong, S. K. *J. C. S. Perkin Trans. 1* **1998**, 371.

[2] a) Dias, E. L., Nguyen, S. T., Grubbs, R. H., *J. Am. Chem. Soc.* **1997**, 119, 3887-3897; b) Weskamp, T.; Schattenmann, W. C.; Spiegler, M.; Herrmann, W. A. *Angew. Chem. Int Ed. Engl.* **1998**, 37, 2490; also see corrigendum: Weskamp, T.; Schattenmann, W. C.; Spiegler, M.; Herrmann, W. A. *Angew. Chem. Int Ed. Engl.* **1999**, 38, 262; c) Scholl, M.; Trnka, T. M.; Morgan, J. P.; Grubbs, R. H. *Tetrahedron. Let.* **1999**, 40, 2247; d) Huang, J.; Stevens, E. D.; Nolan, S. P.; Petersen, J. L. *J. Am. Chem. Soc.* **1999**, 121, 2674; e) Scholl, M., Ding, S., Lee, C. W., Grubbs, R. H. *Organic Letters* **1999,** 1, 953-956.

[3] a) Chang, S.; Jones, L.; Wang, C. M.; Henling, L. M.; Grubbs, R. H. *Organometallics*, **1998**, 3460. b) Sanford, M. S.; Henling, L. M.; Grubbs, R. H. *Organometallics*, **1998**, 17, 5384.

[4] Ulman, M.; Grubbs, R. H. *Organometallics*, **1998**, 17, 2484.

[5] a) Belderrain, T. R.; Grubbs, R. H. *Organometallics* **1997**, 16, 4001. b) Similar chemistry was independently reported: Olivan, M.; Caulton, K. G. *Chem. Comm.* **1997**, 1733.

[6] The use of ethyl diazoacetate to initiate metathesis was also studied by Demonceau, A.; Noels, A. F.; Saive, E.; Hubert, A. J. *J. Mol. Cat.* **1992,** 76, 123.

[7] France, M. B. Ph. D. Thesis. California Institute of Technology, **1995**.

[8] Ulman, M.; Grubbs, R. H. *J. Org. Chem.* **1999**, 64, 7202.

[9] The decomposition data obtained for the first 20 minutes of decomposition did not fit second order kinetics. For a more detailed discussion of the decomposition pathways for the ruthenium catalysts, see Chapter 4.

[10] The catalysts based on N-heterocyclic carbene ligands reported in references 2b-e are very active for propagating olefin metathesis, but the rates of catalyst initiation are rather slow and significantly lower than for the ester carbenes. In metathesis initiated by the ester carbenes, the ester carbene functionality is lost in the first catalyst turnover so the rates of propagation are equivalent to those achieved with the other bis-phosphine initiators. In claiming that the ester carbenes are the most active catalysts, the implication is only for the first turnover after which the ester functionality is lost.

[11] Pangborn, A. B.; Giardello, M. A.; Grubbs, R. H.; Rosen, R. K.; Timmers, F. J. *Organometallics* **1996**, 15, 1518.

# Chapter 4

## Ruthenium-Carbene Based Olefin Metathesis Initiators:

## Catalyst Decomposition and Longevity

## Abstract

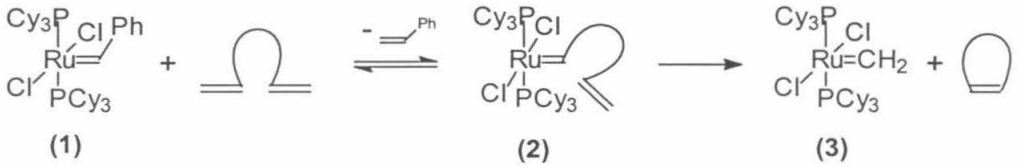
Thermolytic decomposition pathways were studied for several ruthenium-carbene based olefin metathesis catalysts. Substituted carbenes were found to decompose through bimolecular pathways while the unsubstituted carbene (the methylidene) was found to decompose unimolecularly. The stability of several derivatives of the bis-phosphine ruthenium-based catalysts was studied for its implications to ring-closing metathesis. The reasons for the activity and stability of the different ruthenium-based catalysts is discussed.

## Introduction

In recent years, the use of ruthenium carbene based olefin metathesis initiators[1] has gained wide acceptance in organic[2] and polymer syntheses.[3] Ruthenium based catalysts exhibit greater functional group tolerance, as well as greatly enhanced air and water stability, relative to other popular single component catalyst systems based on molybdenum and tungsten.[4] However, thermolytic decomposition limits the usefulness of the ruthenium system in many challenging reactions. Understanding and controlling the decomposition pathways is essential for the increased efficiency of these catalysts.

Although the benzylidene complex, $(PCy_3)_2Cl_2Ru{=}CHPh$ **(1)**, is used to initiate most metathesis reactions, the propagating species in ring closing metathesis (RCM)[2, 5] is usually either an alkylidene,[6] $(PCy_3)_2Cl_2Ru{=}CHR$ **(2)**, where R represents the substrate attached to the catalyst, or the methylidene, $(PCy_3)_2Cl_2Ru{=}CH_2$ **(3)** (Scheme 1), since the original phenyl of the starting carbene is lost in the first turnover. The propylidene, $(PCy_3)_2Cl_2Ru{=}CHCH_2CH_3$ **(4)**, and the methylidene **(3)** were chosen as representative catalytic species for these decomposition studies. Since only the methylidene is observed

by NMR in a significant quantity during an RCM reaction in progress, the understanding of its stability is critical for designing viable catalyst systems. The work reported in this chapter involved NMR studies on several ruthenium carbene complexes, monitoring their rates of decomposition and their ability to carry out RCM under forcing conditions. The results show which ruthenium catalysts are best suited for RCM and which ligand systems are needed to produce the most viable catalysts.




(1) (2) (3)

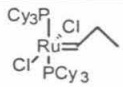
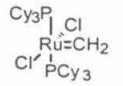
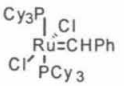
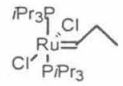
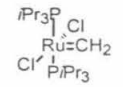
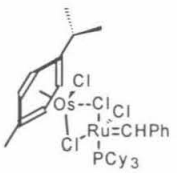
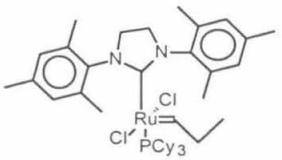
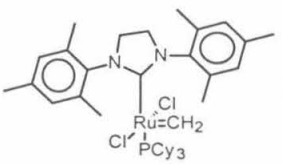
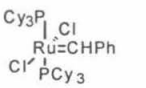
**Scheme 1** – Pathway for Ring Closing Metathesis (RCM).

## Results and Discussion

Under standard decomposition conditions (0.023M in $C_6D_6$ at 55 °C), the propylidene **(4)** has a half-life of around 8 hours while the methylidene **(3)** has a half-life of approximately 40 minutes (Table 1). For reference, a solution of the benzylidene **(1)** has a half-life of about 8 days.

Attempts to fit the propylidene **(4)** decomposition data to simple rate equations were unsuccessful. The data, covering several half-lives, fit neither first nor second order kinetics plots. For the second order equation, the fitted data was significantly nonlinear at short reaction times but fairly linear at intermediate times.

**Table 1** – Thermolytic half-lives of complexes in $C_6D_6$.

| Carbene | Temp | Conc. | Half-Life |
|---|---|---|---|
|  **(4)** | 55 °C | 0.023 M | 8 hrs |
|  **(3)** | 55 °C | 0.023 M | 40 min |
|  **(1)** | 55 °C | 0.023 M | 8 days |
|  **(7)** | 55 °C | 0.023 M | 10 hrs |
|  **(8)** | *25 °C* | *0.039 M* | 30 min |
|  **(11)** | 55 °C | 0.023 M | 30 min |
|  **(16)** | 55 °C | 0.023 M | 3.5 days |
|  **(17)** | 55 °C | 0.023 M | 6 hrs |
|  + CuCl | 55 °C | 0.023 M | 10 min |

To gain an understanding of the pathway of decomposition, the NMR spectra of the decomposition reaction mixture was examined. The $^{31}P$ NMR spectrum of the propylidene **(4)** decomposition reaction mixture showed that the predominant product

was free $PCy_3$ but a number of other small unidentifiable phosphine signals also grew in over the course of the decomposition. This multitude of phosphine signals prevented the determination of the discrete inorganic decomposition products. When decomposition was carried out in the presence of excess phosphine, the rate of decomposition slowed significantly (Figure 1). However, because the catalytic activity of the ruthenium system depends on the dissociation of a phosphine ligand,[7] slowing the rate of decomposition with the addition of excess phosphine would also inhibit productive metathesis.

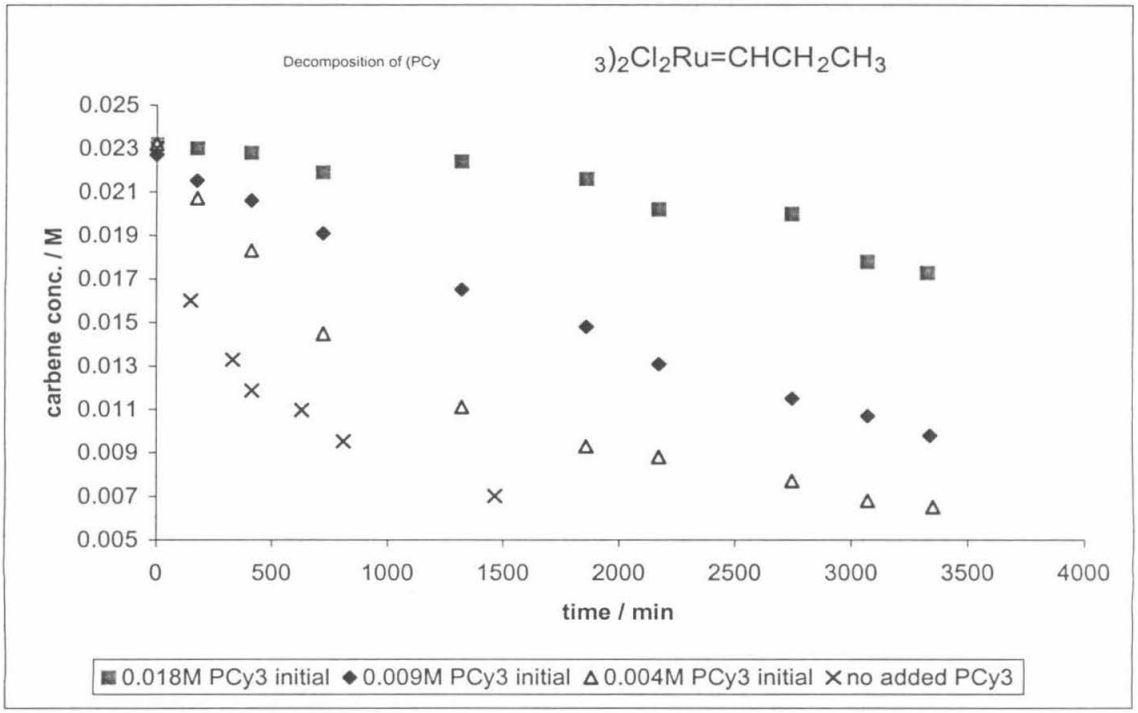
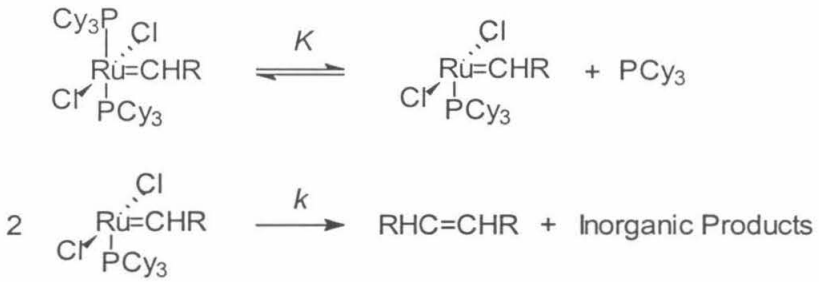



**Figure 1** - Phosphine dependence of decomposition at 55 °C.

The most notable aspect of the $^1H$ NMR spectrum of the decomposition of propylidene **(4)** was the initial quantitative formation of *trans*-3-hexene (dimerization of the organic fragment of the complex) while there was still a large amount of intact carbene present. Over time, additional olefinic peaks appeared in the spectrum. These

were accompanied by the formation of a new quartet carbene signal (19.66 ppm, $J_{HH}$ = 4.9 Hz) next to the propylidene **(4)** $H_\alpha$ triplet (19.60 ppm, $J_{HH}$ = 4.9 Hz). The presence of minute signals at –7 ppm suggested that *some* of the decomposition products were ruthenium hydrides. These provide a possible explanation for the formation of the new olefins and the new carbene. The hydrides could isomerize the dimerized carbene fragments, the 3-hexene, to 2-hexenes and possibly other olefins. Metathesis of 2-hexenes would form the ethylidene, $(PCy_3)_2Cl_2Ru{=}CHCH_3$ **(5)**, which accounts for the quartet carbene signal (coupling to $CH_3$).[1c]

These observations are consistent with a decomposition mechanism involving dissociation of a phosphine followed by coupling of the two monophosphine species[8,13] (Scheme 2). The build up of generated free phosphine as the decomposition progresses is expected to inhibit the formation of the mono-phosphine species and retard the rate of decomposition. This effect would be most significant at low conversion when the greatest changes in phosphine concentration are taking place, which is consistent with the data.




**Scheme 2** – Proposed pathway for alkylidene decomposition.

Assuming a pre-equilibrium in the first step and the formation of *n* moles of *free* phosphine for every mole of decomposed $(PCy_3)_2Cl_2Ru{=}CHR$ **(2)**, the following rate equation was deduced for alkylidene decomposition:

$$\frac{d[conc]_t}{dt} = \frac{Kk}{n^2}\frac{[conc]_t^{\,2}}{([conc]_0 - [conc]_t)^2} \quad (1)$$

$$f(conc) = 2([conc]_0)\,Ln\frac{[conc]_0}{[conc]_t} + \frac{([conc]_t - [conc]_0)([conc]_t + [conc]_0)}{[conc]_t} = \left(\frac{kK}{n^2}\right)t \quad (2)$$

where $[conc]_t$ is the concentration of the alkylidene at time t, $[conc]_0$ is the initial alkylidene concentration, $K$ is the equilibrium constant for the first step and $k$ is the rate constant for the second step. An integration of equation 1 produced equation 2. Fitting the observed data to equation 2 yielded a fairly good fit at low and intermediate conversion but a poor fit at high conversion (Figure 2). This is presumably because at high conversion the generated free phosphine is consumed by the intractable ruthenium byproducts such that the data does not fit the equation which incorporates the *expected* amount of free phosphine (in other words, $n$ is variable over the latter stages of decomposition).

In contrast to the propylidene **(4)**, the methylidene **(3)** decomposition data, surprisingly, fit a *first order* kinetics plot and the presence of excess free phosphine did not effect the rate of decomposition. No ethylene formation was observed by $^1H$ NMR from methylidene decomposition and while the $^{31}P$ NMR exhibits many small peaks, the major peaks are free phosphine and an unknown at 34.6 ppm. Attempts to identify this unknown by crystallography were unsuccessful. This unknown is not the phosphine ylide, $Cy_3P{=}CH_2$, which was independently prepared.

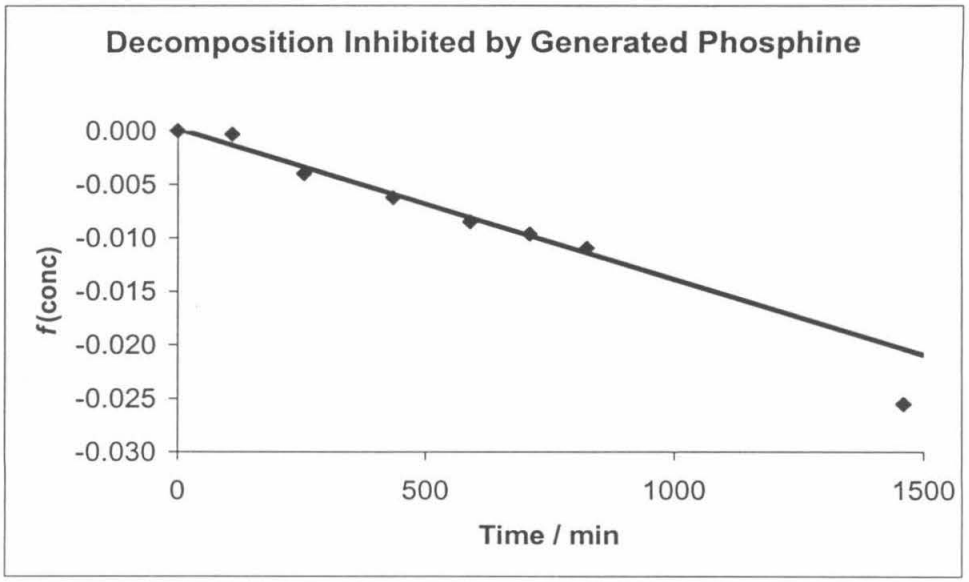
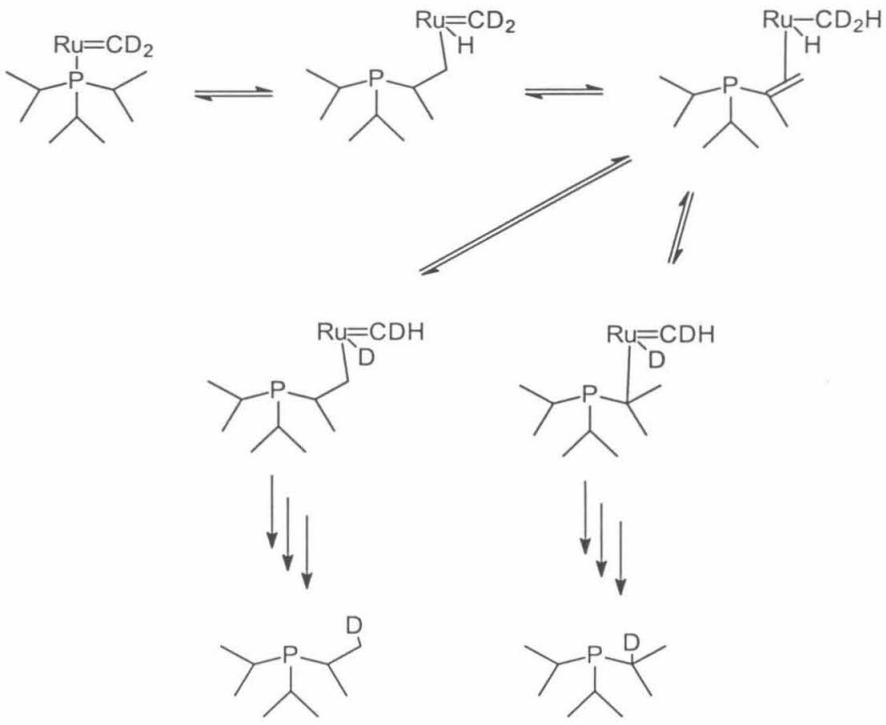



**Figure 2** – Decomposition data fit of 0.0383M propylidene **(4)** to mechanism in Scheme 1. The *f*(conc) represents the function of equation 2.

To better understand the decomposition of the methylidene **(3)**, the deuterated carbene complex analog, $(PCy_3)_2Cl_2Ru{=}CD_2$ **(6)**, was studied by $^2H$ NMR. The deuterium signal, originally a fairly sharp 19.3 ppm peak corresponding to the carbene, was observed as a broad signal at 2.5 ppm in the decomposition mixture. Since the chemical shift suggests that the carbene fragment becomes a saturated aliphatic product, there is presumed to be either an activation of the phosphine[9] or solvent activation involved in the decomposition pathway. However, similar decomposition products occur in benzene, THF and methylene chloride. Furthermore, a sample of $d_2$-methylidene **(6)** stored as a solid in a dry box for several years also showed some decomposition with the deuterium label partially showing up as a broad signal around 2 ppm. This supports the phosphine activation hypothesis for methylidene decomposition, though solvent activation cannot be excluded as a contributing pathway.

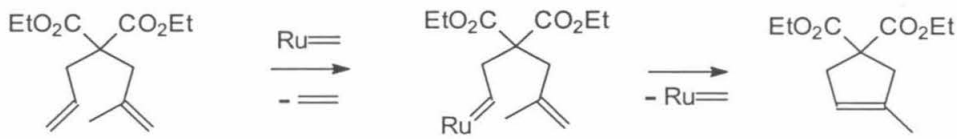
To simplify the investigation of phosphine activation, the triisopropyl phosphine analogs of the propylidene and methylidene were synthesized, since this phosphine only has two types of protons. The triisopropyl phosphine propylidene, $(P\textit{i}Pr_3)_2Cl_2Ru{=}CHCH_2CH_3$ **(7)**, exhibited a half-life of approximately 10 hours under standard conditions (Table 1). This is not surprising since $P\textit{i}Pr_3$ dissociates slightly less readily than $PCy_3$[11a] and dissociation is proposed to be the first step toward decomposition. Otherwise, the kinetics were analogous to the $PCy_3$ case with inhibition by newly generated free phosphine. However, the triisopropyl phosphine methylidene, $(P\textit{i}Pr_3)_2Cl_2Ru{=}CH_2$ **(8)**, was unexpectedly very unstable. It completely decomposed in less than 8 minutes at 55 °C and so its decomposition was studied at 25 °C. The half-life of a 0.039 M solution was just over 30 minutes at 25 °C and the data fit first order kinetics fairly well. However, upon the addition of free phosphine the rate of decomposition was *slightly* retarded, though not enough to invoke a phosphine dissociative mechanism, and the data fit neither first nor second order kinetics. Decomposition of the deuterated analog $(P\textit{i}Pr_3)_2Cl_2Ru{=}CD_2$ **(9)** and isolation of the phosphine showed incorporation of the deuterium into *both* the primary and tertiary positions on the isopropyl groups, suggesting an isopropenyl intermediate[10] (Scheme 3) and strongly supporting the role of phosphine activation in triisopropyl phosphine methylidene **(8)** decomposition, if not necessarily in $PCy_3$ methylidene **(3)** decomposition.




**Scheme 3** – Proposed pathway for deuterium incorporation into both positions on the triisopropyl phosphine.

The metathesis activity of $PCy_3$ and $PiPr_3$ carbene complexes is similar, with that of the $PCy_3$ about 10 percent greater.[7] Both phosphines are fairly bulky (Tolman cone angle of 170° and 160°, respectively) and exhibit similar electronic parameters (20.564 and 20.592 $cm^{-1}$, respectively) with $PCy_3$ being slightly larger and slightly more electron donating.[11] It is unclear why the $PiPr_3$ methylidene **(8)** is so much less stable. Since at least some of the possible decomposition pathways involve phosphine activation, perhaps $PiPr_3$ activation proceeds faster than $PCy_3$ activation in the present system.[9] However, the slight retarding effect of excess phosphine on the $PiPr_3$ methylidene **(8)** decomposition, but not on the $PCy_3$ methylidene **(3)** decomposition, might invoke a different pathway for decomposition in the $PiPr_3$ case.

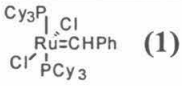
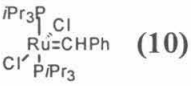
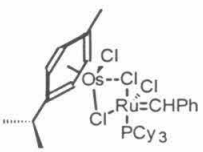
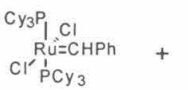
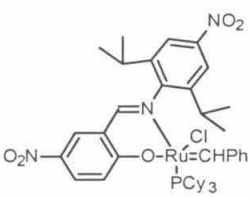
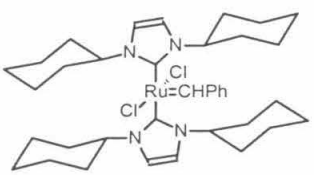
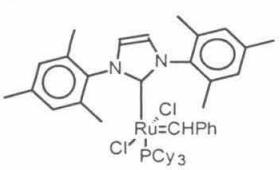
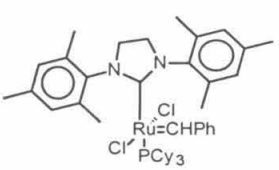
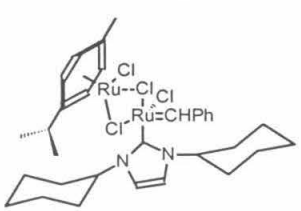
To test the effects of methylidene stability on RCM yields, a series of ring-closing metathesis reactions were performed with several different recently developed ruthenium carbene initiators. The RCM substrate chosen was diethyl allyl methallyl malonate,[5b] which led to a methylidene propagating species and reacted slow enough so that the stability of the methylidene was a major factor in the observed conversion (Scheme 4). The ring-closing results are shown in Table 2.




**Scheme 4** – RCM of diethyl allyl methallyl malonate by propagating methylidene.

During the course of the RCM reaction for **(1)** and **(10)**, the only propagating carbene species observed in significant quantities by $^1$H NMR were the corresponding methylidenes. From a study comparing relative rates for the reactions between ruthenium carbenes and various olefins (Chapter 2)[12a] and earlier work on polycyclizations whereby two distinct products would be formed depending on which olefin the catalyst reacted with first,[12b,c] it can be surmised that initially the catalyst reacts with the less substituted olefin of the diene substrate and then cyclizes to form the methylidene and product. Since the methylidene is the only intermediate observed in significant quantity, we can conclude that its stability is crucial to propagation and longevity.

**Table 2** – Ring closing reactions with diethyl allyl methallyl malonate and various initiators, 5 mol% (0.04 M) catalyst in $C_6D_6$.

| Carbene | Yield | Time at which reaction progress ceased |
|---|---|---|
|  **(1)** | 91% at 25 °C<br>80% at 55 °C | 5 days<br>8 hrs |
|  **(10)** | 67% at 25 °C<br>51% at 55 °C | 2 days<br>1 hr |
|  **(11)** | 18% at 25 °C<br>18% at 55 °C | <10 min<br>< 4 min |
|  + CuCl | 55% at 25 °C<br>65% at 55 °C | 1.5 hrs<br>0.5 hrs |
|  **(12)** | 100% at 55 °C | 2 days, *benzylidene* still present |
|  **(13)** | 20% at 25 °C<br>33% at 55 °C | 4 hrs<br>3 hrs |
|  **(14)** | 98% at 55 °C | 4 hours, methylidene still present |
|  **(15)** | > 95% at 55 °C | < 10 min, methylidene still present |
|  **(18)** | 86% at 55 °C | < 15 min |

Due to a combination of respective methylidene stability and propagation rates, the $PCy_3$ based initiator **(1)** is significantly better for RCM than the $Pi Pr_3$ based analog **(10).** The higher temperature data in particular shows the significance of methylidene stability. The triisopropyl phosphine based catalyst decomposed long before ring-closing all of the available substrate. The bimetallic species[13] **(11)** performed metathesis very rapidly but has a very short life-span. While the bimetallic methylidene cannot be synthesized,[13] the half-life of the 0.023 M benzylidene solution is only approximately 30 minutes at 55 °C (the decomposition data fits second order kinetics). The CuCl activated reaction[9,13] is even more rapid and even less stable, but the high rate of propagation compensates for the rate of decomposition, especially at 55 °C. The benzylidene **(1)** has a half-life of under 10 minutes under standard conditions in the presence of insoluble CuCl[14] (again the decomposition data fits second order kinetics).

The salen ligand bound initiator **(12)**[15] is incredibly stable but performed RCM very slowly. The reaction takes months at room temperature but was fairly rapid at 55 °C, while no catalyst decomposition was observed. However, no propagating species were observed and the only carbene species evident in the NMR spectrum was the starting material. The complex also did not react readily with ethylene, 1-hexene or 3-hexene to generate new carbenes.[16] It would appear that only a small quantity of an active species was generated which performed most of the metathesis while the remaining benzylidene was inactive.

The activity of the bis-dicyclohexyl imidazolin-2-ylidene ruthenium carbene **(13)** for RCM was also investigated.[17] This was the first reported complex of a new class of ruthenium catalysts containing an imidazolinylidene ligand. Despite the extraordinary

activity reported for this catalyst, very limited reactivity was found with the substrate used here under standard conditions. The ring-closing was slow and the intermediates, which were not observed, are presumed to be unstable. Furthermore, attempts to react the bis-imidazolinylidene benzylidene complex with ethylene or *trans*-3-hexene to generate, respectively, the methylidene and propylidene analogs led only to carbene decomposition. Additionally, attempts to synthesize the methylidene and propylidene analogs by adding the imidazolinylidene ligand to the respective phosphine complexes also led only to decomposition. This further supports the hypothesis that the rate of decomposition of the propagating carbenes for this system is quite high with respect to the rate of propagation.

We also examined a modification on the Herrmann catalyst developed in the Grubbs laboratory.[18, 19] This mono-imidazolinylidene mono-phosphine carbene complex **(14)** has been shown to exhibit remarkable activity for the synthesis of tri and tetra-substituted olefins through RCM at elevated temperatures. For ring-closing, the activity at room temperature was found to be very slow but at elevated temperatures fairly rapid activity was observed with high conversion. Furthermore, a methylidene carbene signal was still present in the NMR at the end of the reaction. The marked difference in activity between **(13)** and **(14)** seems to be the ability to lose a ligand in order to generate an active species but then to recoordinate the ligand and reform a stable species.[20] Presumably the imidazolinylidene ligand cannot readily dissociate and reassociate and the "naked" complex is allowed to decompose. To further illustrate this difference, we were able to force the mixed ligand complex **(14)** to react with ethylene, 1-hexene and 3-hexene to form new observable carbenes, unlike the bis-imidazolinylidene complex **(13)**.

The development of complex **(14)** led to an analog with a saturated ligand backbone, **(15)**. While sterically similar, the saturated ligand (imidazolylidene) and the unsaturated ligand (imidazolinylidene) do have some electronic differences, in particular the imidazolylidene is a somewhat stronger sigma donor, but definitive results are still inconclusive.[21] Remarkably, complex **(15)** is far more active for RCM than complex **(14)** but otherwise reacts similarly with acyclic olefins. Furthermore, the methylidene and propylidene derivatives of **(15)** are the most stable ones considered so far, as shown in Table 1 (salen-bound methylidene and propylidene were not synthesized). However, acyclic metathesis with mono-N-heterocyclic carbene species is not as clean as with the bis-phosphine catalysts, as discussed in Chapter 5 of this thesis.

Finally, we examined another similar metathesis initiator **(16)** recently reported by Herrmann's group.[22] This complex combined an imidazolinylidene ligand with the bimetallic catalyst system to achieve the highest activity so far. However, the lack of a reassociating ligand limits this complex's utility. While it is the fastest metathesis initiator yet, the corresponding propagating species is short lived and the catalyst cannot take the reaction to completion. Attempts to react it with ethylene to form the corresponding methylidene led only to decomposition and no new carbene species were observed by NMR.

## Conclusion

From these studies, it is concluded that alkylidene decomposition is predominantly second order, requiring phosphine dissociation, while methylidene decomposition is primarily first order. However, the exact nature of the inorganic

decomposition products is not known. No bimolecular decomposition product (ethylene) was observed from bis-phosphine methylidenes. However, it has been reported that a ruthenium-ethylene complex was observed from the attempted generation of a mono-phosphine bimetallic methylidene[13] suggesting that bimolecular decomposition can occur for the methylidenes but is generally slower, due to the need to dissociate a phosphine, than their unimolecular decomposition pathway. As a result, bimolecular methylidene decomposition is only observed for mono-phosphine methylidene complexes. Furthermore, the high instability of mono-phosphine or mono-L-type-ligand carbene complexes drastically limits their usefulness as metathesis catalysts.

The first order decomposition of methylidenes is very significant in that they are the key propagating species in many ring-closing reactions. The fact that substrates which are difficult to cyclize require high catalyst loadings can now be explained by the unimolecular decomposition of the propagating methylidene catalyst. It is also clear that the choice of phosphine, or phosphine substitute, is critical for effective and stable catalyst systems because even minor alterations in ligand properties can have dramatic consequences. For most applications, the utility of a catalyst is determined by the ratio of the rate of catalysis to the rate of decomposition. Ligand changes that accelerate both processes are not significant improvements in the catalyst system.

## Experimental

All reactions were set up in a nitrogen filled dry box and carried out with the exclusion of air in Teflon-lined screw-cap NMR tubes. The ethylene generated during the RCM reactions was not vented from the reaction mixture so that all reactions were

carried out under equilibrating conditions. All compounds were synthesized as previously reported. The deuterated solvent were purchased from Cambridge Isotope Labs. Benzene-$d_6$ was purified by passing it through a column of LaRoche A-2 alumina and Engelhard Q-5 reactant (supported copper oxide).[23] Methylene chloride-$d_2$ was dried over calcium hydride for 48 hours, degassed by three freeze-pump-thaw cycles and vacuum transferred into a Schlenk tube.

**Typical Decomposition Experiment:** In a ½ dram vial in a dry box, 13.8 μmole of the corresponding complex was weighed out. Anthracene was added as an internal standard along with 0.60 mL $C_6D_6$. The vial was closed and shaken to dissolve the solids. Using a pipet, the solution was then transferred to a screw-cap NMR tube and the cap sealed with electrical tape. The reaction was monitored by $^1$H NMR for several half-lives at 55 $^{o}$C to simulate RCM conditions. Each complex's decomposition was repeated at least two independent times (on different days) to establish reproducibility.

**Typical RCM Experiment:** In a ½ dram vial, 4.1 μmole of the corresponding complex was weighed out in the dry box. 1.0 mL $C_6D_6$ was added and the vial was closed and shaken to dissolve the complex. 20 μL of diethyl allyl methallyl malonate[5b] (20.4 mg) was then added and the vial was again shaken and the solution transferred via pipet into a screw-cap NMR tube and the cap was then sealed with electrical tape. Heating typically began 2.5 minutes after mixing, either using a variable temperature NMR probe for fast reactions or using a temperature controlled oil bath for slow reactions. Data was collected until no further significant conversion occurred (over the next day, a few percent additional conversion was often observed but ignored in the cases in which the

reaction was otherwise effectively complete in under an hour). Each reaction was repeated at least two independent times (on different days) to confirm reproducibility.

**Phosphine Extraction:** Freshly made $(P\textit{i}Pr_3)_2(Cl)_2Ru{=}CD_2$ (from the reaction of $(P\textit{i}Pr_3)_2(Cl)_2Ru{=}CHPh$ and $D_2C{=}CD_2$)[1c] was placed in a J. Young NMR tube in $CH_2Cl_2$. Decomposition was monitored by $^{31}P$ NMR until there was no starting species left. An aqueous solution of $P(CH_2OH)_3$[24] and $NEt_3$ was added. The layers were shaken until the dark brown lower organic layer became tan in color, signifying that most of the metal had been extracted into the aqueous phase. $^{31}P$ NMR of the organic phase showed free $P\textit{i}Pr_3$ along with minor impurities. $^2H$ NMR of the organic phase showed two major signals at 1.8 ppm (1 H) and 1.1 ppm (3.3 H) along with a minor peak for naturally abundant $CDHCl_2$ and three other minor resonances at 6.3, 6.4 and 7.4 ppm.

## References and Notes


[1] a) Nguyen, S. T.; Johnson, L. K.; Grubbs, R. H. *J. Am. Chem. Soc.* **1992**, 114, 3974. b) Nguyen, S. T.; Grubbs, R. H. *J. Am. Chem. Soc.* **1993**, 115, 9858. c) Schwab, P.; Grubbs, R. H.; Ziller, J. W. *J. Am. Chem. Soc.* **1996**, 118, 100. d) Stumpf, A. W.; Saive, E.; Demonceau, A.; Noels, A. F. *J. Chem. Soc., Chem. Comm.* **1995**, 1127. e) Hashmi, A. S. K. *J. Prakt. Chem.* **1997**, 339, 195.

[2] Grubbs, R. H.; Chang, S. *Tetrahedron.* **1998**, 54, 4413 and references cited therein.

[3] For several reviews see: a) Grubbs, R. H.; Tumas, W. *Science*, **1989**, 243, 907. b) Schrock, R. R. *Acc. Chem. Res.* **1990**, 23, 158. c) Stelzer, F. *J. M. S. - Pure Appl. Chem.*, **1996**, A33, 941.

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# Chapter 5

## Concluding Summary and Remarks on N-Heterocyclic Carbene Based Catalysts

## Abstract

The difference in catalyst activity and initiation is discussed for the bis-phosphine based and mixed N-heterocyclic carbene/phosphine based ruthenium olefin metathesis catalysts. The mixed ligand catalysts initiate far slower than the bis-phosphine catalysts but are far more active. A scheme is proposed to explain the difference in reactivity between the two types of catalysts.

## Introduction

The development of single component catalysts for olefin metathesis reactions has produced a ruthenium-based family of catalysts that are both highly active and very tolerant of substrate functionality. Within a period of eight years, the ruthenium system progressed from being able to only metathesize highly strained olefins to being able to react with acrylates and tetrasubstituted olefins.[1] Upon each improvement to the system, derivative catalysts were made to study the specifics of each ligand variation and to examine how they affect the system as a whole.

Chapter 2 of this thesis addressed the relative rates of reaction of different olefins with the bis-phosphine ruthenium catalysts and the substituent orientation in metallacycle formation. It was found that increasing bulk on the olefin decreases the rate of reaction while the orientation of substituents on the metallacycle always kinetically favors a 2,4-configuration. However, bulky olefins lead to the formation of bulky carbenes which induce phosphine lability and therefore activate the carbene complex to further reactivity. This lability can be eased by the formation of a less bulky carbene, namely the methylidene in the case of bulky terminal olefins, which slowly forms through a 2,3-metallacycle.

In varying the structure of the carbene ligand, it was discovered that ester carbenes are very active initiators for olefin metathesis. Chapter 3 discussed the synthesis of the ester carbenes from Ru(0) precursors and the activity of these complexes. The ester carbene functionality in itself is a less thermodynamically stable species than the alkylidenes. The result is that alkylidenes typically do not readily metathesize acrylates because the reaction is endothermic and the equilibrium favors the alkylidene. However, when metathesis of acrylates is initiated by an ester carbene, there is little, if any, free energy difference between the reactants and products, and so conversion takes place. In fact, the ester carbenes are such high energy species that they ring-open cyclohexene and form the ester terminated alkylidene. However, one of the drawbacks of ester carbenes is that they are thermally unstable and decompose at room temperature over a number of hours, depending on the ester group.

The study of ester carbene stability led to the examination of the stability of other carbenes, particularly those involved in the RCM reaction. Chapter 4 considered the modes of decomposition of ruthenium alkylidenes and methylidenes as models for the carbenes which would be present during RCM. As expected, the alkylidenes decompose via a bimolecular pathway involving phosphine dissociation. However, it was surprising to discover that methylidenes decompose via a unimolecular pathway.

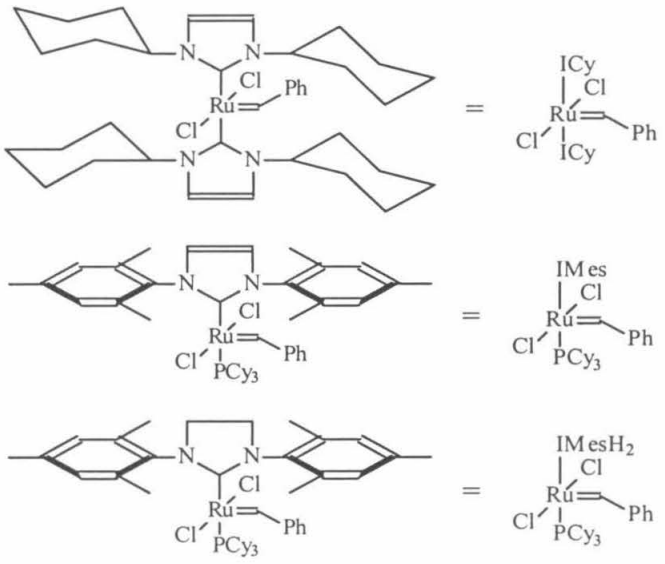
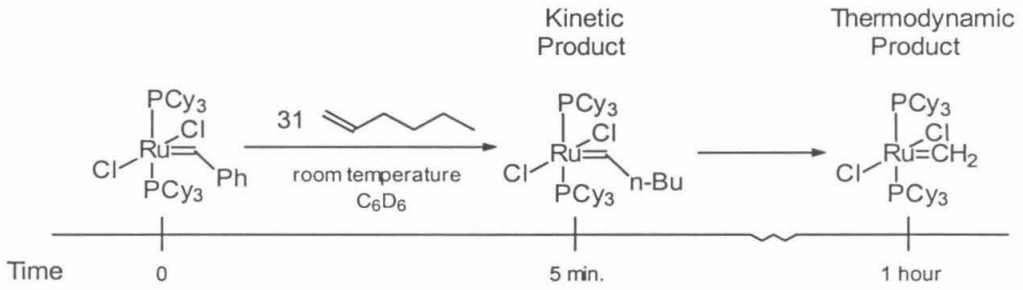



**Figure 1** – N-heterocyclic carbene ligand based olefin metathesis catalysts.

The recent introduction of N-heterocyclic carbene (NHC) ligands[2] to ruthenium-based olefin metathesis systems[3] (Figure 1) has increased the substrate range and catalyst activity for both organic[4] and polymer[5] syntheses, especially with the saturated N-heterocyclic carbene (SNHC) ligands.[1,3d] The stability of these complexes was examined and it was discovered that the mixed ligand complexes were significantly more stable than the bis-phosphine catalysts. As a result, these complexes were better able to complete RCM reactions at lower catalyst loadings. However, while these catalysts are very active for RCM, cross metathesis and ROMP, simple acyclic metathesis reactions of the SNHC bound ruthenium carbene complexes themselves are very slow.

## Results and Discussion




**Scheme 1** – Acyclic metathesis with bis-phosphine catalysts.

In the case of bis-phosphine complexes, the reaction of the carbene with an acyclic olefin produced complete conversion to new carbenes, as discussed in Chapter 2. For example, the reaction of the benzylidene, $(PCy_3)_2Cl_2Ru{=}CHPh$, with 1-hexene led to immediate conversion to the pentylidene, $(PCy_3)_2Cl_2Ru{=}CHCH_2CH_2CH_2CH_3$, as the kinetic product, followed by slower conversion of the pentylidene to the methylidene, $(PCy_3)_2Cl_2Ru{=}CH_2$, as the thermodynamic product (Scheme 1). Oddly, this is not the case with the $IMesH_2$ ligand complexes. The analogous reaction of $(PCy_3)(IMesH_2)Cl_2Ru{=}CHPh$ is slow to initiate, but the initiated species is highly active and reacts very rapidly with additional substrate. The result is that only part of the starting benzylidene is converted to the pentylidene, which is then, presumably, further converted to the methylidene. This process occurs while a significant amount of the benzylidene is still completely uninitiated (Figure 2). The only case where $IMesH_2$ catalyst initiation is complete and reasonably rapid is with ethylene as the substrate, which cleanly forms the methylidene.

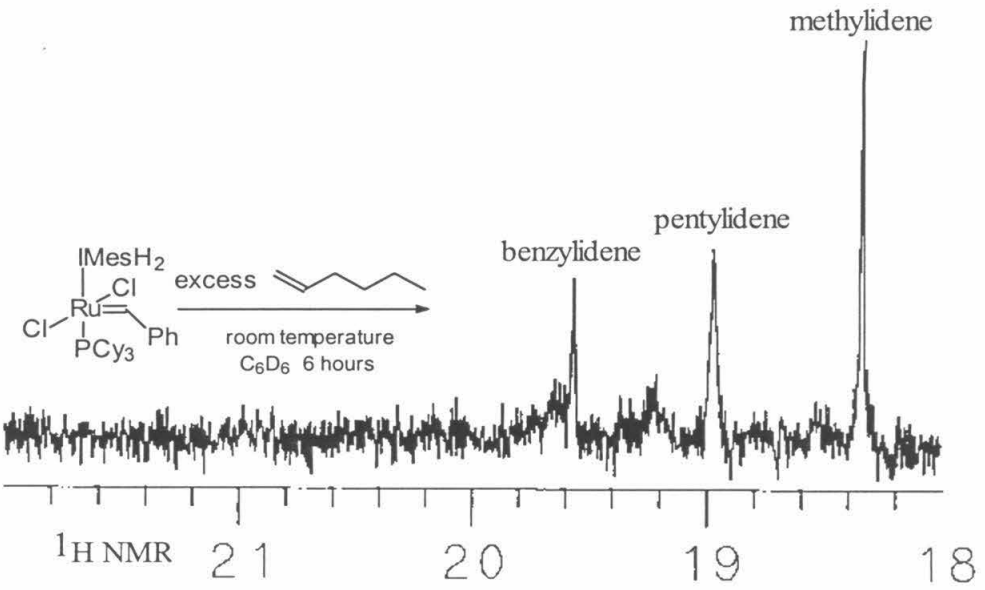



**Figure 2** – Metathesis of 1-hexene by $IMesH_2$ substituted benzylidene.

The reaction of the $IMesH_2$ methylidene with 3-hexene or 1-hexene led to no observed metathesis reactivity. In contrast, the bis-phosphine methylidene is active for the metathesis of these olefins, albeit slowly (as discussed in Chapter 2), and it cleanly forms the propylidene and pentylidene, respectively. However, the $IMesH_2$ methylidene is in fact metathesis active, but it initiates far slower than other $IMesH_2$ bound species. For example, Figure 3 shows the reaction progress of the RCM of diethyl allyl methallyl malonate with the $IMesH_2$ benzylidene and methylidene.

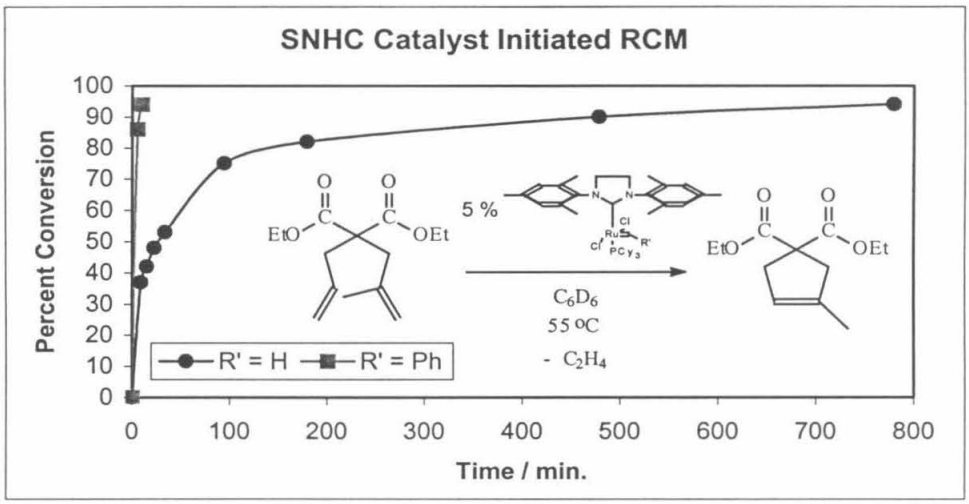
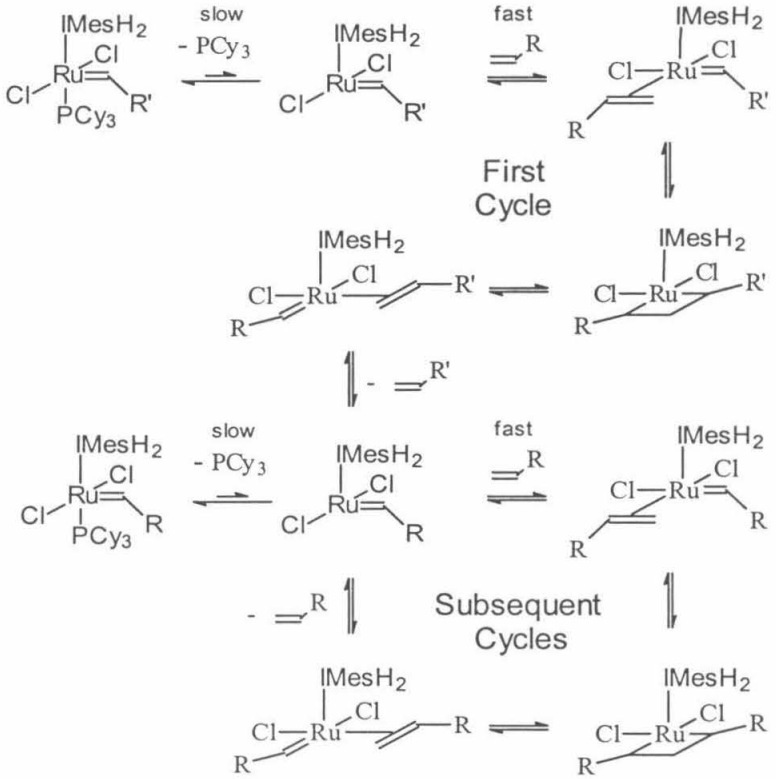



**Figure 3** – RCM of diethyl allyl methallyl malonate with $IMesH_2$-based initiators.

Clearly the propagating species in both cases should be the $IMesH_2$ methylidene, yet the benzylidene initiated reaction is approximately 80% complete before its rate starts to slow down, while the methylidene catalyzed reaction hardly initiates in the same time frame. If the reaction rate difference between the two initiators was merely due to methylidene initiation, then under these 5 mole percent catalyst conditions we would not expect much more than 5% conversion before the two rates would become equal. It can therefore be proposed that the metathesis pathway depicted in the introduction to this thesis, whereby the phosphine dissociates for the duration of one catalyst cycle and then reassociates, does not necessarily apply to $IMesH_2$-based catalysts. A more likely pathway is depicted in Scheme 2 (the minor pathway - without phosphine dissociation - is not shown because it should remain unchanged and insignificant).




**Scheme 2** – Proposed revised metathesis pathway for $IMesH_2$ based systems.

The first step to initiate metathesis requires $(PCy_3)(NHC)Cl_2Ru{=}CHR'$ to dissociate a phosphine and form $(NHC)Cl_2Ru{=}CHR'$. This pre-equilibrium is very slow and heavily favors the undissociated side. Once the phosphine-free complex is generated, it would be extremely active for metathesis. After the first metathesis cycle, the catalytic species can either be quenched with a phosphine or react again. For the $IMesH_2$ case, the pathway to react again is very fast and the catalyst goes through many cycles before being quenched by free phosphine. Herein lies the difference between the $IMesH_2$ methylidene and benzylidene initiated RCM reactions. The benzylidene initiates faster, therefore producing a larger amount of the initial phosphine-free species; these species react many times and ring close the bulk of the substrate before being quenched by free

phosphine. The methylidene, on the other hand, never initiates to a large extent so that even though both reactions are propagated by the same species, the amount of that species initially generated is small for the methylidene initiated reaction and the outcome is an effectively less active catalyst.

For comparison, Figure 4 depicts the RCM of diethyl allyl methallyl malonate using the bis-phosphine benzylidene and bis-phosphine methylidene catalysts. The two rates are almost identical, with the methylidene being slightly faster, presumably due to experimental error.[6] As a result, it can be concluded that the rates of initiation are less significant for the bis-phosphine catalysts than the mixed ligand derivatives.

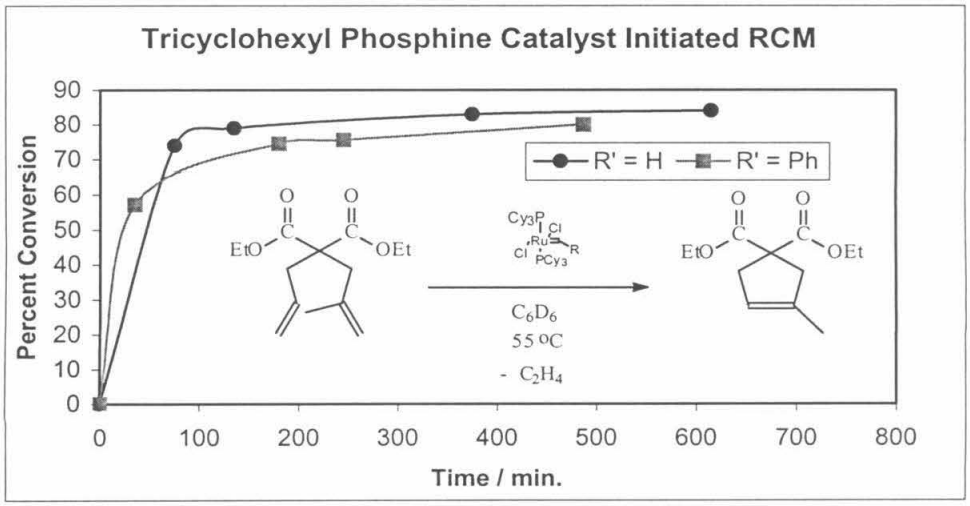



**Figure 4** – RCM of diethyl allyl methallyl malonate with $IMesH_2$-based initiators.

The fact that *complete* conversion of $IMesH_2$ based catalysts to the corresponding methylidene is readily accessible with ethylene can be explained by the size of the substrate. It is feasible that ethylene can coordinate to the NHC/phosphine complex and aid in phosphine dissociation by sterically pushing it off of the metal, similar to the way

bulky carbenes promote phosphine dissociation (Chapter 2). Bulkier substrates, however, cannot readily access the ruthenium due to the cover provided by the phosphine and the imidazolinylidene ligands, and they must wait for the phosphine to dissociate on its own before coordinating to the metal center.

## Conclusion

The work described in this thesis should provide a better understanding of the activity, selectivity and stability of the ruthenium-based olefin metathesis catalysts. With this information in mind, researchers, particularly organic synthetic chemists, can better apply the ruthenium-based catalysts to achieve their synthetic goals.

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[6] The bis-phosphine methylidene catalyzed reaction was monitored on the JEOL GX-400 NMR while all the other reactions were monitored on the GE QE-300 Plus NMR. Differences in integration techniques would be responsible for the slight differences in observed reaction rate.

# Appendix

## Synthesis of Complexes

This appendix contains the procedures used for the synthesis of all compounds used in this thesis, except for well known compounds published elsewhere. Work performed in the glove box was conducted under a nitrogen atmosphere with less than 10 ppm oxygen. Work carried out on the Schlenk-line/vacuum-line was performed under argon. Vacuum attained on the Schlenk line was 60 to 100 mtorr. All solvents were degassed by three freeze-pump-thaw cycles or by argon purging through a needle for 30 minutes per liter of solvent. Solvents were dried by standard techniques, including sodium/benzophenone ketyl and $CaH_2$, as appropriate. Reagents were purified as specified in the procedures below. Reactions starting with $(Cy_3P)_2Cl_2Ru{=}CHPh$ used the complex prepared by the diazo route as published.[1] Reactions starting with $(IMes)(PCy_3)Cl_2Ru{=}CHPh$[2] or $(IMesH_2)(PCy_3)Cl_2Ru{=}CHPh$[3] used the complex synthesized according to the reported procedure. All NMR spectral characterization of previously reported compounds (as referenced in this thesis) matched the published data.

**$(Cy_3P)_2Cl_2Ru{=}CH_2$**

1.64 g $(Cy_3P)_2Cl_2Ru{=}CHPh$ was placed in a 50 mL Schlenk in the glove box. On the vacuum line, 20 mL benzene was added and the solution canula filtered into another Schlenk. The vessel was pressurized with 1 atm ethylene for one hour. The solvent was evaporated until a viscous substance was obtained. The residue was washed 3 times with 5 mL portions of pentane and the ethylene procedure repeated. The final product was dried overnight under vacuum. $^1H$ 19.40 ppm, $^{31}P$ 43.76 ppm in $C_6D_6$.

**$(Cy_3P)_2Cl_2Ru$=CH-n-Bu**

0.5 g $(Cy_3P)_2Cl_2Ru$=CHPh was placed in a Schlenk in the glove box. On the vacuum line, 5 mL methylene chloride was added to dissolve the complex. 3 mL *trans*-5-decene (degassed by vac/argon purge) was added to the reaction. After stirring overnight the reaction was concentrated and washed 2 times with pentane at –78 °C. The olefin reaction was repeated three more times and the residue was vacuum dried overnight. $^1H$ 19.80 ppm triplet ($J_{HH}$ = 5.1 Hz), $^{31}P$ 36.57 ppm in $C_6D_6$.

**$(Cy_3P)_2Cl_2Ru$=CHEt**

0.77 g $(Cy_3P)_2Cl_2Ru$=CHPh was placed in a Schlenk in the glove box. On the vacuum line, 20 mL methylene chloride was added to dissolve the complex. 0.5mL *trans*-3-hexene (filtered through activated alumina and purged with argon) was added and allowed to stir for 6 hours. The reaction was concentrated and the residue was washed 3 times with pentane at –78 °C. The olefin reaction was repeated 3 more times to achieve high conversion. The residue was vacuum dried overnight. $^1H$ 19.60 ppm triplet ($J_{HH}$ = 5.5 Hz), $^{13}P$ 36.9 ppm in $C_6D_6$.

**$(Ph_3P)_2Cl_2Ru$=CH-*i*-Pr**

The procedure for the synthesis of the diazo compound was adapted from the literature.[4] 1.25 g tosylhydrazide was dissolved in 30 mL hot methanol in an erlenmeyer flask. 5 mL isobutyraldehyde was added dropwise. After 20 minutes, the reaction was cooled in an ice bath and pentane was added to precipitate the hydrazone. The solid was filtered, washed with pentane and vacuum dried. 1.6 g of the hydrazone was placed in a 50 mL

Schlenk and evacuated to remove residual oxygen. 15 mL dry THF was added and the mixture cooled to 0 °C. 4.6 mL 1.6 N *n*-butyl lithium was added over 15 minutes. After 15 minutes of stirring the reaction was warmed to room temperature and after an additional 20 minutes of stirring the solvent was removed under vacuum. The temperature of the reaction under vacuum was raised to 136 °C for 1 hour. The residual diazo was dissolved in 6 ml ether and added to 1.16 g $Cl_2Ru(PPh_3)_3$[5] in 15 mL methylene chloride at –78 °C over 5 minutes. After 10 minutes of stirring the reaction was allowed to warm to room temperature. The Schlenk was placed in a warm water bath and the solvent was removed under vacuum. The residue was washed 2 times with 5 mL portions of ether and dried under vacuum overnight. $^1H$ 17.70 doublet of triplets ($J_{HH}$ = 8.0 Hz, $J_{HP}$ = 10.4 Hz), $^{13}P$ 30.67 ppm in $C_6D_6$.

**($iPr_3P)_2Cl_2Ru$=CHEt**

The procedure for the preparation of the mixture of the benzylidene and the benzyl carbene was adapted from Thomas Wilhelm's work.[6]

1 g $[RuCl_2(COD)]_x$ was placed into a Fischer-Porter bottle in the glove box. On the vacuum line, 150 mL degassed *sec*-butanol was added along with 0.5 mL triethylamine and 1.4 mL triisopropyl phosphine. The bottle was pressurized to 2 atm hydrogen and placed in an oil bath at 80 °C overnight. The reaction was cooled to room temperature, purged with argon to expel hydrogen and canula transferred to a Schlenk. Upon cooling to 0 °C, 0.8 mL phenylethylene (activated alumina filtered and argon purge degassed) was added and allowed to stir for 45 minutes at room temperature. 3.6 mL 1.0 N HCl/ether was added and stirred for 90 minutes. Some red precipitate started to form. 100 mL

methanol was added and the reaction cooled to –78 °C to precipitate the remainder of the product. The solvent was removed by canula filtration and the residue washed with cold methanol and vacuum dried. Upon examining the product mixture by NMR, it was found to contain 35% benzylidene, $(i\mathrm{Pr}_3\mathrm{P})_2\mathrm{Cl}_2\mathrm{Ru}{=}\mathrm{CHPh}$, and 65% benzyl carbene, $(i\mathrm{Pr}_3\mathrm{P})_2\mathrm{Cl}_2\mathrm{Ru}{=}\mathrm{CHCH}_2\mathrm{Ph}$. This mixture was dissolved in methylene chloride, reacted with *trans*-3-hexene and washed with methanol. This process was repeated several times to achieve high propylidene content, as in the case above for the tricyclohexyl phosphine analog. $^1$H 19.57 ppm triplet ($J_{HH}$ = 4.9 Hz), $^{31}$P 46.79 ppm in $C_6D_6$.

**$(i\mathrm{Pr}_3\mathrm{P})_2\mathrm{Cl}_2\mathrm{Ru}{=}\mathrm{CH}_2$**

The benzylidene and benzyl carbene mixture from above was treated with 1 atm ethylene in methylene chloride for 5 minutes. The reaction was then rapidly concentrated, washed with pentane and vacuum dried overnight. This methylidene compound is thermally unstable in solution and high purity was not obtained. $^1$H 19.40 ppm, $^{31}$P 51.50 ppm in $C_6D_6$.

**$(\mathrm{ICy})_2\mathrm{Cl}_2\mathrm{Ru}{=}\mathrm{CHPh}$**

Cyclohexyl amine (23 mL) was combined with 3 g paraformaldehyde in 100 mL toluene. The mixture was refluxed for 15 minutes to dissolve all the polymer. Upon cooling to 0 °C, 6.5 ml concentrated hydrochloric acid was added and the mixture was stirred for 40 minutes. 11.5 mL 40% aqueous glyoxal was added and the reaction was stirred overnight at 70 °C. The layers were separated and the aqueous phase was extracted twice with methylene chloride. These extracts were dried over sodium sulfate and handled

under Schlenk techniques thereafter. The solution was filtered, concentrated and the residue triturated with ether. After several ether washings, the beige solid was vacuum dried and stored in the glove box thereafter ($^1$H 10.9 ppm).

A setup was constructed, in the fume hood, such that two Schlenks were connected by a glass tube through their ground glass joints. One Schlenk was set up in the box with 0.360 g of the imidazolium salt. The other was set up with a 1 cc piece of potassium. The setup was assembled under argon and fully evacuated. The potassium Schlenk was cooled to –78 °C and an ammonia source was hooked up to the Schlenk arm. Ammonia was condensed over the potassium to remove any water. After 3 mL of ammonia was condensed, the ammonia source was turned off and the cooling bath was moved over to the other Schlenk to vacuum transfer the ammonia to the imidazolium salt. Care was taken to ensure the transfer was slow and that the blue potassium solution was not bumped over to the imidazolium salt. When the transfer was complete, the system was exposed to argon and the potassium Schlenk, along with the connecting tube, was removed. 2.5 mL dry THF was added to the reaction along with 24 mg sodium hydride. A rubber septum was placed in the ground glass joint and an 18 gauge needle was fed through the septum as an exhaust. Argon was allowed to bleed through the system as the cooling bath was removed and the stirred reaction evaporated ammonia. The pH of the effluent gas was tested with pH paper to ensure complete evaporation of the ammonia. An additional 10 mL THF was added along with a solution of 0.5 g $(Cy_3P)_2Cl_2Ru{=}CHPh$ in 10 mL THF. The reaction was allowed to stir overnight at room temperature. The mixture was then canula filtered, concentrated, dissolved in toluene and precipitated with

pentane at –78 °C. The toluene dissolution/pentane precipitation process was repeated once more. The precipitated solid was vacuum dried overnight. $^1$H 20.38 ppm in $CD_2Cl_2$.

**$(IMesH_2)(PCy_3)Cl_2Ru{=}CH_2$**

70 mg $(IMesH_2)(PCy_3)Cl_2Ru{=}CHPh$ was dissolved in 5 mL benzene and pressurized with 1.5 atm ethylene at 50 °C for 1.25 hours. The solvent was evaporated and the residue washed twice with pentane at –78 °C. The yellow solid was vacuum dried overnight. $^1$H 18.43 ppm, $^{31}$P 39.71 ppm in $C_6D_6$.

**$(IMesH_2)(PCy_3)Cl_2Ru{=}CHEt$**

309 mg $(PCy_3)_2Cl_2Ru{=}CHEt$ and 154 mg $IMesH_2$ ligand[7] were combined in a 10 mL Schlenk in the glove box. On the vacuum line, 5 mL benzene was added and the reaction was stirred for 20 minutes. The solvent was removed under vacuum; the residue was washed 3 times with pentane at –78 °C and dried under vacuum overnight. $^1$H 18.98 ppm triplet ($J_{HH}$ = 4.3 Hz), $^{31}$P 30.75 ppm in $C_6D_6$.

**(Cymene)ClRu($\mu$-Cl)$_2$Ru=CHPhCl(ICy)**

135 mg $(ICy)_2Cl_2Ru{=}CHPh$ and 139 mg (p-cymene)ruthenium(II) chloride dimer were mixed in a 10 mL Schlenk in the glove box. On the vacuum line, 6 mL methylene chloride were added and the reaction was allowed to stir at 40 °C for 3 hours. The solvent was removed under vacuum; the residue was redissolved/resuspended in benzene and precipitated with heptane. The solid was then once washed with benzene to remove

residual impurities. The yellow-brown product was vacuum dried overnight. $^1$H 21.09 ppm in $CD_2Cl_2$.

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