FIRST REGENERATION OF A RUTHENIUM-BASED OLEFIN METATHESIS CATALYST AND THE USE OF DI-GRIGNARD REAGENTS TO FORM METALLACYCLOBUTANE COMPLEXES

A thesis submitted in partial fulfillment of the requirements

For the degree of Master of Science in Chemistry

By

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California State University, Northridge
DEDICATION PAGE

To my loving family, for all of your unconditional love and support.

To Dr. Schrodi, for being my mentor and role model.

And to everyone else, past, present, and future that have helped me attain my dreams.
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<tr>
<td>Cat.</td>
<td>Catalyst</td>
</tr>
<tr>
<td>PPh$_3$</td>
<td>Triphenylphosphine</td>
</tr>
<tr>
<td>PCy$_3$</td>
<td>Tricyclohexyphosphine</td>
</tr>
<tr>
<td>Ar</td>
<td>Aromatic</td>
</tr>
<tr>
<td>THF</td>
<td>Tetrahydrofuran</td>
</tr>
<tr>
<td>THF-$d_8$</td>
<td>Deuterated tetrahydrofuran</td>
</tr>
<tr>
<td>CDCl$_3$</td>
<td>Deuterated chloroform</td>
</tr>
<tr>
<td>CD$_2$Cl$_2$</td>
<td>Deuterated methylene chloride</td>
</tr>
<tr>
<td>DEDAM</td>
<td>Diethyl diallylmalonate</td>
</tr>
<tr>
<td>HRMS</td>
<td>High Resolution Mass Spectrometry</td>
</tr>
<tr>
<td>FAB</td>
<td>Fast Atom bombardment</td>
</tr>
<tr>
<td>DCM</td>
<td>Dichloromethane</td>
</tr>
<tr>
<td>PSI</td>
<td>Pounds per square inch</td>
</tr>
<tr>
<td>Cp</td>
<td>Cyclopentadienyl</td>
</tr>
<tr>
<td>h</td>
<td>Hour</td>
</tr>
<tr>
<td>d</td>
<td>doublet</td>
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xx
s  singlet

sept  septet

m  multiplet
ABSTRACT

FIRST REGENERATION OF A RUTHENIUM-BASED OLEFIN METATHESIS CATALYST AND THE USE OF DI-GRIGNARD REAGENTS TO FORM METALLACYCLOBUTANE COMPLEXES

By
Daniel Tabari
Master of Science in Chemistry

A method for the regeneration of a decomposed ruthenium-based olefin metathesis catalyst to an \textit{in situ} ruthenium-indenylidene complex was developed. The regeneration method allows for the treatment of the isolated decomposed inorganic product from the first-generation Hoveyda-Grubbs catalyst with a previously prepared derivative of propargyl alcohol. The structure of the regenerated catalyst was characterized by $^{31}$P $^{1}$H NMR spectroscopy and High-Resolution Mass Spectrometry. The structure of the regenerated complex was confirmed by comparing to a previously prepared ruthenium-indenylidene from [Ru($p$-cymene)Cl$_2$(PCy$_3$)] starting material. The regenerated catalyst is air stable and possesses catalytic activity similar to that of the first-generation Hoveyda-Grubbs catalyst and the previously prepared ruthenium-indenylidene in RCM. This research has provided a means to potentially recycle expensive ruthenium metal from commercial catalysts that decomposed due to metathesis conditions. This study has provided much needed insight into the reactivity of the putative decomposition product of first-generation Hoveyda-Grubbs catalyst.
The synthesis of a gem-dimethyl di-Grignard reagent was successful. This di-Grignard was prepared in synthetic yields that were comparable to previously published quantities. The methyl substituents on the propane backbone served to effectively protect the structure from undergoing elimination decomposition pathways, which served to reduce synthetic side-reactions and resulting by-products amongst the product profile. This gem-dimethyl di-Grignard reagent was successfully characterized by NMR spectroscopy. The synthesis of a previously reported metallacyclobutane of molybdenum was successful by reaction of the gem-dimethyl di-Grignard reagent with a molybdenum di-chloride complex. This molybdenacyclobutane was characterized by NMR spectroscopy. A ligand that has been reported to be active in the Ziegler-Natta polymerization of ethylene and the ROMP of olefins was successfully synthesized. This ligand was used to attempt chelation to a molybdenum solvent-adduct to afford a metal-ligand tri-chloride complex. This synthesis proved difficult in its effective characterization by spectroscopic techniques. It is anticipated that upon isolation of this product, treatment with a standard reducing agent will afford the corresponding di-chloride metal-ligand complex. This di-chloride metal complex will be amenable to treatment with the previously prepared gem-dimethyl di-Grignard reagent to afford a novel metallacyclobutane of molybdenum complex. Given the precedence of the ligand used in this chemistry, it is hoped that this novel metallacyclobutane will be active in catalyzing olefin metathesis reactions.
I. Olefin Metathesis

1.1 The Discovery Of Olefin Metathesis From Ziegler-Natta Polymerization

Metathesis is derived from the Greek term meaning transposition. Ion metathesis is engaged when ions are exchanged within a solution comprised of two ion pairs with the aim of generating the most stable ion pairs (Equation 1). Similarly, olefinic carbenes can be exchanged, if different, to generate a novel recombination yielding two symmetrical olefins (Equation 2) or the two carbynes of an alkyne to produce the two symmetrical alkynes (Equation 3).

\[ A^+B^- + C^+D^- \rightleftharpoons A^+D^- + C^+B^- \]  

\[
\begin{array}{c}
\text{[catalyst]} \\
R_1C\equiv CR_2 \\
\end{array} \rightleftharpoons \begin{array}{c}
\text{[catalyst]} \\
R_1C\equiv CR_1 + R_2C\equiv CR_2 \\
\end{array} \]  

As is the case with the majority of catalytic processes, olefin metathesis was discovered serendipitously. Olefin metathesis was derived from the study of Ziegler-Natta polymerizations with various metal systems. In 1953 at the Max-Planck Institute for Coal Research in Germany, Ziegler observed the efficient accumulation of polyethylene when catalytic amounts of TiCl_4 and Et_2AlCl dissolved in alkanes were combined with ethylene at atmospheric pressure. Ziegler’s polyethylene process proved
to be industrially invaluable, and the magnitude of this discovery was highlighted in 1954 when Natta implemented Ziegler-type catalysts in the polymerization of propylene and other similar \( \alpha \)-olefins.\(^7\) Together, Ziegler and Natta’s contributions radically evolved the landscape of organometallic chemistry and brought forth far-reaching implications for industry and academia. As such, the pair was recognized for their efforts in heterogeneous olefin polymerization with the awarding of the 1963 Nobel Prize.\(^8,9\)

Ziegler-Natta catalysts used in industry have been predominantly of the heterogeneous type. Fundamentally they are composed of a mixture of an alkylaluminum co-catalyst and a high-valent early-transition metal pre-catalyst, active at 25 °C and 1 atm. Ziegler-Natta catalysis requires much milder conditions than conventional thermal polymerizations and yields substantially higher ratios of linear to branched products. Due to the increased desire for well-defined complexes that could be modified and tailored to the catalytic process, much effort has been made in the development of well-defined homogeneous Ziegler-Natta polymerization catalysts. When the first homogeneous catalyst \([\text{Cp}_2\text{TiCl}_2/\text{AlEt}_2\text{Cl}]\) was reported, it shifted the focus within organometallic research to Group IV metallocene complexes for decades.\(^10,11,12,13,14,15\) There was a consensus that an electron-deficient metal cation served as the active species in metallocene-catalyzed olefin polymerization. Modifications of carbon- or nitrogen-ligands, such as analogues of cyclopentadienyl groups or bis-imino pyridine groups, allowed for precise and discrete control of the physical properties of the polymeric product.\(^16\) Generally, these metallocene polymers were targeted such that they displayed resistance to heat and remarkable tensile strength by modifying the stereochemistry of the growing polymer chain.
Further investigations of Ziegler-Natta catalysis revealed that the alkyl-titanocene complex $[\text{Cp}_2/\text{Ti}(\text{R})\text{Cl}]$ was a direct result of the ligand exchange between $\text{Cp}_2\text{TiCl}_2$ and the $\text{R}_2\text{AlCl}$ co-catalyst.\textsuperscript{17} This alkylaluminum halide complex was shown to polarize the Ti-Cl interaction and allow for olefin insertion. Cossee consolidated many of the principles of the proposed insertion mechanisms of the time to delineate the major chain lengthening reactions of olefins (e.g., dimerization, oligomerization, and polymerization) in what is referred to as the Cossee mechanism. Each olefin polymerization reaction is characterized by similar successive alkene insertions into a metal-carbon bond in order to access novel carbon-carbon linkages (Scheme 1.1). All three processes are differentiated, however, by the relative rate coefficients of chain growth via insertion ($k_g$) and chain termination by $\beta$-elimination ($k_t$). Ziegler-Natta polymerization as well as metallocene catalysis were specifically shown to be the result of inefficient chain termination.\textsuperscript{16}

Olefin metathesis was first observed and reported in 1931 involving propene at high temperatures. The first catalyzed olefin metathesis processes were discovered in the 1950’s when scientists at Du Pont, Standard Oil, and Phillips Petroleum, led by Eleuterio, Peters, Evering, Banks, and Bailey, reported that when heated with molybdenum (as the
metal, the oxide, or [Mo(CO)₆] on alumina), propene generated ethylene and 2-butenes.¹⁸

In 1960, Eleuterio and Truett reported the polymerization of norbornene by a WCl₆/AlEt₂Cl system.¹⁸ However, it was not until 1967 that ring opening metathesis polymerization (ROMP) and the disproportionation of acyclic olefins were recognized as being the same reaction.¹⁸ During the latter half of the 1960’s, Phillips developed a chemical process to convert propylene into ethylene and 2-butene—the triolefin process—which made the scientific field conscious of the new metathesis reaction.¹⁹ By the late 1960’s, metathesis catalytic systems were often oxides such as WO₃/SiO₂, implemented in the transformation of propene to ethylene and butenes, or Ziegler-Natta like systems such as WCl₆ (or MoCl₅) + AlX₃R₃-n (or SnR₄).² Calderon was the first to use the term metathesis to describe his observations in 1967.²⁰

1.2 The Carbene Mechanism

![Figure 1.1](image)

**Figure 1.1** Suggestions for the cyclobutane intermediate postulated prior to the work of Chauvin.
It soon became apparent that the olefin metathesis reaction required distinct intermediates and mechanistic pathways that were at the time not evident.\textsuperscript{3} As it would later show, further elucidation of the metathesis mechanism would provide for future enhancement of catalysts. At first, it was proposed that a pair-wise mechanism existed. It was thought that a concerted exchange of alkylidenes via a so-called “quasicyclobutane” mechanism took place, during which olefins would coordinate to the metal center and exchange alkylidene moieties by means of a symmetrical intermediate.\textsuperscript{3} In 1968, Calderon postulated a mechanism containing an \( \eta^4 \pi \)-cyclobutane-metal species (Figure 1.1, 1). Although Calderon proposed this \( \pi \)-cyclobutane intermediate metal species mechanism, it was shown that metathesis did not yield cyclobutane and catalysts failed to produce olefins by reaction with cyclobutane analogues.\textsuperscript{20} Accordingly, metathesis products were not thought to result in a cyclobutane moiety nor were metathesis transition metal catalysts thought to produce olefins via cyclobutane derivatives.\textsuperscript{18} An alternate mechanism was presented in 1971 by Pettit that rejected Calderon’s proposition.\textsuperscript{3,21} Pettit offered that the reaction proceeded by means of a reversible transformation of two coordinated olefinic moieties into a multi-three-centered species, characterized by four methylene units with \( sp^3 \)-hybridized carbons, yielding a quasicyclobutane (Figure 1.1, 2). After Pettit’s proposed mechanistic pathway, in 1972 Grubbs proposed a mechanism predicated upon (2 + 2) cycloaddition of the two olefins in the metal’s coordination sphere to generate a metallacyclopentane intermediate which would breakdown via a retro (2 + 2) cycloaddition with a change in the symmetry plane (Figure 1.1, 3).\textsuperscript{2,22} However, Chauvin proved that the metallacyclopentane rearrangement failed to produce olefins.
In 1971, Chauvin introduced a novel mechanism to elucidate his surprising findings.\textsuperscript{23} He observed that when a pair-wise “quasicyclobutane” mechanism was viable the resultant olefins generated from the cross products were observable early in the reaction process.\textsuperscript{23} Although the pair-wise mechanism would provide an explanation for this situation, Chauvin proceeded to postulate a mechanism that included the fragmentation of the olefin by means of what is referred to as the carbene or the non-pairwise mechanism.\textsuperscript{3}

Working with the principles of Fischer on the synthesis of a tungsten-carbene complex, of Natta on cyclopentene polymerization by ring opening catalyzed by WCl\textsubscript{6} and AlEt\textsubscript{3}, and of Banks and Bailey on the generation of ethylene and 2-butene from propene catalyzed by [W(CO)\textsubscript{6}] on alumina, Chauvin proposed in 1971 his metathesis mechanism (Scheme 1.2).\textsuperscript{23} It was predicated upon a metal-alkylidene species. In this mechanism, the olefinic substrate coordinates to the metal center, which shifts to generate the metallacyclobutane intermediate. The new olefin would engage in a shift within the metallacyclobutane, in a perpendicular direction to the shift of the initial olefinic substrate. This action generates a metal-alkylidene species. The olefin coordinated to the metal alkylidene would then be liberated. The novel olefin possesses a catalyst-derived carbene and another carbene generated from the initial olefin. The newly produced metal-alkylidene possesses one of the starting olefin carbenes and can resume its role in the catalytic cycle. Contingent upon the orientation of the olefin that is coordinated, the new catalytic process can yield two distinct metallacyclobutanes, one of which leads to a symmetrical olefin and the second producing the initial olefin. This cycle is referred to as degenerate olefin metathesis.
Scheme 1.2 The Chauvin Mechanism to account for the appearance of the metallacyclobutane intermediate.

In addition to suggesting the metallacyclobutane mechanism, Chauvin conducted and published a series of experiments to confirm his postulations. He reacted a mixture of cyclopentene and 2-pentene which generated C-9, C-10, and C-11 dienes in a 1:2:1 ratio. The interaction of cyclooctene and 2-pentene produced almost exclusively a C-13
product. In 1973, Chauvin showed that a \( \text{WCl}_6 + \text{MeLi} \) mixture catalyzed the production of propene by reaction of 2-butene, which was thought to propagate by means of tungsten methylation, subsequently followed by \( \alpha \)-elimination of \( \text{W-CH}_3 \) to generate a tungsten-alkylidene, concluding in metathesis.\(^{24}\)

Chauvin’s mechanism was groundbreaking and carried several new intellectual implications. First, it postulated the role of a metal-carbene to initiate catalysis of metathesis. This implicated that synthesized metal-alkylidenes could behave as catalysts with olefins to generate the metathesis process. Later, different researchers proved that tungsten-carbenes stabilized by heteroatoms were olefin metathesis-active.\(^2\) Casey and Burkhardt showed that \([\text{W(CO)}_5(=\text{CPh}_2)]\) would react with isobutene to generate 1,1’-diphenylethylene (Equations 4 and 5).\(^{25}\) In 1976 Chauvin showed that several Fischer-type carbenes would allow for metathesis.\(^{24}\) Katz was the first to produce a series of works which validated the Chauvin mechanism, but implemented specific carbenes
distinct from alkylidenes. In 1980 Schrock produced the catalysis of metathesis by way of non-stabilized transition-metal-alkylidene complexes and definitively validated the Chauvin mechanism for olefin metathesis. This, coupled with Katz’s series of reactions, substantiated the belief that the pair-wise mechanism would not validate the metathesis pathway. Furthermore, this was perpetuated by Schrock’s showing that metal alkylidene complexes could be generated by means of ‘metathesis-like’ conditions.

\[
\begin{align*}
\text{CD}_2 &= \text{CD}_2 \\
\text{+} &\rightarrow \text{H}_2\text{C} = \text{CH}_2 \\
\text{+} &\rightarrow \text{H}_2\text{C} = \text{CD}_2 \\
\text{+} &\rightarrow \text{D}_2\text{C} = \text{CD}_2 \\
\end{align*}
\]

**Scheme 1.3** Ring-closing experiment with deuterated terminal olefins to elucidate the metathesis mechanism.

In 1974, Grubbs conducted a mechanistic investigation surrounding a ring-closing metathesis reaction with deuterium labeled 1,1,8,8-tetraduetro-1,7-octadiene to provide for a distinction amongst the pair-wise and non-pairwise mechanisms (Scheme 1.3). This compound was mixed with the hydrogenated analogue and was permitted to undergo metathesis with catalysts which were already shown to yield non-metathesis reactive cyclohexene and deuterated analogues of ethylene. Because unreactive cyclohexene was yielded, the system allowed for the determination of the fate of the terminal olefins to be characterized as well as the calculation of the anticipated product mixtures to be assessed.
for the pair-wise or the non-pairwise exchange of the terminal methylenes, respectively.

Beginning with a 1:1-mixture of D₄:D₀-1,7-octadiene, a 1:2:1 ratio of the labeled ethylenes was produced as the kinetic products in contrast to the 1:1, 6:1 ratio predicted for the pair-wise mechanism.²⁹ The pair-wise mechanism was conclusively rejected by Katz’s study by implementing ring-closing reactions to yield 6-membered rings and labeled acyclic olefins, which ultimately paved the way for the acceptance of the Chauvin mechanism.³⁰ The square scheme implicated in alkene metathesis also extends to other various catalytic organometallic mechanisms (Scheme 1.4). In 2005, Chauvin became a recipient of the Nobel Prize for his immense contributions to chemistry in the realm of olefin metathesis.³¹

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**Scheme 1.4** Diverse organometallic transformations predicated on Chauvin’s metallo-square intermediacy.
1.3 Schrock’s Work On Metal-Alkylidene Complexes

Aside from the investigation of the metathesis mechanistic pathway, studies were entrenched in the design and development of alkylidene complexes. Conventional catalysts predominantly fall into one of two categories, the ill-defined and the well-defined catalysts, respectively. The ill-defined type are made of a metal-containing complex that exerts catalysis, yet do not possess a direct relation to the catalytic species in reaction.\textsuperscript{32} Characterization of the ill-defined active species is near unfathomable because these systems contain less than one percent active metal.\textsuperscript{33,34} Despite being extremely active, ill-defined catalysts tend to be short-lived, decomposing within minutes of reaction.\textsuperscript{32} Catalytic systems of the ill-defined type often yield side products and are easily deactivated by functional groups which exhibit Lewis basicity.\textsuperscript{32} Accordingly, ill-defined catalysts are difficult to tune and control in experimental environments.\textsuperscript{32}

Conversely, well-defined catalysts can be isolated.\textsuperscript{32} Furthermore, these characterizable complexes tend to be exceedingly similar to catalytic intermediates.\textsuperscript{32} As such, the endeavor towards well-defined catalytic alkylidene complexes ensued. The discovery of well-defined alkylidene species was linked to the study of alkyl complexes of transition metals. For up to a century, researchers had presumed that metal-alkyls were naturally unstable due to the purported low energy of the metal-carbon interaction.\textsuperscript{2} In the early 1970’s, Wilkinson produced stable binary metal-alkyls that were void of $\beta$-hydrogens, presenting that the instability was kinetic by way of $\beta$-elimination, because many had attempted to synthesize binary metal-ethyl complexes.\textsuperscript{35} Organometallic chemists were then able to create a wide array of thermally stable binary metal-alkyl complexes containing alkyl groups which lacked $\beta$-hydrogens, including methyl, benzyl,
neopentyl, trimethylsilylmethyl, and mesityl groups. While at Dupont, Schrock attempted the synthesis of [Ta(CH₂CMe₃)₅], which lacked β-hydrogens and, in theory, should have been a stable complex. The compound was not afforded due to an α-elimination by σ-bond metathesis while trying to coordinate the fifth neopentyl group. This yielded a mole of neopentane and yielded the isolation of the first stable metal-alkylidene, [Ta(CH₂CMe₃)₅(=CHCMe₃)], characterized by a high +5 oxidation state (Scheme 1.5).

Scheme 1.5 σ-bond metathesis for the α-elimination in the first synthesis of a stable metal-alkylidene complex as defined by Schrock.

By the mid 1970’s, the organometallic community had yet to access metal-alkylidene complexes capable of catalyzing olefin metathesis. The metallacyclobutanes that were generated were produced from the reaction of alkylidene complexes with olefins which adhered to common β-elimination pathways of metal-alkyls containing fewer than 18 valence electrons on the metal, while possessing β-hydrogens. Coordinative liberation, however, produced catalytically active species. Schrock’s
tantalum alkylidenes were active in olefin dimerization. A metallacyclopentane would be generated by the coordination of two equivalent olefins to the unsaturated metal center, which upon β-elimination accesses metal butenyl hydride intermediates that reductively eliminate to yield 1-butene (Schemes 1.6 and 1.7).37

\[
\text{R}_3\text{Ta} = \text{C} \quad \text{H} \quad \text{CMe}_3 \quad \text{R}_3\text{Ta} \quad \text{H} \quad \text{H} \quad \text{CMe}_3
\]

**Scheme 1.6** Schrock’s depiction of the reaction of a tantalum-alkylidene complex with an olefin.

\[
\begin{align*}
\text{M} & \quad + \quad \text{M} \\
\text{M} & \quad \text{R} \\
\text{R} & \quad \text{M} \\
\text{R} & \quad + \\
\text{R} & \quad \text{H} \\
\end{align*}
\]

**Scheme 1.7** The major modes of metallacyclobutane breakdown as contained by the reactions between transition metal-alkylidene complexes and olefins.
In 1980 Schrock reported on a tantalum-alkylidene complex, [Ta(=CH-t-Bu)Cl(PMe3)(O-t-Bu)2], which was shown to catalyze the metathesis of cis-2-pentene.\(^{38}\) This was the first substantiation of Chauvin’s mechanism of metathesis with a well-defined high oxidation state alkylidene. The justification for the metathesis catalyzing ability of this structure was the presence of alkoxide ligands.

Despite the fact that several catalysts with activity restricted to strained olefin polymerization were produced from late metal precursors, the exceedingly active catalysts came from the alkylation of high oxidation state early metal halides.\(^{39}\) Schrock’s initial high oxidation state alkylidenes did not propagate olefin metathesis.\(^{40}\) Low oxidation state Fischer carbenes exhibited low activity in olefin metathesis catalysis.\(^{41}\) Intermediates within the reaction could not be observed despite the fact that the fragments of initial carbenes were observed as terminal groups on the polymers yielded by the catalysts.\(^{42}\) Tebbe’s, Schrock’s, and Osborn’s high oxidation state late metal complexes made for the transition to the generation of well-defined catalysts.\(^{43,44,45}\) Well-defined catalysts are those whose propagating species could be observed and controlled. These complexes carved the path towards modern metathesis catalysts.\(^3\)

It was shown by Tebbe that titanium methylene complexes catalyze non-productive metathesis exchange of the methylenes amongst terminal olefins. Despite the catalyst not being increasingly active, the system served as a suitable example because the complex was particularly stable and the methylidene moiety involved in propagation was observable and was consequently studied.\(^{46}\) The Grubbs group began a study with the ‘Tebbe Reagent’ in a Wittig-like reaction in the conversion of esters into vinyl ethers (Scheme 1.8).\(^{47}\) Another study focused on the synthesis of unsymmetrical Tebbe
complexes in the implementation of a mechanistic study to discern the structure of the metallacycle intermediate. Interestingly, upon addition of pyridine a metallacyclobutane complex was generated as a stable species whose structure was then established.\(^{48}\)

These studies served to establish the metallacyclobutane as a competent intermediate in olefin metathesis. Osborn and Ivin discovered a catalytic system which exhibited both the propagating carbene complex as well as the metallacycle.\(^ {49}\) Schrock, then Basset, developed the early metal complexes which were singular in composition and displayed adequate activity levels.\(^{50,51}\) Molybdenum and tungsten proved to be the most active metal centers in alkene metathesis. Schrock eventually generated a series of molybdenum- and tungsten-alkylidene complexes of the type \([M(=\text{CHCM}_{2}\text{Ph})(=\text{N-Ar})(\text{OR}_{2})]\), with \(R\) containing considerable steric. Nonetheless, the ground-breaking moment arrived when Schrock developed both tungsten and molybdenum alkylidene complexes which included bulky imido ligands.\(^ {52}\) These complexes displayed considerable activity and stability for study. These complexes allowed for the first efficient and manageable catalysts for metathesis and served as the foundation for Grubbs’ work in organic as well as controlled polymer syntheses.\(^ {53}\) Osborn produced
early well-defined W(VI) alkylidene metathesis catalysts and by way of $^1$H-NMR spectroscopy proved the living nature of the polymerization system. Basset presented aryloxalkylidene W(VI) catalysts, the first example of which were Lewis-acid-free propagators that provided for the polymerization of substituted norbornenes by means of the ROMP mechanism. Schrock’s most efficient catalysts reported in 1990 exhibited the benefit that, although they were exceedingly active, they were molecular in nature and produced a commercial complex as well as chiral variations for the first applications of asymmetric catalysis. To date, these complexes are the most active of the olefin metathesis catalysts. Schrock was awarded the 2005 Nobel Prize in chemistry for his various indelible efforts in chemistry, including the validation of the Chauvin mechanism, the progress made in understanding and engineering metathesis catalysts, as well as the isolation of the first metal-carbene.

By 1980, Schrock had presented a metathesis-active tungsten-alkylidyne catalyst. Osborn and Basset showed the efficacy of tungsten complexes in olefin metathesis catalysis (Figure 1.2). Schrock’s production of well-defined catalysts allowed for the opportunity to implement olefin metathesis to the generation of functionalized small molecules. In particular, it was demonstrated that tungsten and molybdenum alkylidenes induced the ring-closing metathesis towards the generation of 5, 6, and 7 membered rings. The molybdenum system displayed high activity and tolerated a large gamut of functionality. This progress opened olefin metathesis to the realm of synthetic organic chemistry. The quality of this reaction was actualized when catalysts became available that could be implemented with conventional organic techniques and could be tolerated by a large range of functional groups.
Figure 1.2 First molecular metathesis catalysts of Mo and W, respectively.
1.4 Ruthenium-Based Olefin Metathesis Catalysts and Grubbs’ Contributions

![Grubbs' complex reported in 1988.](image)

**Figure 1.3** Grubbs’ complex reported in 1988.

The 1980’s saw researchers develop ruthenium-based catalysts.\(^3\) In particular, Grubbs was intrigued by the 1965 Natta publication on catalysis by RuCl\(_3\) of cyclobutene and 3-methyl cyclobutene polymerization by ring opening in butanol.\(^61\) In 1988, Grubbs reported the polymerization of 7-oxonorbornene yielding a high molecular weight monodisperse polymer by the action of either RuCl\(_3\) or [Ru(H\(_2\)O)\(_6\)](OTs)\(_2\) (Figure 1.3). The most fascinating component of this catalysis was its implementation in aqueous media.\(^62\) Through the same reaction pathway, Grubbs proved the genesis of a ruthenium-alkylidene intermediate, followed by the polymerization of minimally constrained cyclooctene when ethyl diazoacetate, in an aqueous solution of [Ru(H\(_2\)O)\(_6\)](OTs)\(_2\), was the ligand donor (Scheme 1.9).\(^62\)
Scheme 1.9 An example of Grubbs’ metathesis mechanism for ring-opening metathesis polymerization of cyclic olefins.

It was shown that the ruthenium-centered systems could promote the same reactions as Schrock’s molybdenum-centered alkylidene complexes while exhibiting enhanced functional group tolerance and stability under conventional organic methods. The early transition metal-based catalysts needed pure inert atmospheres for effective implementation in organic reactions, whereas ruthenium complexes held the benefit of being handled in atmospheres of oxygen in the solid state while reactions could be conducted under atmospheres of nitrogen with standard instrumentation. Grubbs’ investigations showed that a strained olefin as well as ruthenium(II) were instrumental to the production of an active olefin metathesis catalyst. Accordingly, the foundation for the synthesis of a well-defined ruthenium-based metathesis catalyst was established.
The next series of examinations focused on whether a well-defined, active ruthenium carbene catalyst could be generated. \([\text{RuCp\{C(Me)OMe\}}(\text{CO})(\text{PCy}_3)][\text{PF}_6]\), a Fischer-type ruthenium system which was stabilized by a carbene methoxy group, was accessed in 1971 by Green and served as the first documented ruthenium-carbene.\(^6\) Cyclopropanation perpetuates this ruthenium complex towards olefins due to the extreme electrophillic nature of the carbene ligand. This is the result of its positive formal charge and is enhanced by the electron-withdrawing carbonyl ligands.

Grubbs successfully stabilized benzyldienes bearing electrophilic ligands, made possible by the charge neutrality of the complexes. This allowed for a decreased electrophilicity of the carbene, in addition to imparting considerable versatility to the ruthenium metal.\(^2\) Ruthenium(II) complexes with diphenylcyclopropene were reacted by coupling the requirement for ruthenium(II) with the established principles for tungsten carbene synthesis.\(^6\) This yielded a stable 16-electron ruthenium carbene complex that was both highly active in norbornene polymerization as well as stable in protic media.\(^6\) The fundamental architecture of the active (bistriphenylphosphine)-dichlororuthenium alkylidene complex has been preserved in the latest metathesis catalysts. Initially, the bis(triphenylphosphine) complex was metathesis-active strictly with strained and electron-abundant olefins. Ligand exchanges were initiated to enhance the activity of the catalysts. Applying the knowledge from the Schrock group implied that catalytic activity increased upon the enhanced electrophilicity of the transition metal center.\(^6\) By executing an opposite ligand exchange and substituting the basic cyclohexylphosphine ligand, the desired activity was achieved.\(^6\) This complex with the more basic ligand
allowed unstrained olefin polymerization and propagated acyclic olefin reactions (Scheme 1.10).\(^6\)

\[
(PPh_3)RuCl_2 + \begin{array}{c}
\text{Ph} \\
\text{Ph}
\end{array} \rightarrow \begin{array}{c}
\text{Ph} \\
\text{Ph}
\end{array} \stackrel{\text{Cl} \text{C} \text{Ph}}{\text{Cl} \text{C} \text{Ph}} \stackrel{\text{Cl} \text{C} \text{Ph}}{\text{Cl} \text{C} \text{Ph}} \stackrel{\text{Cl} \text{C} \text{Ph}}{\text{Cl} \text{C} \text{Ph}} \stackrel{\text{Cl} \text{C} \text{Ph}}{\text{Cl} \text{C} \text{Ph}}
\]

**Scheme 1.10** Imparting the metal-center with more electrophilic nature to afford a more active catalytic structure.

**Figure 1.4** Grubbs’ complex reported in 1995.

**Figure 1.5** 1\(^{st}\) generation Grubbs catalyst commercialized in 1995.

Thus, in 1992 Grubbs produced the first well-defined molecular ruthenium-carbene which proved to initiate the ROMP of low-strain olefins in addition to the catalytic RCM of dienes marked by functionalization. These vinylidene complexes of the type \([\text{RuCl}_2(\text{PR}_3)(=\text{CH-CH=CPh}_2)] \) (\(\text{R} = \text{Ph} \) or \(\text{Cy}\)) were highly efficient and capable molecular catalysts for these polymerizations as well as other metatheses, including the
ring closing of terminal bisolefins.\textsuperscript{70} 1995 brought novel well-defined molecular catalysts of the type \([\text{Ru}(=\text{CHPh})\text{Cl}_2(\text{PR}_3)_2]\) \((R = \text{Ph or Cy})\), the structures of which are in the family of those vinylidenes presented several years earlier, and were generated and commercialized with a cyclohexyl group (Figure 1.4).\textsuperscript{71} The first-generation Grubbs catalyst corresponds to the structure \([\text{Ru}(=\text{CHPh})\text{Cl}_2(\text{PCy}_3)_2]\) and to this day is used by chemists due to its tolerance to atmosphere as well as its stability to a diverse range of functional groups, excluding amines and nitriles when in basic media (Figure 1.5).\textsuperscript{71,72}

As the desire for bigger quantities of catalysts increased, enhanced efficient means for their syntheses became necessary. Although difficult to scale up, the cyclopropene pathway was beneficial for the generation of catalysts on a gram-scale. Studies commenced on the implementation of diazo compounds as propagators for the ill-defined complexes and showed that stable ruthenium species could be produced by similar means. The production of ruthenium benzylidene complexes demonstrated the enhanced activity and quick initiation of these catalysts.\textsuperscript{73} These studies established the foundation for subsequent ruthenium metathesis technology.
Mechanistic studies on the 1st-generation Grubbs catalyst provided the information that the mechanistic pathway began with phosphine dissociation to yield the reactive 14-electron ruthenium intermediate (Scheme 1.11). With the aim of accelerating the dissociation, Grubbs integrated Arduengo’s N-hetero cyclic carbene (NHC) ligand in place of a phosphine, which was especially stable (Figure 1.6). NHC ligands are strong σ-donors, void of π-acceptor capacity, and have gained notoriety in organometallic catalysis and chemical processes. Hermann first accessed ruthenium complexes with two of these carbenes with the purpose of olefin metathesis catalysis, but their activity was minimally adequate at best.
Studies by Hermann indicated that the exchange of catalytic phosphines with very stable NHCs generated fascinating alterations in reactivity. In 1998, it was reported that complexes containing cyclohexyl analogue NHCs, characterized by the phosphines of its precursor being exchanged with dialkyl imidazolin-2-ylidene NHC ligands, yielded a catalytic complex with a far enhanced activity than that of the original species. Grubbs proceeded to access analogues of this complex by substituting the phosphines with NHC’s. The instrumental ligand system was found to be Arduengo’s NHC bearing mesityl groups: 1,3-dimesitylimidazoline-ylidene (IMes). This IMes ligand generated a stable complex characterized by a singular phosphine exchanged by an NHC. This species, which was discussed by Nolan and Hermann, exhibited excellent stability and activity. The NHC made for a good electron donor to stabilize the catalytic intermediates and the phosphine provided for the labile ligand needed for the generation of the 14-electron species. Predicated on previous mechanistic studies, it was postulated that the enhanced activity of the NHC systems was due to the excellent σ-donating capacity of the NHC ligands and the subsequent enhanced trans effect.
Grubbs’ 2nd-generation catalyst of the type \([\text{RuCl}_2\{\text{IMes}\}(\text{PCy}_3)(=\text{CHPh})]\) and its catalytic metathesis activity were proven by Nolan, Grubbs, Förstner, and Hermann (Figure 1.7). It still stands as the most widely applied catalyst towards effective cross-metathesis processes, despite its intolerance to nitriles and amines. This new commercial catalyst was especially active despite its enhanced thermal stability as compared to its 1st generation counterpart.

In a detailed study of the mechanistic pathway for metathesis with ruthenium complexes, it was determined that the pathway proceeded by the loss of a neutral ligand to generate a 14-electron species. It was thought that the enhanced activity of the more basic phosphine was a ramification of the intermediate metallacycle stabilization. This was justified by the fact that proceeding from the carbene olefin species to the metallacycle included oxidation of the ruthenium center as well as preferring the addition of a π-acidic olefin. Basic phosphines with less sterics were shown to coordinate too strongly to the ruthenium and were prohibitive to ligand dissociation and initiation.
processes. Larger cone angle phosphines than that of cyclohexylphosphine were shown to be exceedingly labile to effectively produce a stable catalytic complex.3

![Chemical structures](image)

**Figure 1.8** Olefin Metathesis catalysts derived from the Grubbs-ruthenium scaffold.
Hoveyda, Hofmann, Grela, and Blechert reported similar, extremely active, highly stable, and especially functional group-tolerant metathesis-active ruthenium catalysts (Figure 1.8). Hoveyda’s first catalyst was derived from Grubbs’ 1st generation scaffold. It is characterized by a single phosphine and a chelated carbene. Hoveyda’s second catalyst also contains Arduengo’s carbene in lieu of the phosphine moiety. The activity of the Hoveyda catalysts compare very favorably to the 2nd generation Grubbs complex and are particularly applicable towards arduous instances of metathesis of polysubstituted olefins. Grela produced an analogue of Hoveyda’s catalyst with enhanced efficiency, active even at 0 °C, when the aryl moiety of the benzylidene ligand possessed a meta- or para-nitro group, or dual methoxy substituents as well. Grela successfully weakened the Ru-ether bond in a means to promote ether dissociation, which produced the catalytically active 14-electron species. Blechert generated the most successful analogue of the Ru-benzylidene catalysts by sterically weakening the Ru-ether linkage in order to integrate an aryl (phenyl or naphthyl) component upon the benzylidene aryl moiety ortho- to the ether oxygen. Although contingent upon the type of metathesis, as well as the tolerance to the requisite functional group, the Blechert catalysts have been proven to be far more catalytically efficient and stable than all of the other ruthenium catalysts.
Figure 1.9 Commercially available ruthenium-indenylidene complexes.

Ruthenium indenylidene complexes have exhibited promise in providing greater thermal stability than their benzylidene analogues, while also showing excellent catalytic activity and selectivity (Figure 1.9). Different groups have engineered and studied ruthenium-3-phenylidenylidenes. Utilizing the ruthenium-3-phenylidenylidene scaffold, Nolan integrated olefin-metathesis active ligands such as NHCs and 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene (IPr). Synthesis of such complexes is desirable because they are marked by safe, manageable, and commercially available starting precursors.
1.5 Olefin Metathesis Reactions

1) Cross Metathesis (CM)

2) Ring-Closing Metathesis (RCM)

3) Acyclic Diene Metathesis Polymerization (ADMEP)

4) Ring-Opening Metathesis Polymerization (ROMP)

5) Enyne Metathesis (EYM)

6) Ring-Opening Cross Metathesis (ROCM)

Scheme 1.12 Depiction of the family of olefin metathesis processes as stipulated by the Chauvin mechanism and catalyzed by either Schrock- or Grubbs-type catalytic complexes.

The Olefin Metathesis reaction has quickly assumed an invaluable role in the design and synthesis of organic compounds and drug candidates, yet it still holds much promise in the generation of therapeutics. It is characterized by the rearrangement of
covalent carbon-carbon bonds and is implemented to couple, cleave, ring-close, ring-open, or polymerize alkenes. These processes are catalyzed by transition metal alkylidene complexes, the most common of which are the ruthenium-based Grubbs complexes. Specifically, olefin metathesis reactions include ring-closing metathesis (RCM), ring-opening metathesis polymerization (ROMP), acyclic diene metathesis polymerization (ADMET), cross metathesis (CM), ring-opening cross metathesis (ROCM), and enyne metathesis (EYM). The wide tolerance of functional groups, as well as their efficiency, have greatly popularized both the Schrock and Grubbs catalysts throughout organic chemistry. Furthermore, the stability and ease of handling of the Grubbs complexes in atmosphere has encouraged their high volume use. Of the six families of metathesis processes, all are capable of being catalyzed by the Schrock and Grubbs catalysts and can propagate elaborate organic transformations (Scheme 1.12). Terminal bis-olefin ring-closing metathesis (RCM) has fast become a powerful reaction amongst the organic community, as it can be executed under an ambient atmosphere of air by means of the 1st generation Grubbs catalyst. Cross metathesis has experienced hindered applications because of the yield of products seen in cross reactions of rudimentary olefins. Intended cross product yields are limited to 50% of a thermodynamic ratio of E:Z isomers when a 1:1 ratio of olefins is applied. However, the more reactive NHC-catalysts allowed for more exotically functionalized olefins to engage in pure metathesis. Sterics in the allylic position, including alkyl substitution superimposed on the double bond reduces the rate of homodimerization. Steric bulk also enhances E isomer selectivity.
1.6 Applications Of Olefin Metathesis

\[ \text{Tr} = \text{Trityl group: triphenylmethyl} \]

**Scheme 1.13** N-heterocyclic ring systems that can be accessed by olefin metathesis in the design and synthesis of pharmaceutical template and scaffolds.

**Scheme 1.14** Pharmaceutical scaffolds and templates accessed by metathesis of large-ring structures.
The olefin metathesis reaction is a powerful and versatile process which lends itself to diverse applications. Products can be tuned to discrete qualifications which are contingent upon both the metathesis reaction engaged as well as the catalyst implemented.\textsuperscript{87} RCM has fast become the most adopted metathesis reaction exerted in organic synthesis. The most facile process of this type is the accessing of five-membered rings, yet can also be applied to the genesis of larger rings upon diolefinic precursors (Scheme 1.13).\textsuperscript{88} Similarly, organic synthetic chemists can access large macrocycles, some of which are imparted with biologically and medically critical qualities (Scheme 1.14).\textsuperscript{88} When extremely active catalysts are needed, as is the case for cross metatheses, the Schrock or 2\textsuperscript{nd} generation Grubbs catalysts are utilized. These processes are beneficial to the synthesis of insect pheromones as well as the processing of oils and perfumes. The family of Schrock catalysts hold the benefit of high stereoselectivity, up to 99\%, which is crucial to enantioselective organic syntheses. In 2005 Boehringer Ingelheim reported the application of RCM for the commercial synthesis of hepatitis C therapeutics.\textsuperscript{89}
Figure 1.10 Nucleation of an $\alpha$-helix by providing a non-native covalent hydrocarbon constraint to serve as the surrogate to the conventional $i$ and $i + 4$ hydrogen bonding interaction.

RCM has also found immense application in the engineering of stapled peptide therapeutics.\textsuperscript{90,91} The structural instability of peptides limits their ability to modulate intracellular protein-protein interactions, rendering many peptides “undruggable.”\textsuperscript{92} Peptide stapling by the Hydrogen Bond Surrogate (HBS) approach restricts peptidomimetics in the $\alpha$-helical conformation and imparts them with stability against protolysis and thermolysis.\textsuperscript{90,91} HBS helices are accessed by providing a surrogate interaction for the hydrogen bond between the carbonyl oxygen of the $i^{th}$ residue and the NH moiety of the $i + 4^{th}$ residue by virtue of a non-native covalent hydrocarbon constraint (Figure 1.10).\textsuperscript{90,93} This is synthetically achieved by the derivitization of these nucleating residues to produce a bis-olefinic precursor that is then stapled via ring-closing metathesis.\textsuperscript{90} This forms a constrained macrocycle which preorganizes the polypeptide chain and nucleates $\alpha$-helicity.\textsuperscript{90} HBS $\alpha$-helices derived from biologically relevant sequences were shown to be stable to proteolytic and thermal degradation while binding
to a native protein with high specificity and complementarity.\textsuperscript{93,94} HBS helices hold therapeutic promise in inhibiting HIV-1 host fusion with a CD4\textsuperscript{+} T-cell.\textsuperscript{95,96} HBS C-peptides were engineered to target the N-heptad region of the gp41 subunit of the fusion competent gp120/gp41 \textit{Env} HIV-1 complex.\textsuperscript{95} This therapeutic inhibits the conformational reorganization of the gp120/gp41 pre-hairpin intermediate into the post-fusion six-helix bundle, thereby inhibiting viral fusion.\textsuperscript{95} As such, HBS $\alpha$-helices may be integrated into post-exposure prophylactics to reduce viral loads.\textsuperscript{96}

![Diagram of Grubbs Chiral Catalyst](image)

\textbf{Scheme 1.15} The first chiral ruthenium metathesis catalyst capable of engaging in enantioselective catalysis as reported by Grubbs in 2001.

Enantioselective metathesis catalysis continues to be a considerable hurdle. In 1997 Schrock reported the first chiral metathesis catalyst. In 1998, Schrock and Hoveyda, followed by Grubbs, showed the first efficient enantioselective ROMP by way of a molybdenum catalyst.\textsuperscript{97} Grubbs reported in 2001 of the first chiral ruthenium metathesis
catalyst capable of initializing catalytic enantioselectivity (Scheme 1.15). Schrock and Hoveyda have presented pragmatic molybdenum-centered chiral catalysts easily prepared from inexpensive and readily available optically pure (R)- or (S)-binaphthol, as well as chiral [Mo(=N-Ar)(=CHCMe2Ph)(η^2-MeOCH₂CH₂OMe)(OTf)]. This process accesses a complex that is an enantioselectively metathesis-active catalyst which does not require discrete isolation. Although air- and moisture-sensitive, Schrock’s molybdenum catalysts are highly efficient in the presence of phosphane, thioether, nitrile, sterically protected free alcohol, metal carbonyl, and amine moieties.

Newly engineered NHC complexes have enhanced reactivity and selectivity amongst olefin metathesis catalysts. NHC catalysts are characterized by reactions with electron-deficient double bonds. Enhanced reactivity with π-acidic acrylates is the result of improved electron donating capacity of the NHC compared to tricyclohexylphosphine. For the same reasons that generate high yields of cross products in small molecules, the generation of alternating polymers upon a cyclic olefin reacting with a diacrylate are afforded.

Scheme 1.16 The hydrolysis of polyunsaturated triacylglycerides to yield one moiety of glycerol and three moieties of unsaturated fatty acids, which can be manipulated and modified via metathesis reactions.
Olefin metathesis has also become an innovative approach to generating bio-renewable molecules, especially the metathesis of vegetable oils, the result of which is a facile approach to extracting fine chemicals and polymeric materials. Conventional seed oils are typically triacylglycerides of saturated and unsaturated fatty acid chains. Hydrolysis of fatty acids yields one moiety of glycerol and three equivalents of oxygen-ester fatty acid chains (Scheme 1.16). These fatty acid chains can then be manipulated and modified by various metathesis processes, the products of which are used as antifungal therapeutics as well as animal-feed supplements (Scheme 1.17). Anti-inflammatory and antifungal agents have been accessed by metathesis processes. Green chemistry has also found its place in the realm of metathesis applications, including the synthesis of biodegradable polymers.

**Scheme 1.17** The efficient metathesis of polyunsaturated fatty acid chains.
Through the valiant work of Schrock, Grubbs, and other contributors, olefin metathesis catalyst technology has made great strides. The well-defined molybdenum-based systems are especially active and have proven effective in asymmetric catalysis. The ruthenium-centered systems, including the Grubbs-type scaffolds and ruthenium-indenylidene complexes, exhibit excellent catalytic activity for most metathesis reactions as well as a remarkable tolerance to moisture and atmosphere. These latter two properties make the Grubbs-type ruthenium catalysts very easy to handle and to use in diverse synthetic and materials applications. Despite the widespread implications for the popular ruthenium catalysts, they are marred by inherent shortcomings which somewhat limit their more widespread use. Foremost, ruthenium metal is very expensive and potentially toxic, making its post-catalysis isolation and recovery essential and difficult. Furthermore, it has been widely proven that ruthenium-based catalysts decompose under the conditions and environments imposed by metathesis reactions, generating inorganic decomposition species which render the complexes inactive over time. It becomes imperative, then, for a method to be developed which can effectively regenerate the inorganic decomposition product derived from the ruthenium catalysts. The regenerated ruthenium-complexes should catalyze metathesis reactions while exhibiting activities that are comparable to the commercially available catalysts. In the chapter that follows, it will be shown that commercially available ruthenium olefin metathesis catalysts can be decomposed under an atmosphere of ethylene, liberating a ruthenium-based decomposition species. It will be shown that the reaction of this decomposition species with an activated propargyl alcohol will produce an in situ regenerated ruthenium-
indenylidene complex which displays RCM activity that is equivalent to the commercially available predecessors.

The third chapter will feature the design and synthesis of molybdenum complexes that catalyze olefin metathesis. Despite the immense applications of the Schrock or the Grubbs type catalysts, more widespread use has been somewhat prohibited due to expensive starting materials. Furthermore, the toxicity of the ruthenium(II) complexes and the high oxidation state molybdenum systems have posed restrictions on catalyst engineering and use. Furthermore, the Schrock-type systems are limited by their sensitivity to H$_2$O, O$_2$, and many functional groups. As a result, there exists an practical need for the design and synthesis of catalytic systems based on inexpensive and non-harmful transition metals. The development of novel olefin metathesis catalysts is contingent upon the tuning of low-valent and inexpensive metal-ligand systems.

The third chapter will highlight the efforts made in the quest for new stable and active olefin metathesis catalysts. It is believed that Ziegler-Natta olefin polymerization and olefin metathesis both involve bond-breaking and bond-forming steps that are shared by both processes. As such, it is believed that certain ligand-metal systems shown to be Ziegler-Natta olefin polymerization-active maintain a propensity to catalyze olefin metathesis reactions. Furthermore, it is believed that these complexes can be prepared to maintain a structure that is analogous to modestly stable intermediates of the olefin metathesis catalytic cycle. Specifically, the synthesis of metallacyclobutanes of molybdenum have been attempted by treatment of ligand-metal dichloride complexes with di-Grignard reagents. It is believed that certain ligand-metal complexes can induce the necessary agostic electronic properties necessary for the conversion of the
metallacyclobutane of molybdenum to a molybdenum alkylidene. It is hoped that the molybdenum alkylidene will be catalytically active in olefin metathesis reactions.
II. FIRST REGENERATION OF A RUTHENIUM-BASED OLEFIN METATHESIS CATALYST

2.1 Introduction

Olefin metathesis has fast developed into a practical and prevailing method for carbon-carbon bond formation within organic and polymer synthesis. The ruthenium-
centered complexes (1-4) have become the most widely used olefin metathesis catalysts in both academic and industrial applications due to their tolerance to oxygen, moisture, and diverse organic functional groups. Despite the benefits, preparations of these important catalysts are relatively difficult. Syntheses commonly entail several steps and illicit the isolation of the complexes to exclude catalytically-inhibiting byproducts, including trialkylphosphine ligands liberated during initiation of the catalytic cycle. As such, the Schrodi group has been interested in engineering a single-step procedure that produces robust olefin metathesis catalysts that are free from the need for isolation or purification techniques. Furthermore, the targeted synthetic pathway would be atom-economic calling for minimal equivalency of costly trialkylphosphine ligands per ruthenium metal.

\[
\text{1/2}[\text{RuCl}_2(p\text{-cymene})]_2 \xrightarrow{\text{THF reflux}} \text{2 PCy}_3 \rightarrow \text{PCy}_3 \text{Cl} \quad 5
\]

**Scheme 2.1** Preparation of a ruthenium allenylidene complex.

Past attempts to yield *in situ* olefin metathesis catalysts involved the preparation of ruthenium-vinylidenes and -allenylidenes, respectively. Complexes of these types were shown to be markedly less active in catalytic metathesis than the alkylidene complexes. Specifically, allenylidene complex (5) was easily afforded in a single-step procedure with the reaction of \([\text{RuCl}_2(p\text{-cymene})]_2\) with 1,1-diphenylprop-2-yn-1-ol and two equivalents
of PCy₃ (Scheme 2.1). Complex (5) has been proven inactive in catalyzing olefin metathesis. However, the chemical isomer of (5), the ruthenium indenylidene, exhibits activities comparable with that of ruthenium alkylidenes.

![Scheme 2.2](image)

**Scheme 2.2** Acid-promoted rearrangement of a ruthenium allenylidene to an indenylidene complex.

Ruthenium allenylidenes of the type [Ru]=C≡C≡CPh₂ have been shown to engage in rearrangement to generate ruthenium-indenylidenes when exposed to acidic conditions (Scheme 2.2). This rearrangement is thought to include an electrophilic aromatic substitution of an allenylidene phenyl group. Thus, it was believed that an activated derivative of 1,1-diphenylprop-2-yn-1-ol would promote the generation of an olefin metathesis-active indenylidene as opposed to the inactive allenylidene complex. 1-(3,5-dimethoxyphenyl)-1-phenylprop-2-yn-1-ol (6) was treated with the ruthenium starting material RuCl₂(p-cymene)(PCy₃) (Method 1, Scheme 2.3). Alternatively, the propargyl alcohol (6) was reacted with [RuCl₂(p-cymene)]₂ and one equivalent of PCy₃ (Method 2, Scheme 2.3). Both methods were undertaken by the Schrodi group and produced the ruthenium indenylidene complex (7) as the major product as verified by NMR spectroscopy.⁹⁸
Scheme 2.3 Methods of preparation for a ruthenium indenylidene complex.

Scheme 2.4 RCM of diethyl diallylmalonate with 1 mol% [Ru] of in situ (7).

The in situ catalyst reaction mixture was used as afforded to catalyze the RCM of diethyl diallylmalonate (Scheme 2.4). A kinetic study of the in situ catalyst (7) proved to exhibit the same activity profile as the Hoveyda-Grubbs first-generation catalyst (2) under standard reaction conditions. Generated by either method, this novel in situ RCM catalyst (7) efficiently promoted the robust conversion of various substrates into five-, six-, and seven-membered macrocyclic alkenes. Conversions were afforded in up to an hour of reaction time under mild conditions and with minimal catalyst loading. The in situ catalyst (7) has proven to be remarkably stable, as a catalytic solution afforded by
Method 2 stored at room temperature for 2 weeks under atmosphere still showed high RCM conversion of DEDAM within half an hour at 40 °C.

Studies have shown that ruthenium indenylidene complexes (8-10) express greater thermal stability than their benzylidene counterparts, while also showing robust catalytic activity and discrete selectivity. Nolan implemented the ruthenium-3-phenylindenylidene scaffold and imparted numerous ligands that were proven to be olefin metathesis active, such as unsaturated NHC’s as well as 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene. The synthetic routes to design these active indenylidene catalysts are particularly favorable because they are predicated on non-hazardous, facile to handle, and commercially abundant starting materials and precursors. These complexes also exhibit greater stability under the harshest of synthetic conditions.

Until recently, variations of ruthenium-indenylidene catalysts have focused on modifications of the coordinated NHC ligand, as well as the substitution of the PCy₃ ligand by other electron-withdrawing substituents, such as pyridine or Schiff bases. Alternatively, catalyst systems can be engineered which are characterized by bidentate ligands that include a chelated ether-benzylidene scaffold. It is projected that a (κ²O,C)-
isopropoxy-indenylidene bidentate ligated complex would exhibit stabilization, which would manifest a latency – a profound hallmark of interest for polymer preparations. In many ways, the nature of this novel bidentate ligated complex shares structure and chemical similarities to the Hoveyda-Grubbs first-generation scaffold. Bruneau et al. have reported the synthesis of first-generation complex (13a), which shows elevated thermal stability that far surpasses the stability of the Grubbs- and Hoveyda-Grubbs-type predecessors (Scheme 2.5).

Bruneau et al. approached the synthesis of the diphosphine indenylidene complex (12) by way of reacting propargyl alcohol (11) with [RuCl₂(PPh₃)₃] in refluxing THF. $^{31}$P
NMR spectroscopy was used to monitor the reaction modality. The chemical shifts did not match the expected values for a diphosphine complex like (12) but instead resembled those corresponding to the Hoveyda-type scaffold that characterize a bidentate ligand. After purification by column chromatography and crystallization, the molecular structure was resolved and conclusively showed the anticipated (κ²O,C)-isopropoxy-indenylidene bidentate complex (13a).

Naturally, the structural parameters of (13a) were compared to those of the Hoveyda complex (2). It was determined that the structural difference between the two complexes was with regards to the length of the Ru-O interaction. It was found that this interaction was longer in (13a) than in complex (2), effectively elucidating a weaker interaction in novel complex (13a). Accordingly, the latency of this new complex was confirmed by elevated thermal stability coupled with low catalytic activity at room temperatures, as well as increased activity after thermal activation. Future efforts will aim for the tuning of catalyst activity and stability by way of integration of NHC ligands into the catalyst scaffold. Variations of propargyl alcohols are also anticipated to provide for synthetically diverse complexes with adjustable steric and electronic properties.

Despite the synthetic versatility of ruthenium-carbene catalysts, the lifetime and efficiency of the complexes are limited in fundamental reactions. Furthermore, thermolytic decomposition modes pose harsh restrictions on the practical applications of the ruthenium systems in many reactions. As such, it has been shown that the ring-closing of macrocycles requires elevated catalyst loading when applied in highly-diluted conditions. Also, highly substituted and electron-deficient olefin metathesis calls for increased temperatures and reaction times. Furthermore, decomposition pathways of the
ruthenium carbene catalysts promote undesirable side-reactions and by-products. Indeed, olefin isomerizations and migration are prevalent side reactions in olefin metathesis which profoundly manipulate product profiles and diminish synthetic yields of targeted products.\textsuperscript{104} Moreover, side products generated from undesirable isomerizations can be very difficult to remove by conventional purification methods. It has been shown that olefin isomerization results from the very conditions that are necessary for effective RCM of macrocycles, including high temperatures and catalyst dilution. These behaviors were first observed on substrates possessing allylic functionalities in concert with the first-generation ruthenium complexes.\textsuperscript{105} Alkene isomerization was also reported with second-generation catalysts on diverse substrates.

\begin{center}
\begin{tikzpicture}

% Scheme 2.6 Isotopic study of olefin isomerization resulting in a 1,3-hydride shift.

% Initial state
\node (A) at (0,0) {$\text{[M]} \rightarrow D$};
\node (B) at (2,0) {$\text{[M]}$};
\node (C) at (4,0) {$\text{[M]} \rightarrow D$};
\node (D) at (6,0) {$\text{[M]} \rightarrow D$};

% 1,3-deuterium shift
\node (E) at (2,2) {$\text{1,3-deuterium shift}$};

% Final state
\node (F) at (2,-2) {$\text{[M]} \rightarrow H$};

% Arrows
\draw[->] (A) -- (B);
\draw[<->] (B) -- (C);
\draw[->] (C) -- (D);
\draw[<->] (D) -- (E);
\draw[->] (E) -- (F);
\end{tikzpicture}
\end{center}
Scheme 2.7 Isotopic study of olefin isomerization resulting in a 1,2-hydride shift.

The precise mechanisms that give way to isomerization are not completely understood. Olefin isomerization has been thought to adhere to two discrete pathways: either via $\eta^3$-allyls or by way of an alkyl intermediate by means of a metal-hydride species. The mechanistic pathway implied that the $\pi$-allyl undergoes an intramolecular 1,3-hydride shift (Scheme 2.6). The metal hydride species operates through an intermolecular addition-elimination with the competitive 1,2-hydride shift (Scheme 2.7). Despite the isotopic studies that have been undertaken, the ruthenium intermediate attributed to this unwanted reaction has yet to be elucidated.

Various reaction pathways have been postulated for the transformation of ruthenium carbenes into ruthenium hydrides responsible for the isomerization. Carbonyl hydrides (14) and (15) have been identified as products of the reaction of first- and second-generation Grubbs complexes with primary alcohols under basic conditions.
Despite the scarcity of mechanistic knowledge, these complexes have been known to be capable catalysts for the isomerization, hydrogenation, and hydrovinylation of olefins. Grubbs isolated dinuclear ruthenium hydride (16) as a decomposition product of
methylidene intermediate (17), which is produced during a metathesis cycle. Subsequent investigations have proposed ruthenium insertion into the C-H bond of a methyl on the NHC ligand. This bond activation is frequent for NHC-bearing complexes. This has been observed for the preparation of ruthenium carbene (3), yet has failed to give way to the hydride (18).

![Chemical reaction]

**Scheme 2.8** RCM of diallyl ether and isomerization of the ring-closed product.

The RCM of allyl ether (19) was studied, which produces 2,3-dihydrofuran (20) as the major product after 1 hour of reaction (Scheme 2.8). Upon prolonged reaction times, the product (20) isomerizes to (21). It is believed that this isomerization is a result of the catalyst decomposition products that are generated. The additives acetic acid and 1,4-benzoquinone effectively prohibited the isomerization of (20) to (21). Scavengers that propagate through radical mechanisms, such as phenol and 4-methoxyphenol, were shown to be ineffective in preventing the isomerizations. In general, 1,4-benzoquinones were found to inhibit olefin isomerization of various allylic ether and long-chain aliphatic alkene substrates during olefin metathesis processes with ruthenium-carbene catalysts. Electron-deficient benzoquinones were found to be the most effective additives for bypassing olefin migrations.

The preservation and enhancement of catalytic efficiency of the ruthenium complexes require an emphasis on the important relationship between metathesis rates
and catalyst decomposition (Scheme 2.9). Early studies of catalytic pathways and
decomposition focused on the first-generation Grubbs benzylidenes.\textsuperscript{106} It was shown that
the propagating species in RCM reactions tend to be alkylidenes of the type
(\textit{PCy}_3)_2\textit{Cl}_2\textit{Ru}=\textit{CHR} (22), with \textit{R} corresponding to a substrate linked to the catalyst.
Alternatively, the propagating species can be the methylidene (\textit{PCy}_3)_2\textit{Cl}_2\textit{Ru}=\textit{CH}_2 (23).
The propylidene analogue of the alkylidene (\textit{PCy}_3)_2\textit{Cl}_2\textit{Ru}=\textit{CHCH}_2\textit{CH}_3, in conjunction
with the methylidene, were chosen as the model catalytic species for a decomposition
investigation by Grubbs et al.

\begin{equation}
\begin{array}{c}
\text{Ru} \equiv \text{Ph} + \text{Ph}
\end{array}
\end{equation}

\begin{equation}
\begin{array}{c}
\text{Ru} \equiv \text{CH}_2 + \text{Ph}
\end{array}
\end{equation}

\textbf{Scheme 2.9} Decomposition study of first-generation Grubbs catalyst.

In the Grubbs study, it proved difficult to fit the decomposition data for the
propylidene into elementary rate equations. For short reaction times, the data were
generally nonlinear when fitted to a second-order rate equation, but became more linear
for more prolonged reaction times. \textsuperscript{31}P NMR spectroscopy of the propylidene
decomposition reaction mixture asserted that the major product was a liberated \textit{PCy}_3
ligand. There were also several smaller phosphine signals which grew over the course of
decomposition that were unable to be identified. It is believed that the identification of
the inorganic decomposition species was prohibited due to this array of multiple
phosphine signals. When excess phosphine was exerted upon the decomposition
conditions, decomposition rates notably decreased. Because it is known that the activity
of the ruthenium system is contingent upon phosphine dissociation, excess phosphine would also inhibit productive metathesis cycles.

\[
\begin{align*}
\text{Ru} & \quad \text{CHR} \\
\text{PCy}_3 & \quad \text{PCy}_3 \\
\text{Cl} & \quad \text{Cl} \\
\text{Ru} & \quad \text{CHR} \\
\text{PCy}_3 & \quad \text{PCy}_3 \\
\text{Cl} & \quad \text{Cl}
\end{align*}
\]

Scheme 2.10 Propylene decomposition initiated by phosphine dissociation.

The Grubbs study showed that propylidene decomposition was initiated by phosphine dissociation. This action is followed by the coupling of the two monophosphine species, forming a dinuclear complex (Scheme 2.10). As decomposition continues, the build-up of free phosphine is thought to prohibit the generation of the monophosphine species and slow decomposition rates.

Conversely, the decomposition data for the methylidene (23) nicely fit a first-order kinetic profile, implying that free phosphines would have no bearing on decomposition rates. \(^{31}\text{P}\) NMR spectroscopy showed numerous small peaks, yet the major peaks were attributed to free phosphine and an unknown species at 34.6 ppm. Purification and identification of this species by crystallography were fruitless. It was postulated that this phosphine-based species was not the phosphine ylide \(\text{Cy}_3\text{P}=\text{CH}_2\), which was verified by its discrete preparation and characterization by spectroscopic techniques.
This investigation concluded that alkylidene decomposition modality followed a second-order kinetic profile, a process contingent upon phosphine dissociation. Also, it was determined that methylidene decomposition adhered to first-order kinetics. Despite these findings, the precise nature and composition of the inorganic decomposition products could not be elucidated. It was reported that a ruthenium ethylene complex was observed from the tested generation of a monophosphine bimetallic methylidene, which suggested that bimolecular decomposition would take place for the methylidene complexes, but would be significantly slower than the unimolecular decomposition pathway. Accordingly, bimolecular methylidene decomposition was observed solely for the monophosphine methylidenes. Delineation of first-order methylidene decomposition is crucial in implicating their role in ring-closing reactions. This can be the fundamental reason that substrates shown to be difficult to cyclize require elevated catalyst loadings.

Van Rensburg et al. offered a substrate-induced decomposition pathway for ruthenium-carbene catalysts predicated upon density functional theory (DFT) method calculations (Scheme 2.11). This mechanism involves a β-hydride migration from a ruthenacyclobutane intermediate. As a means of experimental validation, the degenerate metathesis of ethylene by ruthenium methylidene (28) was undertaken. A

**Scheme 2.11** Substrate-induced decomposition route of a ruthenium-methylidene.
completely saturated ethylene solution of (28) in C₆D₆ was reacted at 40 °C for up to 16 hours, at which time ¹H NMR spectroscopy and gas chromatography showed the generation of propene, 1- and 2-butenes, and minute amounts of cyclopropanes and isobutene (Scheme 2.12). Propene generation is offered by a β-hydride mechanism.¹⁰⁷ When propene serves as a substrate following β-hydride transfer of α-methylruthenacyclobutane or β-methylruthenacyclobutane, isobutene can be generated. Potential reductive expulsion of cyclopropane from ruthenacyclobutane (25) validates the discussion that ruthenacyclobutanes serve as precursors to decomposition during substrate-initiated decomposition of (28).

Another Grubbs investigation sought to bridge the acquired knowledge of his earlier decomposition study to the second-generation ruthenium-carbene complexes. Previously, the phosphine product derived from the decomposition of the ruthenium methylidene species was not identified. In the 2007 study, the phosphine product was successfully characterized as CH₃PCy₃⁺Cl⁻ by comparison to a discretely prepared sample of the phosphine salt, as identified by ¹H NMR, ¹³C NMR, and HR-MS.¹⁰² Grubbs made an effort to characterize the major phosphine decomposition species. ³¹P NMR spectroscopy of the ethylene-induced decomposition of (17) and (28) showed a major phosphine complex at 34.6 ppm, corresponding to CH₃PCy₃⁺Cl⁻. Spectroscopic
techniques confirmed the structure of this species and provided unequivocal substantiation for this decomposition product. The $^{13}$C NMR spectrum of the species was especially informative, which revealed a diagnostic doublet for the methyl protons of the phosphonium salt at 1.5 ppm. This information led to the belief that phosphine attack of the methyldene carbon serves as a major decomposition pathway for (17) and (28) when in an environment of ethylene.

Scheme 2.13 Proposed mechanistic pathway for the decomposition of methyldene (17) with ethylene.
Another Grubbs study observed the individual steps involved in the well-characterized decomposition of the NHC-supported ruthenium methylidene (17) (Scheme 2.13).\textsuperscript{108} The considerable accumulation of the phosphonium salt CH\textsubscript{3}PCy\textsubscript{3}\textsuperscript{+}\textsuperscript{Cl} (29) prompted the notion that the decomposition of (17) generally took place by virtue of an attack of the dissociated PCy\textsubscript{3} ligand on the methylidene belonging to (30). Hofmann et al. validated this phosphine attack on the carbene carbon of ruthenium-alkylidenes.\textsuperscript{109} A 12 electron species generated by elimination of the phosphine ylide (31) would bind to a mesityl ring of (30). Two chlorides would bridge the two ruthenium metal centers and the removal of HCl by (31) would give rise to the terminal alkylidene with liberation of phosphonium salt (29). Dinuclear ruthenium hydride complex (16) is produced by the oxidative addition of the terminal alkylidene with migration of the chlorides. A steady-state approximation of (30) provides its respective decomposition rate expression, with the fundamental assumption that nucleophilic attack by the phosphine is the rate-determining step. This rate law remains consistent with the observation that the first-order kinetic decomposition of (17) is independent of phosphine concentration.

Despite the amazing versatility and diverse applications of the Grubbs-type ruthenium catalysts, their more widespread use is somewhat limited. The ruthenium starting materials from which catalytic complex are produced have been shown to be air- and moisture sensitive and can be quite expensive. The catalysts are known to readily decompose under metathesis-conditions. The liberated by-products and decomposition species contribute to catalyst degradation. Furthermore, side-reactions influence product profiles and diminish synthetic yields of desired products. Also, catalyst and by-product isolation is necessary for synthetically pure product distributions. Despite the extensive
research conducted, the discrete decomposition pathways and corresponding by-products are not completely understood.

As such, the Schrodi group has undertaken a very interesting and vital study of ruthenium olefin metathesis catalysts. A method for the complete decomposition of available commercial ruthenium olefin metathesis catalysts was developed. The liberated inorganic decomposition species were isolated for each decomposed catalyst. Each decomposition species was treated with an activated propargyl alcohol with the intention of regenerating the decomposition product to a ruthenium indenylidene complex. The regenerated ruthenium indenylidenes would be similar in nature to previously prepared \textit{in situ} ruthenium indenylidenes derived from commercial ruthenium starting materials. The regenerated ruthenium indenylidenes would then be tested for RCM activity of a conventional substrate. Regenerated complexes confirmed to be active for metathesis would be compared to previously prepared catalysts in terms of reaction time, conversion to the ring-closed product, as well as overall kinetic profile.
2.2 Results and Discussion

Hoveyda-Grubbs 1st generation catalyst, herein referred to as HG-601 (FW = 600.61 g/mol), was purposefully decomposed using the following procedure (Scheme 2.14). HG-601 (2) was loaded in a Fischer-Porter pressure vessel and was dissolved in dry dichloromethane (DCM), generating a brown reaction mixture. The vessel was pressurized with ethylene (120 PSI) and the reaction mixture was heated to 55 °C for 4 hours to afford a dirt brown-colored mixture. The decomposition product was isolated by removing the solvent in vacuo overnight, yielding a dark brown fine powder. The inorganic species accessed by decomposition of HG-601 was thought to contain \([\text{RuCl}_2(\text{PCy}_3)]\) (32) (FW= 452.4 g/mol). As verified by \(^1\)H NMR spectroscopy, the decomposition of HG-601 liberated the 2-isopropoxy styrene Hoveyda Ligand (33).
Figure 2.1 $^{31}\text{P} \quad \{^{1}\text{H}\} \quad \text{NMR (THF-}d_8\): \quad \text{Chemical shift of pure HG-601 (2) (60.57 ppm).}

The $^{31}\text{P}$ NMR spectrum of pure HG-601 in CDCl$_3$ agreed with previously published spectra (Figure 2.1). The tricyclohexylphosphine ligand appeared at $\delta=60.57$ ppm. The $^1\text{H}$ NMR spectrum of the catalyst agreed with previously published values for respective chemical shifts (Figure 2.2). The $^{31}\text{P}$ NMR spectrum of decomposed HG-601 in CD$_2$Cl$_2$ showed a peak at 59.5 ppm, corresponding to HG-601, and a series of peaks between 50 ppm (broad) and 48 ppm, revealing an array of phosphine-containing inorganic species (Figure 2.3). Initially, the degree of decomposition was determined by comparing integration values of $^1\text{H}$ NMR peaks assigned to the downfield doublet resonance corresponding to the carbene proton ($a$) of (2) against the more upfield septet
Figure 2.2 $^1$H NMR (THF-$d_8$): Chemical shifts of pure HG-601 (2) with triisopropyl benzene internal standard.

Figure 2.3 $^{31}$P $\{^1$H$\}$ NMR (CD$_2$Cl$_2$): Chemical shifts of decomposed (32) (59.51 ppm; 50-48 ppm, broad).
(b) corresponding to the methine proton of the liberated Hoveyda ligand (33). The $^1$H NMR spectrum of the decomposed HG-601 in THF-$d_8$ showed a doublet at 17.15 ppm for the carbene proton ($a$), of very low intensity (barely above baseline) indicating that most of the HG-601 was in fact decomposed (Figure 2.4). A sharp singlet at 5.49 ppm indicated the presence of ethylene gas. A septet at 4.58 ppm corresponded to the methine proton of the liberated Hoveyda Ligand (33) ($d$). Accordingly, $^1$H NMR and $^{31}$P NMR spectroscopy confirmed the decomposition of HG-601.

![Figure 2.4 $^1$H NMR (THF-$d_8$): Chemical shifts of decomposed HG-601.](image)

In order to confirm the decomposition of HG-601, the decomposed catalyst was used in a ring-closing metathesis of diethyl diallylmalonate (DEDAM) and the degree of conversion to the ring-closed product was determined (Scheme 2.15). 1 mol % Ru of decomposed HG-601 was added to a 0.1 M solution of DEDAM in CDCl$_3$. The decomposed catalyst (32) was dissolved in anhydrous tetrahydrofuran (THF).
Decomposed catalyst solution was added to the DEDAM substrate and the sample was allowed to react for 60 minutes at 40 °C. The degree of RCM conversion was determined by $^1$H NMR spectroscopy by comparing integration values for the singlet at 2.98 ppm for the methylene protons of the RCM product against the doublet at 2.6 ppm for the methylene protons of the substrate. It was found that less than 3% of the substrate was converted to the ring-closed product, the rest of the substrate being left unreacted. This indicated substantial HG-601 degradation and deactivation.

Although the precise nature and structure of the liberated inorganic decomposition species (32) is unknown, we hypothesized that it contained ruthenium metal, two mono-anionic chloride ligands, and one PCy$_3$ ligand. Thus, it was conjectured that the inorganic decomposition species was [RuCl$_2$(PCy$_3$)] (32). The synthetic preparation and characterization of this complex was studied by Severin et al. In this examination the chloro-bridged complex [(cymene)RuCl$_2$]$_2$ (34) was prepared from RuCl$_3$(H$_2$O)$_n$, which has fast become a primary starting material in organometallic syntheses and reactions.$^{111}$ (34) tends to react with monodentate trialkyl phosphine ligands to yield adducts of the type [(cymene)RuCl$_2$(PR$_3$)]. The integration of sterically bulky phosphines such as PCy$_3$ allows for the thermal cleavage of the cymene \( \pi \)-ligand. The ruthenium complexes that
arise from this behavior have been used as catalysts for RCM and ROMP reactions. The possibility of completely removing the cymene π-ligands of (34) in a nonprotic solvent was examined (Scheme 2.16). A solution of Complex (34) and 2 equivalents of PCy$_3$ in THF was heated for 48 hours, which upon column chromatography purification afforded complex (34). NMR spectroscopy validated the loss of the cymene ligand, which showed just the signals for the bound PCy$_3$ ligand. Crystallographic examination revealed that (35) exists as a trinuclear-ruthenium complex. In this structure, the three [RuCl$_2$(PCy$_3$)] fragments are joined by Ru-Ru single bonds and by bridging chloride ligands.

\[
3[(\text{cymene})\text{RuCl}_2]_2 + \text{PCy}_3 \xrightarrow{70 \, ^\circ\text{C}, \, 48\text{h}} \text{THF} \xrightarrow{-6 \text{ cymene}} 2[\text{RuCl}_2(\text{PCy}_3)]_3
\]

**Scheme 2.16** Preparation of a trinuclear ruthenium cluster from a ruthenium-cymene starting material.

Similar to structurally related trimers containing sterically bulky trialkyl phosphine ligands, complex (35) failed to react with monodentate or bidentate phosphine ligands such as PPh$_3$, even at elevated temperatures. The sheer fact that an inert ruthenium cluster can be accessed by the reaction of (34) with PCy$_3$ poses implications for catalytic applications. Accordingly, the formation of (35) may represent a plausible deactivation and decomposition pathway for ruthenium-centered catalysts. Although theoretically possible, the decomposition species derived from (2) likely does not generate this trinuclear ruthenium cluster.
It is thought that the putative decomposition product [RuCl$_2$(PC$_y_3$)] (32) is electronically unsaturated. This implies that treatment with an activated propargyl alcohol such as 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (36) will form a regenerated in situ isopropoxy ruthenium indenylidene complex (37a) (Scheme 2.17). The synthetic principle for this regeneration reaction is rooted from the previous study by Schrodi et al. that during the in situ preparation of the ruthenium indenylidene the (p-cymene) ligand is lost, essentially generating a [RuCl$_2$(PC$_y_3$)] complex that then undergoes a series of organometallic transformations to afford the ruthenium indenylidene complex. Given this, it is thought that the decomposition product, which is already free of the sterically demanding (p-cymene) ligand, should be ripe for reaction with the activated propargyl alcohol (36).
Scheme 2.18 Formation of a new ruthenium-indenylidene complex (37b).

Figure 2.5 $^{31}\text{P} \quad ^{1}\text{H}$ NMR (CDCl$_3$): Chemical shift of regenerated catalyst (37a) (67.48 ppm).

Thus, efforts ensued to regenerate the inorganic product of HG-601 decomposition (32) into a metathesis-active ruthenium-indenylidene complex.
Decomposition product (32) was treated with propargyl alcohol (36) in THF-$d_8$. The reaction mixture was heated at 70 °C for 18 hours, to give an amber colored reaction mixture. The regeneration product (37a) was analyzed by $^{31}$P NMR (Figure 2.5) and was compared to a previous spectrum of (37b) synthesized from a [RuCl$_2$(p-cymene)(PCy$_3$)] starting material (Scheme 2.18). The spectrum revealed a major species at 67.5 ppm and substantiated the conversion of decomposed HG-601 into a ruthenium-indenylidene complex (37a).

\[
\text{37a} \\
m^+ 758.2397
\]

Figure 2.6 HRMS (FAB) data for complex (37a).

The chemical formula of (37a) was compared to that of (37b) by high resolution mass spectrometry (HRMS) via fast atom bombardment (FAB) ionization. The structure of (37a) was confirmed for C$_{39}$H$_{55}$PCl$_2$O$_2$Ru: 758.2361; found, 758.2397 (4.8 ppm error) (Figure 2.6). The structure of (37b) was confirmed for C$_{39}$H$_{55}$PCl$_2$O$_2$Ru: 758.2361; found, 758.2391 (4.0 ppm error) (Figure 2.7). Thus, the structure of regenerated complex (7a) was validated to be the same as that of complex (37b), providing conclusive evidence of the regeneration of decomposed HG-601 into a ruthenium-indenylidene complex.
Figure 2.7 HRMS (FAB) data for complex (37b).

![HRMS spectrum for complex (37b)](image)

**Figure 2.7** HRMS (FAB) data for complex (37b).

Figure 2.8 Kinetics of RCM of 0.1 M DEDAM in CDCl₃ at 30 °C.

![Kinetics graph](image)

**Figure 2.8** Kinetics of RCM of 0.1 M DEDAM in CDCl₃ at 30 °C.

The catalytic activity of the regenerated ruthenium-indenylidene complex (37a) was determined by way of an RCM kinetics experiment, which was monitored by ¹H NMR spectroscopy over a period of at least 90 minutes up to 120 minutes. 0.1 M DEDAM in CDCl₃ was used as substrate, and 1 mol % Ru regenerated catalyst solution
(37a) was loaded. The reaction was performed at 30 °C. The graph in Figure 2.8 indicates that there was an initial latency period, with RCM conversion reaching approximately 20% after 50 minutes. Conversion was almost 90% after 90 minutes. In the next kinetic experiment, CD₂Cl₂ was used to prepare the 0.1 M DEDAM substrate solution instead of CDCl₃. 1 mol % Ru regenerated catalyst solution (37a) was then loaded. The reaction was performed at 30 °C. The graph in Figure 2.9 shows evidence of an initial latency period, with RCM conversion just exceeding 20% after 50 minutes of reaction. RCM conversion did reach approximately 90% after 115 minutes of reaction time.

![Figure 2.9](image)

**Figure 2.9** Kinetics of RCM of 0.1 M DEDAM in CD₂Cl₂ at 30 °C.

It is evident that the reactions in both of the solvents exhibit a clear latency period up until 50 minutes of reaction time, at which point the kinetic behavior of each profile diverges. The kinetics for the RCM of DEDAM in CDCl₃ makes a more rapid progression to completion at this point than does the RCM of DEDAM in CD₂Cl₂. The
RCM of DEDAM in CD$_2$Cl$_2$ required approximately 105 minutes to achieve the same percent conversion to the ring-closed product as the reaction in CDCl$_3$ after 90 minutes, both at 30 °C. These findings are important in that CD$_2$Cl$_2$ tends to be the solvent of choice to carry out $^1$H NMR monitored RCM reactions in academia and industry alike.

Figure 2.10 Overlay of RCM experiments of 0.1 M DEDAM in CD$_2$Cl$_2$ at 30.0 °C (blue) and at 40.0 °C (red).

Figure 2.10 shows an overlay of the kinetic RCM experiments carried out in CD$_2$Cl$_2$ at 30 °C and 40 °C, respectively. A 0.1 M solution of DEDAM substrate spiked with a 1 mol% Ru of regenerated catalyst solution (37a). The reaction was monitored by $^1$H NMR spectroscopy. At an elevated temperature of 40 °C, it is clear that the initial latency of the catalyst exists until about 20 minutes, at which point the catalytic activity of the regenerated complex increases rapidly, with near full conversion occurring by the 90 minute mark. There is a clear divergence of the kinetic profiles of each reaction at the
10 minute mark. It is at this time that the reaction at 40 °C begins to rapidly ascend towards completion. This figure shows the utility of performing the RCM of DEDAM at 40 °C, which is conventionally the optimal temperature for carrying out RCM experiments of DEDAM due to a satisfactory compromise between accelerated reaction rates and minimizing solvent loss.

**Scheme 2.19** Decomposition of Grubbs 1st generation catalyst to generate putative inorganic species (39).

Grubbs 1st generation catalyst (38) (FW= 822.96 g/mol) was effectively decomposed (Scheme 2.19). (38) was loaded in a Fischer-Porter pressure vessel and dissolved in anhydrous DCM, generating a deep purple-colored reaction mixture. The vessel was pressurized with ethylene (120 PSI) and the reaction mixture was heated to 55 °C for 4 hours to afford a dark green/brown-colored mixture. The decomposition product (39) was isolated by evaporating solvent and drying in vacuo overnight. The product was allowed to dry in the atmosphere of a drybox filled with nitrogen overnight, yielding a dark olive-green colored fine powder.

The extent of decomposition of (38) was assessed by a control RCM of DEDAM (Scheme 2.20). A 0.1 M solution of DEDAM in CDCl₃ was loaded with 1 mol % Ru from decomposition solution (39) (prepared in anhydrous THF). The sample was allowed to react for 60 minutes at 40 °C. Characterization of the reaction by ¹H NMR
spectroscopy revealed a small singlet at 2.98 ppm, corresponding to the RCM product, and a large doublet at 2.6 ppm, revealing the majority of the unreacted substrate. By integration of these two peaks it was determined that \textit{less than} 3\% of the substrate was converted to the ring-closed product, the rest of the substrate being left unreacted. This indicated considerable decomposition and deactivation of (38).

![Scheme 2.20](image)

**Scheme 2.20** Control RCM of 0.1M DEDAM with 1 mol\% Ru decomposition product (39) in CDCl₃ at 40 °C.

The first-generation Grubbs catalyst (38) is a bis-phosphine ligated ruthenium-centered complex. Based on delineated reaction and decomposition pathways for such a complex, when exposed to an atmosphere of ethylene it is expected that the 16e-precatalyst will undergo a phosphine dissociation to render a 14e-complex. This 14e-species will then engage in a metathesis catalytic cycle. It is presumed that the decomposition pathway for this catalyst will be mostly first-order, which may generate more than one decomposition species.

As such, the attempted regeneration of the putative decomposition product (39) was undertaken (Scheme 2.21). The olive-green decomposition powder was combined with the 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol organic precursor (36) in anhydrous THF, yielding a dark green colored reaction mixture. This was allowed to react for 18 hours at 70 °C, at which point an amber-orange colored reaction mixture was produced. Visually, it had appeared as though regeneration of decomposed Grubbs 1st
generation catalyst into (40) had occurred. It was postulated that the regenerated complex was similar in structure to the regenerated complex (37a) from decomposed HG-601.

\[
\text{THF} \\
70 \degree C; 18 \text{ hrs} \]

\[
\begin{align*}
39 & \quad \text{Putative Regenerated Complex} \\
36 & \quad 40
\end{align*}
\]

Scheme 2.21 Attempted regeneration of Grubbs 1st generation decomposition product (39) into a putative phenylindenylidene (40) by reaction with propargyl alcohol (36).

\[
\begin{align*}
\text{EtOOC} & \quad \text{COOEt} \\
\text{EtOOC} & \quad \text{COOEt}
\end{align*}
\]

Scheme 2.22 RCM of 0.1M DEDAM with 1 mol% Ru regeneration catalyst (40) in CDCl\textsubscript{3} at 40 °C.

However, the true integrity of regeneration and catalytic activity of (40) would be determined by way of an RCM of DEDAM (Scheme 2.22). A 0.1M DEDAM solution was prepared in CDCl\textsubscript{3}. 1 mol % Ru regenerated catalyst solution (40) was loaded onto the substrate. The sample was allowed to react for 60 minutes at 40 °C. Characterization of the reaction by \textsuperscript{1}H NMR showed a tall singlet at 2.98 ppm, corresponding to the RCM product, and a doublet at 2.6 ppm, showing the considerable presence of unreacted substrate. Integration of these two peaks revealed that only 30% of the substrate was converted to the ring-closed product, the remainder of the substrate being left unreacted. Although catalytic RCM activity increased, RCM conversion of the substrate was not enough to consider a robust conversion of the decomposition product into a fully catalytic
ruthenium-indenylidene complex. This was not so surprising since the decomposition pathway for (38) is most likely different from that of HG-601.

![Chemical Structure](image)

Scheme 2.23 Decomposition of HG-627 to produce inorganic decomposition species (42).

The decomposition of Hoveyda-Grubbs 2\textsuperscript{nd} generation catalyst (41), herein referred to as HG-627 (FW= 626.62 g/mol), was undertaken (Scheme 2.23). HG-627 (41) was charged into a Fischer-Porter pressure vessel and dissolved in anhydrous DCM, generating a dark green-colored reaction mixture. The vessel was pressurized with ethylene (120 PSI) and the reaction mixture was heated to 55 °C for 4 hours to afford a dark brown-colored mixture. The decomposition product was isolated by evaporating solvent in vacuo overnight. The product was allowed to dry in the atmosphere of a drybox filled with nitrogen, yielding a dark brown-colored powder. The specific structure and nature of the inorganic decomposition product (42) was not immediately known.

![Chemical Structure](image)

Scheme 2.24 Control RCM of 0.1M DEDAM with 1 mol% Ru decomposition product (42) in CDCl\textsubscript{3} at 40 °C.
The extent of decomposition was assessed by performing a control RCM of DEDAM (Scheme 2.24). A 0.1 M solution of DEDAM substrate was prepared in CDCl₃. The sample was spiked with 1 mol% Ru of decomposed catalyst solution which was prepared by dissolving (42) in anhydrous THF. The sample was allowed to react for 60 minutes at 40 °C. Characterization of the RCM reaction by ¹H NMR revealed a small singlet at 2.98 ppm, corresponding to the RCM product, and a large doublet at 2.6 ppm, revealing the majority of the unreacted DEDAM substrate. Integration of these two peaks provided the conclusion that less than 3% of the substrate was converted to the RCM product, the remainder of the substrate being left unreacted. This was evidence that HG-627 was properly decomposed.

\[
\text{THF} \\
70 \degree C; 18 \text{ hrs} \\
\text{42} \quad \xrightarrow{\text{Putative Regenerated Complex}} \quad \text{43} \\
\text{36}
\]

**Scheme 2.25** Attempted regeneration of decomposition product (42) into a putative phenylindenylidene (43) by reaction with propargyl alcohol (36).

To attempt the regeneration of decomposed HG-627, (42) was combined with the 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol organic precursor (36) in anhydrous THF (Scheme 2.25). The sample was allowed to react at 70 °C for 18 hours. An amber orange colored reaction mixture (43) was provided.

The catalytic integrity of the putative regenerated complex (43) was studied by performing the RCM of DEDAM (Scheme 2.26). A 0.1 M solution of DEDAM substrate was prepared in CDCl₃. The substrate was spiked with a 1 mol% Ru solution of regeneration complex (43). The sample was allowed to react for 60 minutes at 40 °C.
Characterization of the reaction by $^1$H NMR spectroscopy revealed a singlet at 2.98 ppm, corresponding to the ring-closed product, and a doublet at 2.6 ppm, corresponding to the substrate. Based on integration of these two peaks, it was determined that only 7% of the substrate was converted to the RCM product, the remainder of the substrate being left unreacted. As such, it can be assumed that the regeneration of decomposed HG-627 was unsuccessful.

The observed failure of regeneration of decomposed second-generation Hoveyda-Grubbs catalyst can be attributed to the known decomposition mode of the complex. The catalyst lacks phosphine ligands, and its decomposition mechanism is predicated upon a substrate-induced β-hydride transfer from its respective ruthenacyclobutane intermediate, as reported by van Rensburg et al. The decomposition of this phosphine-free catalyst will generate an unidentifiable ruthenium hydride species. The steric impediments introduced to the scaffold by the NHC ligand may restrict the necessary electronic movements for the bidentate chelation of the indenylidene ligand. As such, these electronic properties and restrictions are believed to be prohibitive to the effective regeneration of decomposed 

![Diethyl allylmalonate](image1.png)  
**Scheme 2.26** RCM of 0.1M DEDAM with 1 mol% Ru regeneration catalyst (43) in CDCl$_3$ at 40 °C.
second-generation Hoveyda-Grubbs catalyst to an NHC-supported ruthenium indenylidene complex.

2.3 Conclusion

The regeneration of the decomposed inorganic species derived from first-generation Hoveyda-Grubbs catalyst into a metathesis-active in situ ruthenium indenylidene complex was successful. Decomposition of first-generation Hoveyda-Grubbs under an atmosphere of ethylene was complete. The decomposition product was isolated and was treated with an activated propargyl alcohol to afford the corresponding ruthenium indenylidene. The regenerated complex is air stable and a catalyst solution was proven to be very active in the RCM of a conventional bis-olefinic substrate. The activity of the regenerated catalyst compared favorably to that of the same complex produced from a ruthenium starting material as well as to the first-generation Hoveyda-Grubbs catalyst. The level of conversion demonstrated suggests the potential use of this regenerated catalyst in industrial applications of RCM. These results afford much needed insight to the possible decomposition mode of first-generation Hoveyda-Grubbs catalyst and the decomposition products generated as a result. Also, this method provides a means to recycle expensive ruthenium metal from the decomposed catalyst such that it may be incorporated into a regenerated complex that may be applied to olefin metathesis reactions. By all accounts, this is a contribution to the position that the olefin metathesis reactions has assumed in the realm of green and environmentally-friendly chemistry.
Following established procedure, the regeneration of the decomposed inorganic species derived from first-generation Grubbs catalyst into a metathesis-active *in situ* ruthenium indenylidene complex was attempted. Decomposition of first-generation Grubbs under an atmosphere of ethylene was complete. The decomposition product was isolated and was treated with an activated propargyl alcohol in hopes of producing the corresponding ruthenium indenylidene. When the RCM of a conventional bis-olefinic substrate was attempted with the regenerated solution, conversion to the ring-closed product was noted. However, the extent of RCM conversion was not sufficient enough to determine the successful regeneration of the decomposition product to a metathesis-active *in situ* ruthenium indenylidene. It is thought that the decomposition pathway for the first-generation Grubbs catalyst affords a ruthenium-based inorganic species that may not be amenable to treatment with the activated propargyl alcohol for successful regeneration. Furthermore, the array of decomposition species, including phosphonium salts, may contribute to the inhibition of robust regeneration.

Following established procedure, the regeneration of the decomposed inorganic species derived from second-generation Hoveyda-Grubbs catalyst into a metathesis-active *in situ* ruthenium indenylidene complex was attempted. Decomposition of second-generation Hoveyda-Grubbs under an atmosphere of ethylene was complete. The decomposition product was isolated and was treated with an activated propargyl alcohol in hopes of producing the corresponding ruthenium indenylidene. When the RCM of a conventional bis-olefinic substrate was attempted with the regenerated solution, conversion to the ring-closed product was noted. However, the extent of RCM conversion was not sufficient enough to determine the successful regeneration of the decomposition
product to a metathesis-active in situ ruthenium indenylidene. It is thought that the decomposition pathway for the second-generation Hoveyda-Grubbs catalyst affords a ruthenium-based inorganic species that may not be amenable to treatment with the activated propargyl alcohol for successful regeneration. Furthermore, the array of decomposition species, including phosphonium salts, may contribute to the inhibition of robust regeneration.

In the future, the isolation of the decomposition product from the parent catalyst as well as its regeneration to a ruthenium indenylidene will be refined so as to afford a more pure and isolatable complex. Also, the conversion of the regenerated ruthenium indenylidene catalyst to a so-called “second-generation” regenerated complex, supported by an NHC ligand featuring aryl groups substituted by different alkyl groups, will be attempted. It is thought that the second-generation regeneration complex will afford more protection and stability to the integrity and lifetime of the complex as well as more robust and active conversion rates in RCM applications.

2.4 Experimental

GENERAL INFORMATION

NMR spectra were recorded on either a Bruker 400MHz NMR running Xwin-NMR software, or a Varian 400MHz NMR spectrometer running VNMR-J software. Chemical shifts are reported in parts per million (ppm) downfield from tetramethylsilane (TMS) with reference to internal solvent for $^1$H NMR and $^{13}$C NMR spectra. Chemical shifts are reported in parts per million (ppm) downfield from H$_3$PO$_4$ for $^{31}$P NMR spectra. All
glassware was oven dried and reactions were performed under an atmosphere of either nitrogen or argon, unless otherwise noted. All organic solvents were dried by passage through solvent purification columns containing activated molecular sieves. All other commercial chemicals were used as obtained. Hoveyda-Grubbs 1st generation catalyst, Hoveyda-Grubbs 2nd generation catalyst, and Grubbs 1st generation catalyst were graciously donated from Materia, Inc.

Decomposition of Hoveyda-Grubbs 1st generation catalyst and isolation of inorganic decomposition species.

\[
\begin{align*}
\text{RuCl}_2(\text{PCy}_3) & \quad \text{DCM} \\
\text{Cl} & \quad \text{ethylene gas; 120 PSI} \\
i\text{-Pr-O} & \quad 55 ^\circ C; 4 \text{ hrs} \\
\end{align*}
\]

"[RuCl_2(\text{PCy}_3)]"  

Hoveyda-Grubbs 1st generation catalyst (0.5 g, 0.832 mmol), herein referred to as HG-601, was dissolved in anhydrous DCM (10 mL). The dark brown reaction mixture was loaded into a Fischer-Porter pressure vessel equipped with a magnetic stir bar. The reaction mixture was pressurized with ethylene gas to 120 PSI. The mixture was immersed in an oil bath and was allowed to react for 4 hours at 55 °C while vigorously stirring, which resulted in a dirt-brown colored reaction mixture. After reaction, the mixture was allowed to cool to room temperature. The vessel was carefully relieved of the ethylene atmosphere, and the reaction mixture was collected in a round bottom flask.
Bulk solvent was removed by rotoevaporation. The decomposition product was dried overnight using standard Schlenck techniques, which afforded a dark brown, almost black solid film. The decomposition product was taken into a dry box filled with nitrogen gas for work-up and isolation. The solid film was triturated with anhydrous C₅ (5 mL) and the mixture was vacuum filtered. The solid retained by the sinter was washed with anhydrous C₅ (3 x 2 mL). The decomposition product was allowed to dry on the frit in the atmosphere of the dry box over night. The decomposition product was isolated as a fine dark-brown, black powder in 93% yield. ¹H NMR (THF-δ₈): δ 5.32 (sept). ³¹P NMR (161 MHz, CD₂Cl₂): δ 59.51 (s, 1P), 50.39-49.97 (broad), 48.79 (s).

**RCM of diethyl diallyl malonate with decomposed HG-601.**

An NMR tube equipped with a screw-cap septum top was charged with CDCl₃ (490 µL) and diethyl diallyl malonate (DEDAM) (12 µL, 12 mg, 50 µmol, 0.1 M). A solution of decomposed catalyst (22.1 µmol) in anhydrous THF (1 mL) was prepared (0.0221 M). The DEDAM substrate was spiked with the decomposition solution (22.5 µL) via syringe. The sample was allowed to react for 60 minutes at 40 °C. The conversion to the RCM product was determined by comparison of the ratio of integration of the methylene protons in the substrate, δ 2.6 (d), with those of the RCM product, δ 2.98 (s). There was 5.6% conversion of the substrate to the ring-closed product.
Reaction of decomposed HG-601 with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol.

\[
\text{"[RuCl}_2\text{(PCy}_3\text{)]\" + } \begin{array}{c}
\begin{array}{c}
\text{OH} \\
\text{Ph}
\end{array}
\end{array}
\rightarrow \begin{array}{c}
\begin{array}{c}
\text{PCy}_3 \\
\text{Ru}
\end{array}
\end{array}
\]_{\text{Cl}}^{\text{Cl}}_{\text{THF-}d_8}^{\text{O-i-Pr}}_{\text{70}^\circ\text{C; 4 hrs}}^{\text{i-Pr-O}}_{\text{O-i-Pr}}
\]

\text{[RuCl}_2\text{(PCy}_3\text{)] (0.05 g, 0.11 mmol) from decomposed HG-601 and 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (0.072 g, 0.221 mmol) were dissolved in anhydrous THF-}d_8. \text{ The mixture was allowed to react for 18 hours at 70 °C, which afforded an amber-orange colored reaction mixture. }^{31}\text{P NMR (161 MHz, THF-}d_8\text{): }\delta \text{ 67.48 (s, 1P).}
Procedure for the activity plots of diethyl diallylmalonate at 30 °C

A diethyl diallylmalonate (12 µL, 12 mg, 50 µmmol, 0.1 M) solution in either CDCl₃ or CD₂Cl₂ (490 µL) was prepared in a NMR tube equipped with a screw-cap septum top. The sample was equilibrated in the NMR probe at 30 °C. The substrate was spiked via syringe with previously prepared regenerated catalyst solution (4.5 mmol, 0.5 µL). Data points were collected over a period of 90-120 minutes. The conversion of substrate to the RCM product was determined by comparison of the ratio of integrals of the methylene protons in the substrate, δ 2.6 (d), with those of the ring-closed product, δ 2.98 (s). Upon collecting the data, a kinetics plot was compiled and was compared to previously constructed kinetics plots of various catalysts.
A diethyl diallylmalonate (12 µL, 12 mg, 50 µmmol, 0.1 M) solution in CD$_2$Cl$_2$ (490 µL) was prepared in a NMR tube equipped with a screw-cap septum top. The sample was equilibrated in the NMR probe at 40 °C. The substrate was spiked via syringe with previously prepared regenerated catalyst solution (4.5 mmol, 0.5 µL). Data points were collected over a period of 90 minutes. The conversion of substrate to the RCM product was determined by comparison of the ratio of integrals of the methylene protons in the substrate, δ 2.6 (d), with those of the ring-closed product, δ 2.98 (s). Upon collecting the data, a kinetics plot was compiled and was compared to previously constructed kinetics plots of various catalysts.
Decomposition of Grubbs 1st generation catalyst and isolation of decomposed inorganic species.

Grubbs 1st generation catalyst (0.5 g, 0.608 mmol) was dissolved in anhydrous DCM (10 mL). The deep purple reaction mixture was loaded into a Fischer-Porter pressure vessel equipped with a magnetic stir bar. The reaction mixture was pressurized with ethylene gas to 120 PSI. The mixture was immersed in an oil bath and was allowed to react for 4 hours at 55 °C while vigorously stirring, which resulted in a dark green-brown colored reaction mixture. After reaction, the mixture was allowed to cool to room temperature. The vessel was carefully relieved of the ethylene atmosphere, and the reaction mixture was collected in a round bottom flask. Bulk solvent was removed by rotovaporation. The decomposition product was dried overnight using standard Schlenck techniques, which afforded a dark green-colored solid film. The decomposition product was taken into a dry box filled with nitrogen gas for work-up and isolation. The solid film was tritirated with anhydrous C5 (5 mL) and the mixture was vacuum filtered. The solid retained by the sinter was washed with anhydrous C5 (3 x 2 mL). The decomposition product was allowed to dry on the frit in the atmosphere of the dry box over night. The decomposition product was isolated as a fine dark olive-green colored powder in 84% yield. 1H NMR (THF-d8): δ 5.32 (sept). 31P NMR (161 MHz, CD2Cl2): δ 59.51 (s, 2P), 50.39-49.97 (broad), 48.79 (s).
RCM of diethyl diallylmalonate with decomposed Grubbs 1\textsuperscript{st} generation catalyst.

\[ \text{EtO}_2\text{C} \quad \text{CO}_2\text{Et} \quad \text{1 mol\% [Ru]} \quad \text{EtO}_2\text{C} \quad \text{CO}_2\text{Et} \]

0.1 M; CDCl\textsubscript{3}; 40 °C

An NMR tube equipped with a screw-cap septum top was charged with CDCl\textsubscript{3} (490 µL) and diethyl diallyl malonate (DEDAM) (12 µL, 12 mg, 50 µmol, 0.1 M). A solution of decomposed catalyst (22.1 µmol) in anhydrous THF (1 mL) was prepared (0.0221 M). The DEDAM substrate was spiked with the decomposition solution (22.75 µL) via syringe. The sample was allowed to react for 60 minutes at 40 °C. The conversion to the RCM product was determined by comparison of the ratio of integration of the methylene protons in the substrate, δ 2.6 (d), with those of the RCM product, δ 2.98 (s). There was 10.0% conversion of the substrate to the ring-closed product.
Reaction of decomposed Grubbs 1st generation catalyst with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol.

"[RuCl2(PCy3)]" +

\[
\begin{align*}
\text{OH} & \quad \text{Ph} \\
\equiv & \quad \equiv \\
i-\text{Pr} & \quad i-\text{Pr} \\
i-\text{Pr}-\text{O} & \quad -\text{O}-i-\text{Pr}
\end{align*}
\]

THF

70 °C; 18 hrs

Decomposed Grubbs 1st generation catalyst (0.05 g, 0.11 mmol) and 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (0.072 g, 0.221 mmol) were dissolved in anhydrous THF-\(d_8\). The mixture was allowed to react for 18 hours at 70 °C, which afforded an amber-orange colored reaction mixture.

**RCM of diethyl diallylmalonate with putative regenerated Grubbs 1st generation catalyst.**

\[
\begin{align*}
\text{CO}_2\text{Et} & \quad \text{CO}_2\text{Et} \\
\text{EtO}_2\text{C} & \quad \text{EtO}_2\text{C}
\end{align*}
\]

1 mol% [Ru]

0.1 M; CDCl₃; 40 °C

A diethyl diallylmalonate (12 µL, 12 mg, 50 µmmol, 0.1 M) solution in CDCl₃ (490 µL) was prepared in a NMR tube equipped with a screw-cap septum top. The substrate was spiked via syringe with previously prepared Grubbs 1st generation regenerated catalyst solution (4.5 mmol, 0.5 µL). The sample was allowed to react for 60 minutes at 40 °C.
The conversion of substrate to the RCM product was determined by comparison of the ratio of integrals of the methylene protons in the substrate, $\delta$ 2.6 (d), with those of the ring-closed product, $\delta$ 2.98 (s). It was found that 30% of the substrate was converted to the RCM product, the remainder of the substrate being left unreacted.

**Decomposition of Hoveyda-Grubbs 2$^{nd}$ generation catalyst and isolation of decomposed inorganic species.**

![Chemical Structure](image)

Grubbs 1$^{st}$ generation catalyst (0.5 g, 0.797 mmol) was dissolved in anhydrous DCM (10 mL). The dark green reaction mixture was loaded into a Fischer-Porter pressure vessel equipped with a magnetic stir bar. The reaction mixture was pressurized with ethylene gas to 120 PSI. The mixture was immersed in an oil bath and was allowed to react for 4 hours at 55 °C while vigorously stirring, which resulted in a dark brown colored reaction mixture. After reaction, the mixture was allowed to cool to room temperature. The vessel was carefully relieved of the ethylene atmosphere, and the reaction mixture was collected in a round bottom flask. Bulk solvent was removed by rotoevaporation. The
decomposition product was dried overnight using standard Schlenck techniques, which afforded a dirt-brown colored solid film. The decomposition product was taken into a dry box filled with nitrogen gas for work-up and isolation. The solid film was triturated with anhydrous C₅ (5 mL) and the mixture was vacuum filtered. The solid retained by the sinter was washed with anhydrous C₅ (3 x 2 mL). The decomposition product was allowed to dry on the frit in the atmosphere of the dry box over night. The decomposition product was isolated as a fine dirt brown colored powder in 59.7% yield.

**RCM of diethyl diallylmalonate with decomposed Hoveyda-Grubbs 2nd generation catalyst.**

\[
\text{EtO}_2\text{C} \quad \text{CO}_2\text{Et} \quad \text{1 mol\% [Ru]} \quad \text{EtO}_2\text{C} \quad \text{CO}_2\text{Et}
\]

\[
0.1 \text{ M; } \text{CDCl}_3; \text{40 °C}
\]

An NMR tube equipped with a screw-cap septum top was charged with CDCl₃ (490 µL) and diethyl diallyl malonate (DEDAM) (12 µL, 12 mg, 50 µmol, 0.1 M). A solution of decomposed catalyst (5.0 µmol) in anhydrous THF (1 mL) was prepared (0.005 M). The DEDAM substrate was spiked with the decomposition solution (5 µL) via syringe. The sample was allowed to react for 60 minutes at 40 °C. The conversion to the RCM product was determined by comparison of the ratio of integration of the methylene protons in the substrate, δ 2.6 (d), with those of the RCM product, δ 2.98 (s). There was 3.0% conversion of the substrate to the ring-closed product, with the remainder of the substrate being left unreacted.
**Reaction of decomposed Hoveyda-Grubbs 2\textsuperscript{nd} generation catalyst with 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol.**

\[
\text{Decomposed Hoveyda-Grubbs 2nd generation catalyst} + \quad \begin{array}{c}
\text{OH} \\
\text{Ph} \\
\end{array} \rightarrow \quad \begin{array}{c}
\text{THF} \\
\text{70 °C; 18 hrs} \\
\end{array} \\
\]

Decomposed Grubbs 1\textsuperscript{st} generation catalyst (0.05 g, 0.104 mmol) and 1-(3,5-diisopropoxyphenyl)-1-phenylprop-2-yn-1-ol (0.0677 g, 0.209 mmol) were dissolved in anhydrous THF-\textit{d}_8. The mixture was allowed to react for 18 hours at 70 °C, which afforded an amber-orange colored reaction mixture.

**RCM of diethyl diallylmalonate with putative regenerated Hoveyda-Grubbs 2\textsuperscript{nd} generation catalyst.**

\[
\text{EtO}_2\text{C} \quad \begin{array}{c}
\text{CO}_2\text{Et} \\
\end{array} \rightarrow \quad 1 \text{ mol\% [Ru]} \quad \begin{array}{c}
\text{EtO}_2\text{C} \\
\text{CO}_2\text{Et} \\
\end{array} \quad \begin{array}{c}
\text{0.1 M; CDCl}_3; 40 °C \\
\end{array} \\
\]

A diethyl diallylmalonate (12 µL, 12 mg, 50 µmmol, 0.1 M) solution in CDCl\textsubscript{3} (490 µL) was prepared in a NMR tube equipped with a screw-cap septum top. The substrate was spiked via syringe with previously prepared Grubbs 2nd generation regenerated catalyst solution (5 mmol, 4.8 µL). The sample was allowed to react for 60 minutes at 40 °C. The conversion of substrate to the RCM product was determined by comparison of the ratio of integrals of the methylene protons in the substrate, δ 2.6 (d), with those of the ring-closed
product, \( \delta \) 2.98 (s). It was found that 7\% of the substrate was converted to the RCM product, the remainder of the substrate being left unreacted.
III. THE USE OF DI-GRIGNARD REAGENTS TO FORM METALLACYCLOBUTANE COMPLEXES

3.1 Introduction

![Chemical Structure](image_url)

1. 2,6-Diisopropylphenyl imidoneoplylidene molybdenum bis(hexafluoro-t-butoxide)
   Commercial Schrock Catalyst

Despite the diverse applications of tolerant ruthenium olefin metathesis catalysts of the Grubbs type, more prevalent use has thus far been limited due to the high costs and the potential toxicity of the Ru(II) complexes. Also, Mo(VI) systems such as (1) possess excellent activity, but their wide use is compromised by their high sensitivity to H₂O, O₂, and many functional groups. As a result, there exists an urgent need for the design and synthesis of catalytic systems based on abundant and innocuous transition metals. In spite of this, progress has been arduous at best due to the inherent complications associated with preparations of low oxidation-state transition metal-alkylidene complexes of the type [M=CRR’] (R,R’: H, alkyl, or aryl). Future development of novel olefin metathesis catalysts, then, is contingent upon the tuning of low-valent and inexpensive metal-ligand systems.
Our group has embarked on the search for such novel olefin metathesis catalysts. As previously mentioned, the discovery of the olefin metathesis reaction grew out of Ziegler-Natta olefin polymerization studies. We have postulated that specific ligand-metal systems verified to be active in Ziegler-Natta polymerization possess a logical potential to catalyze olefin metathesis reactions. This hypothesis is rooted in the belief that Ziegler-Natta polymerization and olefin metathesis both involve bond-breaking and bond-forming steps that are common to both processes (Scheme 3.1). In Ziegler-Natta polymerization, chain lengthening reactions are thought to proceed by insertions of an alkenes in a metal-alkyl bonds, known as the Cossee mechanism. These olefin insertions entail the cleavage of two metal-carbon interactions (cleavage of the M-C* interactions in Scheme 3.1a) as well as the formation of a new discrete C-C bond (formation of the C_a-C_b bond in Scheme 3.1a).\textsuperscript{112} Similarly, the olefin metathesis pathway includes the conversion of a metal-alkylidene-olefin complex into a metallacyclobutane intermediate.\textsuperscript{112} This is achieved by the breaking of a metal-carbon interaction (breaking of the M-C* interaction in Scheme 3.1b) and the formation of a new carbon-carbon bond (formation of the the C_a-C_b bond in scheme 3.1b).\textsuperscript{112} Reversely, the conversion of a metallacyclobutane to a metal-alkylidene-olefin complex entails the breaking of a C_a-C_b
interaction which leads to the generation of a new metal-carbon interaction (the M-C* interaction). This step—the conversion of the metallacyclobutane to metal-alkylidene-olefin complex—is a key step in the olefin metathesis mechanism and results from C_a-C_b bond activation generated by a (C_a-C_b)-to-metal agostic interaction (also noted (C-C)ÆM below). Similarly, C-C agostic interactions are believed to be critical to Ziegler-Natta catalysis.

Scheme 3.2 Mechanistic pathway for C-H activation by way of agostic (C-H)ÆM interactions.

Agostic interactions are those between coordinately-unsaturated transition metals with either C-H (Scheme 3.2) or C-C bonds. In such interactions, two electrons shared between the covalent C-H or C-C σ-interaction are drawn to the vacant d-orbital of a transition metal. The result of this behavior is essentially a two-electron-three-centered bond.
The electronic properties that describe and characterize agostic interactions are well represented in the fundamental example of an H₂ ligand approaching a metal center (Figure 3.1). The bonding orbitals of the H₂ ligands are σ in nature and are stabilizing due to the two spin-paired electrons that reside in this bonding orbital, resulting in a bond order of 1. If a metal possesses sufficient electron density, it may back-donate electrons into the σ* antibonding orbital of the H₂ molecule. Electrons that reside in the antibonding orbital decrease the molecular bonding order. This labilizes the H-H bond, making it a weaker interaction and thereby lengthening the H-H σ bond. As a result, the H₂ oxidatively adds to the metal center, generating a metal-hydride complex. This simple example of agostic interactions have been proven to be critical electronic principles in several organometallic transformations, including β-H elimination (Scheme 3.3), metal-catalyzed C-H activation, and oxidative-addition reactions.¹¹³
Having considered the nature of (C-H)→M and (H-H)→M interactions, it is necessary to address related (C-C)→M interactions. This discussion would elucidate the electronic behavior of selective C-C bond activations. A fundamental limitation of certain organometallic interactions arises from the inherently directional properties of carbon-centered bonds with p orbital character (Figure 3.2). Consequently, metal centers may be presented with challenges in accessing σ-electrons from C-C bonds. As such, it becomes imperative to organize cage-like arrays of carbon atoms about an electron-deficient metal center such that the metal is in the environment of the targeted C-C interactions instead of the more prevalent C-H bonds.

\[ \text{Scheme 3.3} \] β-H elimination mechanism, converting a metal-alkyl to the corresponding metal-hydride and coordinated olefin.

There exist mechanistic correlations amongst agostic interactions, namely alkyl species, and β-elimination pathways (Scheme 3.3). β-elimination is when a d⁰ metal
center lacks the electron density to \( \pi \)-back donate to the \( \sigma^* \) antibonding orbital of the C-H interaction. \( \pi \)-back donation would disrupt the C-H bond in the \( \beta \)-elimination pathway, a characteristic shared with oxidative addition. Electronically, agostic C-H bonds provide stabilization to unsaturated species. It has been known that \( \beta \)-elimination pathways require a vacant metal d orbital to proceed. Also, for a C-H bond to be rendered labile and destabilized a d orbital robust with electron density is necessary. These contrasting requirements are reconciled by the integration of a ligand that binds to the metal center possessing both \( \sigma \)-acidic and \( \pi \)-basic properties.

Furthermore, the electron transformations implied by C-H activation allow for spectroscopic analysis. The reduced C-H bond order in agostic complexes allows for characterization by NMR and IR spectroscopy. It has been proven that there is a high-field shift of the agostic proton in \( ^1 \)H NMR. The lowering of the C-H coupling constant via NMR and of the C-H stretching frequency via IR are direct results of the diminished C-H bond order of the agostic interaction.
Figure 3.3 MO interactions involved in (C-C)→M agostic interactions. $\sigma$ donation of electron density of a C-C bond to a $d_{z^2}$ orbital of a metal M (left) and $\pi$ back donation of electron density from M to vacant $\pi^*$ orbital of the C-C interaction (right).

The (C-C) agostic interactions arise from two fundamental electron-to-orbital transactions (Figure 3.3). $\sigma$ (C-C) electron donation to an empty metal orbital is usually the dominating interaction. There is also the strong possibility that $\pi$-back bonding occurs from a discrete metal $d$ orbital to a vacant $\sigma^*$ (C-C) antibonding orbital. Metallacyclobutane complexes active in olefin metathesis are thought to be characterized by two C-C bonds that are amenable to interaction with the metal center (Figure 3.4).
Validation for this concept was offered by various $^{13}$C NMR spectroscopic shifts documented for $C_\alpha$ or $C_\beta$ in bis(cyclopentadienyl) complexes of molybdenum and zirconium, possessing 16 and 18 electrons, respectively.$^{116,117}$ For complexes of Mo and W that are inactive in olefin metathesis, $C_\beta$ resonances were shifted 50 ppm downfield of the $C_\alpha$ resonances. Conversely, 60-80 ppm upfield shifts were noted for olefin metathesis active complexes of Ti, Zr, and Hf. Although chemical shifts cannot always be relied upon for evidence of agostic interactions, it has been accepted that the differences in $\delta$ ($C_\alpha$) - $\delta$ ($C_\beta$) shifts are a measure of the metal-to-$C_\beta$ separation in metallacyclobutanes.$^{118}$

**Figure 3.4** Carbon cage-like array about a transition metal center resulting in a metallacyclobutane exhibiting agostic behavior.
Electron-deficient metallacyclobutanes were studied to determine the degree of (C-C)→M interactions in complexes (2), (3), (4), (5) of Ti, Zr, Mo, and W (Figure 3.5). Data showed the existence of agostic (C-C)→M interactions in the complexes void of considerable electron density, such as those for Ti and Zr, but not for Mo. This can be justified by noting that bis(cyclopentadienyl) ligands are strongly electron donating, prohibiting the electron deficiency required of the metal center to draw (C-C)→M agostic interactions.

M-C_α-C_β angles for the Ti and Zr complexes were shown to be 10° more acute than those of the Mo and W compounds. The opposite holds for the respective C_α-M-C_α and the C_α-C_β-C_α angles. The Zr-C_α distance is similar to those of the Mo and the W complexes. However, the Zr-C_β is somewhat shorter than the Mo/W-C_β distances.
Furthermore, the $\text{C}_\alpha$-$\text{C}_\beta$ bonds are consistently broadened for (6-8) as opposed to those documented for (2) and (3).

It is probable that (C-C)$\rightarrow$M agostic complexes will trend towards small lengthening of C-C interactions, especially given the directional nature of C-C bonds. This would remain on par with the trend for H$_2$ and C-H analogues of complexes. $^{119}$ $^{13}$C NMR spectroscopy substantiates the existence of (C-C)$\rightarrow$M agostic interactions in electron-deficient species. Typical single carbon-carbon bonds exhibit $^{13}$C-$^{13}$C coupling constants of 30-39 Hz, whereas the values of $^{13}$C-$^{13}$C coupling constants (also noted $J$(C-C) below) for electron-deficient complexes are considerably lower, averaging between 21-24 Hz. Conversely, $\text{C}_\alpha$-$\text{C}_\beta$ coupling constants for 18-electron compounds of Mo and W reside in normal ranges between 31 and 32 Hz.

Studies have proven that these (C-C)$\rightarrow$M agostic interactions would be expected in electron-deficient metallacyclobutanes. For both the Schrock molybdenum- and the Grubbs ruthenium-centered systems, metallacyclobutane intermediates appear which are readily viewed as being electron-deficient. The pre-catalysts of ruthenium systems are generally 16-electron complexes. Sterically bulky phosphine ligands, such as triphenyl phosphines, lead to the conversion of 14-electron complexes. A low-temperature spectroscopic examination of 14-electron ruthenacyclobutanes showed the presence of a low $J$(C-C) value of 15.0 Hz. The same study also demonstrated large $J$(C-H) values, 155 and 165 Hz. Both these findings are to be expected for the anticipated (C-C)$\rightarrow$Ru agostic interactions.
On the other hand, the molybdenum complexes lack ligands which dissociate, making possible for 18-electron configurations for intermediates without the presence of agostic interactions. This is due to the electronic properties of their distinct alkoxide ligands, which behave as $\pi$-donors. These catalysts are unique in the electron-withdrawing properties of functional groups on the alkoxide ligands. This quality serves to diminish the electron-donating ability of the ligand, which energetically promotes the $(C-C)\rightarrow Mo$ agostic interactions for the complex.

Structural studies for metallacyclobutanes have brought forth vital information to the issues surrounding electron-deficiency and their properties. Ruthenacyclobutane structures are predicated upon 18-electron complexes. As would be anticipated, there is no validation for Ru-$C_\beta$ interactions. This is validated by Ru-$C_\beta$ bond lengths being between 0.5-0.6 Å longer than documented Ru-$C_\alpha$ bond lengths. There is a similar observation for many molybdenum Schrock complexes, in which Mo-$C_\beta$ bond lengths generally exceed the Mo-$C_\alpha$ bond lengths by about 0.6 Å. Accordingly, the presence of $(C-C)\rightarrow M$ agostic interactions in metathesis reactions justifies the necessity of the discrete reactivity of Schrock catalysts on the electronic properties of their associated alkoxide ligands.
Scheme 3.4 Synthesis of 2,2-dimethyl metallacyclobutanes from Mo/W-bis(cyclopentadienyl) precursors.

There exist different methods to prepare metallacyclobutane complexes. Metallacyclobutanes of Mo and W have been accessed by nucleophilic attack on $\eta^3$-allyl complexes. Metallacyclobutanes of W have also been generated by [2 + 2] addition of olefins to carbene-tungsten complexes. Additionally, the treatment of metal-dihalide complexes with 1,3-divalent organomagnesium reagents (di-Grignard reagents) can in some cases afford the corresponding metallacyclobutane species. Thus, 1,3-bis(bromomagnesio)-2,2-dimethylpropane (7) was treated with Cp$_2$MoCl$_2$ (8a) and Cp$_2$WCl$_2$ (9a) to generate the metallacyclobutane of molybdenum (8b) and tungsten (9b), respectively (Scheme 3.4).

Molybdenacyclobutanes such as 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (8b) have shown resistance to dissociating into an alkene and a metal-carbene complex, which are requisite of a catalytic metathesis pathway. The reason for this inactivity may be attributed to the strongly electron-donating properties of the dicyclopentadienyl ligands of the complex. Because these ligands are inclined to donate electrons to the metal, the molybdenum center becomes saturated with electrons. It is by this means that the molybdenum center lacks the requisite electron-deficiency that would
promote the crucial (C-C)\(\rightarrow\)Mo agostic interactions within the metallacyclobutane structure. Should these electronic properties be favored, however, then the necessary agostic interactions can be propagated such that a metathesis pathway can operate.

As a summary of what has been presented so far in this introduction, let us reiterate that Ziegler-Natta olefin polymerization and olefin metathesis are related processes that involve similar C-C bond-forming and C-C bond-breaking steps. The activation of the C-C bonds is thought to stem from (C-C)-to-metal agostic interactions, whose presence in Ziegler-Natta polymerization and olefin metathesis intermediates has been strongly suggested by experimental results (NMR, IR spectroscopy and/or X-ray crystallographic data). Therefore, our group has targeted metal-ligand scaffolds that have been shown to catalyze Ziegler-Natta polymerizations as potential systems for the development of new olefin metathesis catalysts.

![Image of 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine]

Yasuda et al. has previously prepared molybdenum(III) complexes supported by ligand (10) which were shown to be especially active in the ROMP of norbornene.
substrate when in the presence of a cocatalyst system. The study by Yasuda et al. showed that this catalyst system was active in Ziegler-Natta polymerization, as well as the ROMP of linear olefins. These catalytic reactions are believed to be initiated by a molybdenum-carbene species. However, identification of the proposed Mo=CHR species by NMR spectroscopy has been elusive due to the paramagnetic electronic nature of the resulting molybdenum species.

Therefore, efforts have been undertaken to prepare alkylidene complexes of molybdenum(II) supported by rigid ligands of the type 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine (10). This synthesis should give way to markedly robust complexes. It is expected that the bis(imino)pyridine complexes of molybdenum(II) will be less sensitive than their molybdenum(VI) Schrock catalyst counterparts. This is because the molybdenum(II) compounds being targeted are characterized by a low-oxidation state metal center, and they also are void of the Mo-alkoxide interactions of the Schrock complexes that are prone to hydrolysis. The bis(imino)pyridine ligand systems can be easily synthesized on a multi-gram scale. Furthermore, they are atmosphere-stable and are very tunable in terms of sterics and electronics.

Additionally, iron and cobalt dichloride complexes supported by bis(imino)pyridine ligands have also proved active in Ziegler-Natta polymerization upon activation with methylalumoxane (MAO). Although comprehensive studies have focused on the nature of these complexes, an understanding of the precise mechanism of the activation sequence as well as the exact nature of the propagating species remains elusive. When bis(imino)pyridine cobalt (I) methyl and dichloride complexes are treated
with either MAO or a borate activator they show activity for ethylene polymerization. This suggests that “preformed” cobalt alkyl complexes are not necessarily required for catalysis.

The structure and oxidation state of iron propagating species are less understood. Several experimental and computational investigations have suggested that cationic iron(II) alkyls and hydrides exist when associated precursors are activated with MAO. Work by Chirik et al. has shown that ferrous alkyl cations are catalytically active. In this study, a five-coordinate ferrous dichloride precursor, \(((2,6-\text{CHMe}_2)_2\text{C}_6\text{H}_3\text{N} = \text{CMe})_2\text{C}_5\text{H}_3\text{N})\text{FeCl}_2\) (11), was treated with a large alkyllithium reagent \(\text{LiCH}_2\text{SiMe}_3\) to produce the ferrous dialkyl complex (12). (12) was treated with the neutral borane \(\text{B(C}_6\text{F}_5)_3\) in an effort to promote alkyl abstraction, which resulted in a silicon methide abstraction that was subsequently followed by a rearrangement. A base-free cationic alkyl complex \([i\text{PrPDI})\text{Fe(CH}_2\text{SiMe}_2\text{CH}_2\text{SiMe}_3)][\text{MeB(C}_6\text{F}_5)_3]\) (13) was recovered. Silicon methide abstraction is favored over iron alkyl removal perhaps due to the steric protection afforded by the bulky aryl substituent of the ligand. They serve to prohibit the approach of a Lewis acid to the metal center.
2,6-Bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine

Ar = 2,6-iPr₂-C₆H₃
The base-free (13) was studied for ethylene polymerization properties, and it was found to exhibit robust catalysis. Polyethylene from single-component polymerization was found to be linear and contained end-groups olefinic in nature, which would be expected for chain termination sequences via β-hydrogen elimination pathways. Indeed, this study served as a critical bridge between the Ziegler-Natta catalysis observed here and potential catalytic ramifications for olefin metathesis reactions. This is keeping in mind that the bond-breaking and bond-forming pathways of Ziegler-Natta polymerization of olefins resemble olefin metathesis pathways.

The 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine ligand is a redox-active ligand system, a property that can be directly attributed to the aromatic ring system of the ligand. Also, the ligand exerts excellent electron-withdrawing capacity upon the metal it is chelated to, which is due to the potential for substantial π-back donation of the vacant anti-bonding orbitals of the ligand. This electron-withdrawing nature confers an electron-deficiency upon the molybdenum center. It is this behavior that creates the
qualities necessary for (C-C)→Mo agostic interactions that will thereby propagate olefin metathesis reactions.

\[
\text{N} \quad \text{N} \\
\text{i-Pr} \quad \text{i-Pr} \\
\text{MoCl}_3
\]

\[
\text{2,6-bis[1-(2,6-diisoproprylphenylimino)-ethyl]pyridine-MoCl}_3
\]

This metal-ligand system can be engineered to generate a metallacyclobutane structure through logical synthetic steps that will promote the desired agostic interactions. The bis(imino)pyridine-molybdenum complex will exist as a tri-chloride structure, 2,6-bis[1-(2,6-diisoproprylphenylimino)-ethyl]pyridine-MoCl$_3$ (14). The complexes can be reduced by one electron to the dichloride analogue (15) by treatment with standard reducing agents such as Na/Hg, Zn, and Mg. It is believed that the complex will retain the ferrous oxidation state due to the inherent redox capacity of the ligand system. Next, the dichloride complex can be converted to a bis(imino)-pyridine Mo(II) olefin metathesis intermediate by treatment with di-Grignard reagents to afford the corresponding metallacyclobutane structure (16).
The production of the di-Grignard reagents featured in this synthetic roadmap has proven to be difficult. Initially, preparations were limited to the availability of dihalide precursors. Also, there were inherent limitations on characterizing product profiles of the observed di-Grignard syntheses. An $^1$H NMR signal at $\delta = 0$ to $\delta = -1$ ppm in a spectrum of the reaction mixture in the synthesis of a 1,3-bis(bromomagnesio)propane soon gave some hope. The synthesis of the di-Grignard at a high yield, say 30%, requires that the
reaction be exerted slowly in Et₂O with an excess of purified magnesium. The dibromopropane must be added to stirring magnesium over a period of up to two days under an inert atmosphere. Still, cyclopropane and other hydrocarbon by-products result, which imply that the Grignard reaction proceeds via a complex free-radical pathway.

\[
\text{BrCH}_2\text{CMe}_2\text{CH}_2\text{Br} + \text{Mg} \rightarrow \text{BrMgCH}_2\text{CMe}_2\text{CH}_2\text{MgBr}
\]

\textbf{Scheme 3.5} Synthesis of 1,3-bis(bromomagnesio)-2,2-dimethylpropane.

Unfortunately, the numbers of di-Grignard compounds that can be accessed directly has been proven to be minimal. The generation of 1,3-bis(bromomagnesio)-2,2-dimethylpropane 17b is synthetically useful, despite its reported meager 10-15% yield (Scheme 3.5). This synthetic product is mostly void of organometallic by-products and can be applied directly to the synthesis of metallacycles.

As previously elucidated, metallacyclobutanes hold great synthetic potential due to their structural and bonding properties, as well as their theorized role as catalytic intermediates in critical processes such as olefin metathesis. Both the main group and transition metal element dichlorides 18a should formally proceed to the synthesis of metallacyclobutanes 18b (Scheme 3.6). Unfortunately, this synthetic procedure is not widely applicable due to the inherent instability of 18b. Despite this, the synthetic route implied in Scheme 3.6 is still useful as one can conclude that 18b is accessed and the secondary products detected do in fact come from 18b.
Scheme 3.6 General method for synthesis of a metallacyclobutane from a dichloride transition metal precursor.

Scheme 3.7 β-elimination pathways for a four-membered metallacycle ring.

It is possible, however, that the yields of \(18b\) are low although it is a structurally stable complex. This is justified by a strong activation of the β-hydrogens in intermediate \(20\) by transition metals (Scheme 3.7). Although \(18b\) is stable, the orientation required for β-elimination is not feasible when contained by the rigid four-membered ring. \(20\) can engage in rotation to assume conformations in which elimination of \(22\) becomes favored. With \(17b\) these pitfalls are averted, leading to better results when using this reagent in synthesis.

Finally, consideration should be given to the nature of the molybdenum starting material for the preparation of the metal complexes outlined here. Molybdenum possesses a vibrant chemical profile when found in low, intermediate, and high oxidation states,
respectively. The fields of organometallic catalysis and solid-state materials chemistry extensively research this interesting metal. Unfortunately, progress with molybdenum metal is limited by very finite commercially available molybdenum starting materials, the most common and convenient of which are Mo(CO)\(_6\) and MoCl\(_5\). [MoCl\(_3\)(THF)\(_3\)] is a versatile intermediate in diverse inorganic syntheses. Conventional preparation of this complex is by way of a reductive pathway from MoCl\(_5\) starting material. MoCl\(_5\) is a significantly strong Lewis acid and is a forceful oxidant. Straight-forward THF-induced reduction is convoluted by acid-catalyzed ring-opening polymerization of the THF solvent. This can be avoided by implementing different solvents in ligand exchange, such as acetonitrile. Beginning with the reaction of MoCl\(_5\) with acetonitrile, [MoCl\(_4\)(CH\(_3\)CN)\(_2\)] is afforded. The nitrile can then be exchanged with THF to access the [MoCl\(_4\)(THF)\(_2\)] adduct. This can then be reduced to the [MoCl\(_3\)(THF)\(_3\)] adduct by action of coarse tin. From here, the chelation of 2,6-bis[1-(arylimino)-ethyl]pyridine ligands becomes feasible, after which reduction will provide for the dichloride analogue. This metallic complex is then ripe for reaction with a 1,3-divalent organomagnesium compound. Should the sterics of the complex allow it, a metallacyclobutane complex is hoped to be generated, which could then be tested in a range of metathesis processes.

The Schrod group has undertaken an important study in the preparation of metallacyclobutanes of molybdenum that may be catalytically active in olefin metathesis. The preparation of di-Grignard reagents has been attempted. Progress was made with the preparation of a gem-dimethyl di-Grignard reagent due to the exclusion of unwanted side reactions. A metallacyclobutane of a bis-cyclopentadienyl molybdenum complex was prepared, as previously published. Molybdenum pentachloride starting material was used
in a series of reductive reactions to afford a tris-THF tri-chloride adduct. This adduct was then treated with a bis-imino pyridine ligand that was previously shown to be active in ROMP of olefins.

3.2 Results and Discussion

\[
\begin{align*}
\text{Br} & \quad \text{Br} & \quad \text{Mg} & \quad \text{MgBr} & \quad \text{THF} & \quad \text{Mg} & \quad \text{MgBr}_2 \\
23 & \quad 24 & \quad 25
\end{align*}
\]

**Scheme 3.8** Synthesis of 1,3-bis(bromomagnesio) propane (24) and equilibrium with 1,2-bis(bromomagnesio)cyclopropane (25).

The synthesis of 1,3-bis(bromomagnesio)propane (24) was attempted from the dropwise addition of a solution of 1,3-dibromopropane (23) in dry Et\(_2\)O to a vigorously stirring suspension of fine magnesium powder in dry Et\(_2\)O over the course of 24 hours (Scheme 3.8). The concentration of di-Grignard (24) produced was determined by titration with a mixture of salicylaldehyde phenylhydrazone in dry THF. It was found that the purported concentration of 1,3-bis(bromomagnesio)propane recovered from the reaction filtrate was 0.0101 M amounting to a 9.3\% yield. Efforts were made to characterize the reagent by \(^1\)H NMR in HMPT-\(d_{18}\), yet the product was only slightly soluble, at best, in the deuterated solvent. Despite this, a \(^1\)H NMR spectrum was collected, yet the chemical shifts failed to correlate with those previously reported for 24.\(^{124}\) The magnesium-carbon interaction of a Grignard reagent behaves such that the
carbon exists in a very electronegative state, essentially as a carbanion, and donates its electrons to the electropositive magnesium in a dative fashion. As such, the protons on the carbanion are heavily shielded, normally resulting in upfield, often negative values for chemical shifts in $^1$H NMR spectra. However, these negative chemical shifts failed to appear for the $^1$H NMR characterization of the 1,3-bis(bromomagnesio)propane reagent (24). It was possible that if 1,3-bis(bromomagnesio)propane was accessed, it was done so with the inclusion of considerable impurities. As such, a method of purifying the di-Grignard reagent was necessary.

The purification of the 1,3-bis(bromomagnesio)propane (24) was undertaken by drying the product in vacuo to afford a residue of product. It was previously reported that 1,3-bis(bromomagnesio)propane existed in equilibrium with its magnesacyclobutane adduct 1,2-bis(bromomagnesio)cyclopropane, and was able to shift towards the magnesacyclobutane by treatment with THF (Scheme 3.8). Although simple in principle, this process is precarious, at best, due to the solubility of the di-Grignard and its synthetic impurities in a large amount of THF. As such, the residue of 1,3-bis(bromomagnesio)propane (24) was carefully treated with small amounts of dry THF to generate a white-colored paste. This was then dried in vacuo, and the purported magnesacyclobutane (25) was treated with HMPT-$d_{18}$ for characterization by $^1$H NMR, yet the magnesacyclobutane proved to be sparingly soluble in the deuterated solvent.

Similar to the 1,3-bis(bromomagnesio)propane parent structure, the magnesacyclobutane (25) can be thought of as a di-carbanion donating its 2 electron pairs in a dative fashion to the electropositive magnesium center. As such, the protons on $C_a$ are heavily shielded, which would result in upfield, negative values for chemical shifts in $^1$H NMR spectra.
However, these negative chemical shifts failed to appear for the $^1$H NMR characterization of the magnesacyclobutane reagent. It was possible that if the magnesacyclobutane was soluble enough in the THF treatment, then the impurities derived from the initial di-Grignard synthesis may have been carried over when shifting the di-Grignard equilibrium.

The equilibrium of the magnesacyclobutane (25) can also be shifted back to the 1,3-bis(bromomagnesio)propane parent species (24) by treatment with Et$_2$O and MgBr$_2$ (Scheme 3.8). It is thought that when Et$_2$O and MgBr$_2$ are added in 1:1 ratios, the magnesacyclobutane would dissolve, affording pure 1,3-bis(bromomagnesio)propane.$^{124}$

With this in mind, 1,2-bis(bromomagnesio)cyclopropane (25) residue was treated with dry Et$_2$O and MgBr$_2$. After reaction, the suspension was dried in vacuo, producing a white solid. The product was treated with Et$_2$O-$d_{10}$ for characterization by $^1$H and $^{13}$C $^1$H NMR, yet the solid proved to be insoluble in the deuterated solvent, thereby inhibiting characterization. It is possible that this behavior was due to the impurities that were retained from the intitial synthesis of 1,3-bis(bromomagnesio)propane (24), the purification steps to access 1,2-bis(bromomagnesio)cyclopropane (25), and the reversion of the magnesacyclobutane to the purified di-Grignard by shifting the delicate equilibrium.
Scheme 3.9 Derivitization of (24) with benzophenone to afford 1,1,5,5-tetraphenylpentane-1,5-diol (26).

As another way to substantiate the di-Grignard synthesis, the putative 1,3-bis(bromomagnesio)propane was derivatized by reaction with benzophenone to access 1,1,5,5-tetraphenylpentane-1,5-diol (26) (Scheme 3.9). As such, a purified solution of 1,3-bis(bromomagnesio)propane (26) in dry Et_2O was combined with benzophenone and resulting product was worked up with 10% NH_4Cl and an Et_2O organic extraction. The resulting filtrate was dried in vacuo and the oil product was dissolved in CDCl_3 for characterization by ^1H NMR. Unfortunately, the spectrum did not correlate with that expected for a diol. Foremost, the broad peak expected for the alcohol protons are absent from the spectrum. Additionally, the protons expected for the C-2 position of the propane backbone of (24) are absent as well. Given the meager results of the attempted synthesis, purification, and characterization of (24), and derivatization via (26) and its characterization, it has been concluded that the synthesis of 1,3-bis(bromomagnesio)propane (24) was not successful.

Scheme 3.10 Reaction profile and by-products of the synthesis of (23).
Despite these setbacks, the synthesis of 1,3-bis(bromomagnesio)-2,2-dimethylpropane was undertaken under the presumption that this synthesis afforded inherent benefits over 1,3-bis(bromomagnesio)propane (30) synthesis. Fundamentally, 1,3-di-Grignard synthesis is arduous when hydrogen atoms occupy the C-2 position. Allylmagnesium bromide (28) is a secondary product formed from the preparation of 1,3-bis(bromomagnesio)propane (Scheme 3.10).\textsuperscript{125} The C-2 hydrogens are activated by virtue of hyperconjugation with the dual electron-abundant carbon-magnesium interactions, resulting in the liberation of magnesium bromide hydride. In the synthesis studied here, magnesium bromide behaves as a Lewis acid catalyst, such that the decomposition rate of the 1,3-bis(bromomagnesio)propane is contingent upon MgBr\textsubscript{2} concentration. Accordingly, the double hydride activation incurred can be a significant hurdle in certain synthetic applications, as has been shown here. The 2,2-dimethyl analogue, however, does not liberate a hydride. Thus, it is considerably stable and avoids side reactions during chemical reactions.

![Scheme 3.11](image)

**Scheme 3.11** Synthesis of 2,2-dimethyl-1,3-bis(bromomagnesio)propane (30).
Thus, 1,3-bis(bromomagnesio)-2,2-dimethylpropane (30) was synthesized by the dropwise addition of a mixture of 1,3-dibromo-2,2-dimethylpropane (29) in dry Et₂O to a vigorously stirring suspension of fine magnesium powder in dry Et₂O (Scheme 3.11). The concentration of di-Grignard (30) produced was determined by titration with a mixture of salicylaldehyde phenylhydrazone in dry THF. It was found that the concentration of 2,2-dimethyl-1,3-bis(bromomagnesio)-propane (30) recovered from the reaction filtrate was 0.012 M amounting to a 7.0% yield. ¹H NMR characterization in THF-d₈ did reveal a negative chemical shift at -0.082 ppm (s), presumably due to the presence of a polarized magnesium-carbon interaction (a) (Figure 3.6). This peak was too small to successfully integrate in order to determine the number of hydrogens which that resonance represents. The methyl protons (b) exhibited a tall peak at 1.10 ppm (s). It would seem from this information that synthesis of 1,3-bis(bromomagnesio)-2,2-dimethylpropane (30) was successful.
Figure 3.6 $^1$H NMR spectrum of (30). Important diagnostic chemical shifts have been indicated by $a$ and $b$, respectively.

![Figure 3.6](image)

**Scheme 3.12** Synthesis of 3,3-dimethyl-1,1,5,5-tetraphenylpentane-1,5-diol (31).

As with the parent analog, (30) was derivatized by reaction with benzophenone to afford a 3° alcohol, 3,3-dimethyl-1,1,5,5-tetraphenylpentane-1,5-diol (31). A solution of 1,3-bis(bromomagnesio)-2,2-dimethylpropane in dry Et$_2$O was combined with benzophenone and resulting product was worked up with 5% NH$_4$Cl and an Et$_2$O organic extraction.
Figure 3.7 $^1$H NMR spectrum of (31). Important diagnostic chemical shifts have been indicated by $a$, $b$, and $c$, respectively.

The resulting filtrate was dried in vacuo and the white solid product was dissolved in CDCl$_3$ for characterization by $^1$H NMR (Figure 3.7). A series of multiplets were revealed from 7.15-7.79 ppm, a clear indication of aromaticity afforded by the phenyl substituents on the product. The spectrum showed a slightly broad peak ($c$) at 4.26 ppm (s, 2H), corresponding to the OH protons of the diol. The chemical shift ($b$) at 2.7 ppm (s, 4H) refers to the -CH$_2$- protons of the propane backbone. The 2,2-dimethyl protons ($a$) showed up at 0.43 ppm (s, 6H). Accordingly, the $^1$H NMR confirmed the synthesis of 3,3-dimethyl-1,1,5,5-tetraphenylpentane-1,5-diol.
Scheme 3.13 Synthesis of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (32).

Having successfully prepared a 2,2-dimethyl di-Grignard reagent, the synthesis of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (32) could be undertaken following previously published procedure (Scheme 3.13). A previously prepared solution of 2,2-dimethyl-1,3-bis(bromomagnesio)propane (30) in dry Et₂O was added to biscyclopentadienyl molbdenumdichloride. After reaction, the mixture was dried in vacuo, and the resulting film was treated with dry THF and 1,4-dioxane. The dioxane possesses excellent dissolving properties that are comparative to Et₂O. The oxygens of the 1,4-dioxane are Lewis basic in nature, allowing the molecule to serve as a metal chelator. Specifically, it can interact with Grignard reagents to crash out magnesium dihalides, and in the case of this particular synthesis magnesium dichloride. Furthermore, 1,4-dioxane serves as a magnesium scavenger to remove residual magnesium in the reaction mixture that may have been carried over from the synthesis of the Grignard reagent. Accordingly, the reaction mixture was filtered and the filtrate was dried in vacuo, affording an amber-orange colored solid.

The product (32) was dissolved in C₆D₆ for characterization by ¹H NMR spectroscopy (Figure 3.8). A chemical shift at 4.4 ppm (s, 10H) corresponds to the protons on the cyclopentadienyl ligands (c). The methyl protons of the
metallacyclobutane \(b\) appeared at 1.173 ppm (s, 6H). Of particular interest is the 0.63 ppm (s, 4H) shift, which corresponds to the \(-\text{CH}_2-\) protons of the metallacyclobutane ring \((a)\), which experience nuclear shielding from the molybdenum metal center they interact with. The \(^1\text{H}\) NMR spectrum showed the presence of organic solvents attributed to the synthesis of \((10)\). The singlet at 3.35 ppm corresponds to the 1,4-dioxane used for purification. The singlet peak at \(\sim 1.12\) ppm refers to the ether used as the initial synthesis medium. Lastly, the singlet peak at \(\sim 1.38\) ppm shows the presence of THF solvent.

![Figure 3.8](image.png) \(^1\text{H}\) NMR spectrum of \((32)\) prior to sublimation. Important chemical shifts have been indicated by \(a\), \(b\), and \(c\), respectively.
Figure 3.9 $^{13}$C $\{^1\text{H}\}$ spectrum of (32) prior to sublimation. Important diagnostic chemical shifts have been indicated by $a$, $b$, $c$, and $d$, respectively.

(32) was analyzed by $^{13}$C $\{^1\text{H}\}$ NMR spectroscopy, which showed a peak at 86.60 ppm, corresponding to the cyclopentadienyl carbons ($d$) (Figure 3.9). The carbons at position ($c$) of the metallacyclobutane ring should have appeared ~49.9 ppm, however the signal was too low to be accurately measured. The methyl carbons ($b$) of the metallacyclobutane ring resulted in a chemical shift at 36.79 ppm. The most diagnostic peak is attributed to the $-\text{CH}_2$- carbons ($a$) of the metallacyclobutane ring at -6.13 ppm. This distinct negative chemical shift is due to the shielding of these carbon nuclei due to the electron-withdrawing properties of the molybdenum center. As such, both the $^1\text{H}$ and the $^{13}$C $\{^1\text{H}\}$ NMR spectra confirm the synthesis of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (32).
Figure 3.10 $^1$H NMR spectrum of (32) after sublimation. Important chemical shifts have been indicated by $a$, $b$, and $c$, respectively.

Next, the purification of the 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (32) product was carried out by sublimation at temperatures up to 120 °C, which afforded orange crystalline product. Sublimation was performed with the hopes of removing as much synthetic impurities as possible. The product was dissolved in C$_6$D$_6$ and was analyzed by $^1$H NMR spectroscopy (Figure 3.10). A chemical shift at 4.32 ppm (s, 10H) corresponds to the protons on the cyclopentadienyl ligands ($c$). The methyl protons of the metallacyclobutane ($b$) appeared at 1.180 ppm (s, 6H). The 0.637 ppm (s, 4H) chemical shift corresponds to the -CH$_2$- protons of the metallacyclobutane ring ($a$), which experience nuclear shielding from the molybdenum metal center they interact with. The $^1$H NMR spectrum of purified 32 showed a strong correlation to that of
the crude product. Generally, purified product produced a $^1$H NMR spectrum that showed fewer organic impurities and a much cleaner baseline than did the crude product.

**Figure 3.11** $^{13}$C {$^1$H} spectrum of (32) after sublimation. Important diagnostic chemical shifts have been indicated by $a$, $b$, $c$, and $d$, respectively.

Purified 32 was analyzed by $^{13}$C {$^1$H} NMR spectroscopy (Figure 3.11). The spectrum showed a peak at 87.21 ppm, corresponding to the cyclopentadienyl carbons ($d$) (Figure 3.11). The carbons at position ($c$) of the metallacyclobutane ring appeared 50.26 ppm. The methyl carbons ($b$) of the metallacyclobutane ring resulted in a chemical shift at 37.41 ppm. The most diagnostic peak is attributed to the –CH$_2$- carbons ($a$) of the metallacyclobutane ring at -5.495 ppm. Thus, both the $^1$H and the $^{13}$C {$^1$H} NMR spectra confirm the synthesis and the purification of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (32).

It had long been established that molybdenacyclobutanes do not conveniently evolve into a metal-carbene complex and a corresponding alkene, as per olefin metathesis
reaction pathways. Of course, then, it comes as no surprise that 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (32) would prove to be markedly ineffective in the RCM of a conventional substrate such as diethyl diallylmalonate. Despite this, the RCM of DEDAM was undertaken by both the crude and sublimated solutions of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane in C₆D₆. The ¹H NMR spectra of these reactions both showed the lack of any conversion of the substrate to the RCM product. This behavior is alluded to by studying the electronic properties of the molybdenum complex and by recalling the properties of conventional metathesis-active metal complexes. Traditional metathesis-promoting complexes are characterized by markedly electron-deficient metal centers, which are facilitated by the electron-withdrawing properties of associated ligands by way of the excellent π-back donation they offer. This electron deficiency creates an environment in which the metal center will be more “receptive” to the electronic movement provided by manipulations of olefins during reactions due to the agostic interactions promoted that would collapse the metallacyclobutane intermediacy. As such, the cyclopentadienyl ligands of the 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane structure are considerable electron-donators, which serve to saturate the molybdenum center with electron density. This acts to prohibit the necessary agnostic interactions for collapse of the metallacyclobutane structure to a metal-carbene and a liberated olefin.

In these series of investigations, it was found that the synthesis of 1,3-bis(bromomagnesio)propane proved to be particularly difficult both procedurally and diagnostically, whereas the synthesis of 1,3-bis(bromomagnesio)-2,2-dimethylpropane
was more facile due to the inherent stability afforded to the structure. Despite this, the synthesis of 2,2-dimethyl-1,3-bis(bromomagnesio)propane (30) was accomplished in meager yields. One potential reason for these synthetic limitations may be that the magnesium powder used in the reactions was implemented as purchased. Published preparations of the digrignard reagents called for magnesium powder that was doubly or even triply sublimed. This purification step may have been a necessary action to prevent the inclusion of residual oxygen or moisture to the Grignard reaction mixture. Magnesium, like other alkaline earth metals, is known to react with oxygen to form a magnesium oxide ion pair and to react with water to generate a magnesium hydroxide ion pair. These species would clearly be prohibitive to succinct formation of the Grignard reagents. An additional synthetic consideration may have been the moisture retained by the Et₂O and THF solvents, despite the great effort taken in drying the organic solvents by passage through drying columns and storage with activated molecular sieves and alumina. This would have without a doubt hindered the requisite moisture- and oxygen-free conditions necessary for synthesis.

![Chemical structure](image)

**Scheme 3.14** Synthesis of 2,6-bis[2,6-diisopropylphenylimino)-ethyl]pyridine (33).
The process of accessing a molybdenum system supported by a rigid bis-imino pyridine ligand began by means of the synthesis of the 2,6-bis(2,6-diisopropylphenylimino)-ethyl]pyridine (33) ligand on the benchtop, as adapted by a previously published method (Scheme 3.14). 2,6-Diacetylpyridine, 2,6-diisopropylaniline, and p-toluene sulfonic acid monohydrate were combined with a stock solution of toluene. The mixture was allowed to reflux for 24 hours at 135 °C. After cooling for several hours, the product was isolated by vacuum filtration and was washed with glacial ethyl alcohol. The solid was dried in vacuo and was isolated as fine yellow crystals in 86.0% yield. The solid was dissolved in CDCl₃ for characterization by ¹H NMR spectroscopy (Figure 3.12). The spectrum showed a doublet at 8.49 ppm (2H) (a),
corresponding to equivalent aromatic protons in the meta position to the nitrogen of the pyridine backbone. A triplet at 7.93 ppm (1H) $(b)$ corresponds to the aromatic protons in the para position to the nitrogen of the pyridine backbone. A multiplet at 7.17 ppm (6H) $(c)$ confirms the aromatic substituents on the imino backbone of the ligand. A septet at 2.80 ppm (4H) $(d)$ shows the methine proton of the isopropyl groups on the phenyl rings. A singlet at 2.27 ppm (6H) $(e)$ corresponds to the methyl protons of the di-imine backbone of the ligand. Lastly, the doublet at 1.19 ppm (24H) $(f)$ corresponds to the methyl groups on the isopropoxy substituents of the phenyl rings. As such, the $^1$H NMR spectrum confirms the clean synthesis of 2,6-bis(2,6-diisopropylphenylimino)-ethyl]pyridine (33).

$$\text{MoCl}_5 + \text{(excess) CH}_3\text{C}≡\text{N} \rightarrow \text{[MoCl}_4(\text{CH}_3\text{CN})_2]$$

Scheme 3.15 Synthesis of bis(acetonitrile)tetrachloromolybdenum (34).

The next phase of this project was to sequentially reduce a molybdenum starting material into a series of solvent-adducts, making the molybdenum amenable to chelation by (33). In a dry box under an atmosphere of N$_2$, the MoCl$_5$ powder was combined with anhydrous acetonitrile and was allowed to vigorously stir for 30 minutes (Scheme 3.15). Mixing was then terminated, and the flask was allowed to rest undisturbed overnight. The product was isolated by vacuum filtration and the solid was washed with anhydrous acetonitrile. The product was allowed to dry under an atmosphere of N$_2$ overnight. [MoCl$_4$(CH$_3$CN)$_2$] (34) was isolated as a fine dark orange-brown powder in 87% yield.
Due to the sensitivity of this adduct to moisture, as well as its tendency to rapidly decompose over time, (34) was immediately used in the next step of the reductive synthesis of this project (Scheme 3.16). (34) was slowly added to vigorously stirring anhydrous THF. The reaction mixture was allowed to stir for 2 hours. The product was isolated by vacuum filtration and the solid was washed with anhydrous THF. The product was dried in vacuo. [MoCl₄(THF)₂] (35) was isolated as a fine orange-brown powder in 90.1% yield. Spectroscopic characterization of this adduct was prohibitive, so the reductive synthesis was continued, partially as a means to characterize the progress made thus far by reactivity, so to speak.

\[
\text{[MoCl}_4\text{(THF)}_2\text{]} + \text{(excess THF)} \xrightarrow{2 \text{ hrs}} \text{[MoCl}_4\text{(THF)}_2\text{] + 2CH}_3\text{CN}}
\]

**Scheme 3.16** Synthesis of trichlorotris(tetrahydrofuran)molybdenum (35).

\[
\text{[MoCl}_4\text{(CH}_3\text{CN)}_2\text{]} \xrightarrow{\text{Sn}} \text{[MoCl}_3\text{(THF)}_3\text{]}
\]

**Scheme 3.17** Synthesis of trichlorotris(tetrahydrofuran)molybdenum (36).
Figure 3.13 $^1$H NMR (CD$_2$Cl$_2$) of (36) and (37).

(35) was combined with vigorously stirring anhydrous THF (Scheme 3.17). Fine tin powder was slowly added to the suspension and was allowed to mix for 20 minutes. The reaction mixture was vacuum filtered, affording a magenta-red colored filtrate and grey tin powder that was retained by the sinter. Remaining product was freed from the sinter by adding several pipettes of anhydrous DCM. The filtrate was concentrated to about 25% of the volume in vacuo. [MoCl$_3$(THF)$_3$] (36) was isolated as a fine bright-orange colored powder in 17.3% yield. The powder was characterized by $^1$H NMR (CD$_2$Cl$_2$) spectroscopy (Figure 3.13). The spectrum showed the presence of mostly a mononuclear molybdenum complex (36), with the presence of some dinuclear molybdenum (37) as well, both of which are paramagnetic in nature and result in broad chemical shifts. The chemical shifts correspond to previously published values. The spectrum showed a broad shift at 65.04 ppm ($a$), which corresponds to the $\alpha$-proton of the equivalent THF ligands.
on the mononuclear complex. A broad chemical shift at 54.92 ppm ($b$) corresponds to the $\alpha$-proton of the distinct THF ligand on the mononuclear complex. A broad chemical shift at 25.10 ppm ($c$) corresponds to the $\alpha$-proton of the equivalent THF ligands on the dinuclear complex. Lastly, a broad chemical shift at 18.01 ppm ($d$) corresponds to the $\alpha$-proton of the distinct THF ligand on the dinuclear complex. The chemical shifts for the $\beta$-protons on the THF ligands of both the mono- and di-nuclear complexes were upfield and grouped with a series of peaks that made distinction difficult. The $^1$H NMR confirmed the synthesis of (36). Due to the sensitivity of (36) to moisture and light, as well as its inclination for rapid decay over short periods of time, it was immediately used in the reaction to attempt chelation to ligand (33) (Scheme 3.18).

**Scheme 3.18** Synthesis of 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine-MoCl$_3$ (38).

According to previously published procedure, (33) was combined with (36) in anhydrous THF. The suspension was set to reflux at 70 °C for 12 hours, which afforded a blue colored reaction mixture. Solvent was dried *in vacuo*, leaving a purple-blue colored solid film. The product was analyzed by $^1$H NMR spectroscopy in both CDCl$_3$ and C$_6$D$_6$, in each of which the product was only partially soluble. The spectrum revealed the presence of very broad chemical shifts, which are indicative of a molybdenum-centered
complex, such as 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine-MoCl₃ (38). The product was again dried in vacuo and was concentrated in anhydrous THF. This mixture was placed in a freezer for several weeks with the intention of crystallizing (38) in order to obtain a cleaner ¹H NMR spectrum. The Schrodi group is still actively pursuing the successful and identifiable preparation of (38).

The difficulty of identifying the successful synthesis of (38) can be thought-provoking. First, it was confirmed that the molybdenum-THF adduct [MoCl₃(THF)₃] was successfully prepared. Furthermore, knowing its physical and chemical sensitivity, this adduct was promptly used in the chelation chemistry. Also, the 2,6-bis(2,6-diisopropylphenylimino)-ethyl]pyridine ligand was confirmed to be successful and free from impurities. The chelation chemistry followed previously published procedure. Finally, all solvents used were stored over activated alumina and molecular sieves prior to use. The most logical explanation for the lack of results in the synthesis of 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine-MoCl₃ may be in fact a mechanical impediment. The means of combining the molybdenum-adduct and the ligand in the anhydrous THF solvent may take additional precautions that have yet to be elucidated by the Schrodi group. Also, it is possible that longer reaction times for reflux are required to successfully access the metal-ligand complex. It is possible that if this reaction were to be prepared on an NMR scale and was monitored by ¹H NMR spectroscopy over time that certain diagnostic chemical shifts may indicate the progress of the reaction. Finally, crystallization experiments for (38) are constantly undertaken by the Schrodi group with the hopes of producing a pure, identifiable product. Upon achieving the successful isolation of 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine-MoCl₃, the Schrodi
group plans to treat this complex with a conventional reducing agent to afford the di-
chloride complex. From here, this di-chloride complex may be treated with a previously
synthesized di-Grignard reagent to attempt the synthesis of the corresponding
metallacyclobutane. Given the previous work with this ligand system and its tendency to
promote olefin polymerization, it is anticipated that this metallacyclobutane of
molybdenum will be active in catalyzing olefin metathesis reactions.

3.3 Conclusion

The synthesis of a parent di-Grignard reagent that was not methylated at the C-2
position was attempted with the preparation of 1,3-bis(bromomagnesio)propane.
Characterization by $^1$H and $^{13}$C {$^1$H} NMR spectroscopy proved inconclusive.
Derivitization of the putative di-Grignard reagent was attempted by derivitization with
benzophenone, the product of which could not be effectively characterized by
spectroscopic techniques. This synthesis proved difficult, as expected, due to the
propensity for C-H activation at the C-2 position of the propane backbone, resulting in a
$\beta$-decomposition pathway. This decomposition mode resulted in numerous inorganic
impurities and by-products that hindered the effective synthesis, isolation, and
characterization of the desired di-Grignard reagent.

The synthesis of a gem-dimethyl di-Grignard reagent was successful with the
preparation of 2,2-dimethyl-1,3-bis(bromomagnesio)propane. This di-Grignard was
prepared in synthetic yields that were comparable to previously published quantities. The
methyl substituents on the propane backbone served to effectively protect the structure
from undergoing a $\beta$-elimination decomposition pathway by way of C-H activation upon the C-2 position. This reduced the synthetic side-reactions and resulting by-products amongst the product profile, which allowed for a successful characterization of the di-Grignard by spectroscopic techniques. A bis-cyclopentadienyl molybdenum metallacyclobutane was successful with the preparation of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane. The structure was verified by $^1$H and $^{13}$C $^1$H NMR spectroscopy, with chemical shifts corresponding to previously published values. The metallacyclobutane of molybdenum was purified by sublimation, and the $^1$H and $^{13}$C $^1$H NMR spectra verified the removal of synthetic by-products and validated the purification method of the complex. The metallacyclobutane of molybdenum was used in an RCM experiment of DEDAM nonetheless. As expected, $^1$H NMR confirmed the lack of conversion of the substrate to the ring-closed product, indicating the lack of catalytic properties of the prepared metallacyclobutane.

The preparation of 2,6-bis(2,6-diisopropylphenylimino)-ethylpyridine ligand was successful following previously published procedure. The sequential reduction of molybdenum pentachloride starting material to a series of solvent-adducts, terminating in trichlorotris(tetrahydrofuran)molybdenum was successful. The chelation of the prepared ligand to the molybdenum adduct to afford 2,6-bis[1-(2,2-diisopropylphenylimino)-ethyl]pyridine-MoCl$_3$ proved difficult in its effective characterization by spectroscopic techniques. It was determined that crystallization of the synthetic product will provide for better characterization and subsequent use in future chemistry. The Schrodi group is currently engaged in this promising endeavor. It is anticipated that upon isolation of this product, treatment with a standard reducing agent will afford the corresponding di-
chloride ligand-metal complex. This di-chloride metal complex will then be amenable to treatment with a previously prepared di-Grignard reagent to afford a novel metallacyclobutane of molybdenum complex. Given the precedence of the ligand used in this chemistry, it is hoped that this novel metallacyclobutane will be active in catalyzing olefin metathesis reactions.

3.4 Experimental

GENERAL INFORMATION

NMR spectra were recorded on either a Bruker 400MHz NMR running Xwin-NMR software, or a Varian 400MHz NMR spectrometer running VNMR-J software. Chemical shifts are reported in parts per million (ppm) downfield from tetramethylsilane (TMS) with reference to internal solvent for $^1$H NMR and $^{13}$C NMR spectra. All glassware was oven dried and reactions were performed under an atmosphere of nitrogen, unless otherwise noted. All organic solvents were dried by passage through solvent purification columns containing activated molecular sieves. Solvents were stored over activated alumina and were filtered prior to use. All other commercial chemicals were used as obtained.
Synthesis of 1,3-bis(bromomagnesio)-2,2-dimethylpropane.

\[
\begin{align*}
\text{Br} & \quad \text{Br} \quad + \quad \text{Mg} \quad \xrightarrow{\text{Et}_2\text{O}} \quad \text{BrMg} \quad \text{MgBr} \\
\text{30}
\end{align*}
\]

Fine magnesium powder (0.64 g, 26.34 mmol) was combined with dry Et₂O (35 mL) and the resulting suspension was stirred vigorously. A solution of 1,3-dibromo-2,2-dimethylpropane (1.01 g, 4.39 mmol) was prepared in dry Et₂O (15 mL) and was added dropwise to the magnesium suspension over the course of 24 hours. The reaction mixture was vacuum filtered through a bed of celite moistened with dry Et₂O. The volume of the filtrate was determined to be 40 mL. The filtrate was titrated with a solution of salicylaldehyde phenylhydrazone (2.9 mg, 0.0137 mmol) in dry THF (5 mL). 1.45 mL of the putative digrignard solution was needed to reach the titration end point. Accordingly, it was determined that the digrignard was produced in 7.01 % yield. The peaks could not be integrated in order to determine the number of hydrogens which a specific resonance represents. \(^1\)H NMR (THF-\text{d}_8): \(\delta -0.082\) (s), \(1.10\) (s).
Synthesis of 3,3-dimethyl-1,1,5,5-tetraphenylpentane-1,5-diol.

\[
\text{BrMg} + \text{MgBr}_2 + \text{Et}_2\text{O} \rightarrow \text{OH} + \text{HO}
\]

Benzophenone (0.0793 g, 0.435 mmol) was added to a previously prepared solution of 1,3-bis(bromomagnesio)-2,2-dimethylpropane (0.0303 g, 0.1088 mmol) in dry Et\(_2\)O (30 mL) and was stirred for 2 hours at room temperature. The reaction mixture was removed from the glove box and was submerged in an icebath. 5\% (1 M) NH\(_4\)Cl (5 mL) was added and was allowed to stir overnight. The reaction mixture was warmed to room temperature and deionized water (5 mL) was added. The organic layer was extracted with Et\(_2\)O (3 x 100 mL). The organic layers were combined and were washed with brine. The organic product was dried over anhydrous magnesium sulfate for 30 minutes. The suspension was vacuum filtered through a celite bed moistened with Et\(_2\)O, resulting in a clear filtrate. The filtrate was dried in vacuo for 2 hours. 3,3-dimethyl-1,1,5,5-tetraphenylpentane-1,5-diol was recovered as a white solid in 147\% yield due to the presence of impurities. \(^1\)H NMR (CDCl\(_3\)): \(\delta\) 7.791 (d), 4.256 (s, 2H), 2.669 (s, 4H), 0.433 (s, 6H).
Synthesis of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane.

A previously prepared solution of 1,3-(bisbromomagnesio)-2,2-dimethyl propane (50 mL, 0.431 mmol, 0.0082 M) in Et₂O was added to biscyclopentadienyl molybdenum dichloride (0.128 g, 0.431 mmol). After 20 minutes of reaction, a dark amber colored reaction mixture was the result. The product was dried in vacuo, leaving an orange colored film. The film was dissolved with dry THF (50 mL) and the mixture was allowed to react for 3 hours. 1,4-dioxane (15 mL) was added to the mixture and was allowed to react for 30 minutes, which resulted in a turbid, caramel colored suspension. The product was isolated by vacuum filtration through a celite bed moistened with dry THF. The filtrate was dried overnight in vacuo, affording an amber-orange colored solid. Resolution of peaks for the \(^{13}\)C \(^{1}\)H NMR spectrum was such that splitting could not be determined and coupling constants could not be adequately calculated. \(^{1}\)H NMR (C₆D₆): \(\delta\) 0.630 (s, 4H), 1.173 (s, 6H), 4.339 (s, 10H). \(^{13}\)C \(^{1}\)H NMR (C₆D₆): \(\delta\) -6.130, 36.786, 66.904, 86.600.
Purification of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane by sublimation.

A previously prepared mixture of 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane in dry THF was transferred to a Schlenk vessel. Solvent was removed in vacuo. The Schlenk vessel was adapted to a cold-finger and the apparatus was attached to a water-circulation system set to 0°C. The dry product was allowed to sublimate overnight at 120 °C, which afforded orange crystals on the cold finger. Resolution of peaks for the $^{13}$C $^1$H NMR spectrum was such that splitting could not be determined and coupling constants could not be adequately calculated. $^1$H NMR (C$_6$D$_6$): $\delta$ 0.228 (s), 0.295 (s), 0.637 (s, 4H), 1.181 (s, 6H), 4.333 (s, 10H). $^{13}$C $^1$H NMR (C$_6$D$_6$): $\delta$ -5.495, 16.181, 37.409, 50.264, 87.208.

RCM of diethyl diallylmalonate with crude and purified 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane.

A solution of crude 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (0.5 mg) in C$_6$D$_6$ (500 µL) was prepared. Another solution was prepared by combining sublimed 1,1-dicyclopentadienyl-3,3-dimethyl-1-molybdenacyclobutane (0.5 mg) in C$_6$D$_6$ (500 µL). These solutions were loaded into separate screw-top NMR tubes that were fitted with septa. 2 drops of diethyl diallylmalonate (20 mg) were loaded into each
NMR sample, and the samples were allowed to react for 60 minutes at 40 °C. The conversion to the RCM product was determined by comparing the ratio of the integrals of the methylene protons belonging to the substrate, ~2.8 (d), with those of the product, ~2.98 (s). Upon inspection of the NMR spectra, it was determined that both the crude and the sublimed samples failed to convert any of the substrate to the desired RCM product.

**Synthesis of 2,6-Bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine.**

![Chemical Structure](image)

2,6-Diacetylpyridine (10.02 g, 61.4 mmol), 2,6-diisopropyl aniline (32.88 g, 18535 mmol), and p-toluene sulfonic acid monohydrate (0.603 g, 3.2 mmol) were combined with stock toluene (200 mL). The reaction mixture was set to reflux at 135 °C for 24 hours. The reaction mixture was allowed to cool to room temperature for 2 hours. Product was isolated by vacuum filtration, and the solid retained by the sinter was washed with glacial ethyl alcohol (30 mL). The solid was dried overnight by standard Schlenck techniques. The product was isolated as fine yellow crystals in 86.0% yield. \(^1\)H NMR (CDCl\(_3\)): \(\delta\) 8.49 (d, 2H), \(\delta\) 7.93 (t, 1H), \(\delta\) 7.17 (m, 6H), \(\delta\) 2.80 (sept., 4H), \(\delta\) 2.27 (s, 6H), \(\delta\) 1.19 (d, 24H).
Synthesis of bis(acetonitrile)tetrachloromolybdenum from molybdenum pentachloride.

\[
\text{MoCl}_5 + \text{(excess) CH}_3\text{C}≡\text{N} \rightarrow [\text{MoCl}_4(\text{CH}_3\text{CN})_2]\]

To vigorously stirring dry acetonitrile (30 mL), MoCl\textsubscript{5} (5.00 g, 18.3 mmol) was slowly added over a period of 30 minutes. The flask was sealed and the reaction mixture was allowed to mix for 2 hours, at which point mixing was stopped and the reaction mixture was allowed to rest undisturbed over night. To isolate the product, the reaction mixture was vacuum filtered and the solid retained by the sinter was washed with dry acetonitrile (30 mL). The product was retained on the frit and was allowed to dry overnight in the nitrogen atmosphere of the dry box. The product was isolated as a fine dark orange-brown powder in 87% yield.

Synthesis of tetrachlorobis(tetrahydrofuran)molybdenum from bis(acetonitrile)-tetrachloromolybdenum.

\[
[\text{MoCl}_4(\text{CH}_3\text{CN})_2] + \text{(excess) THF} \xrightarrow{2 \text{ hrs}} [\text{MoCl}_4(\text{THF})_2] + 2\text{CH}_3\text{CN}
\]

To vigorously stirring dry THF (20 mL), previously prepared [MoCl\textsubscript{4}(CH\textsubscript{3}CN)\textsubscript{2}] (5.1002 g, 15.95 mmol) was slowly added over a period of 15 minutes. The flask was sealed and the reaction mixture was allowed to stir for 2 hours. To isolate the product, the reaction mixture was vacuum filtered. The solid retained by the sinter was washed with dry THF.
(5 mL). The product was transferred to a glass vial and was dried in vacuo for 2 hours. The product was isolated as a fine orange-brown powder in 90.1% yield.

Synthesis of trichlorotris(tetrahydrofuran)molybdenum from tetrachlorobis-(tetrahydrofuran)molybdenum.

\[
\begin{align*}
[\text{MoCl}_4(\text{THF})_2] & \xrightarrow{\text{Sn, THF}} [\text{MoCl}_3(\text{THF})_3] \\
(5.0119 \text{ g, 13.2 mmol}) & \text{ combined with dry THF (60 mL). While vigorously stirring, fine tin powder (9.9492 g, 83.8 mmol) was slowly added over the course of 20 minutes. The reaction mixture was allowed to mix for 20 minutes. The reaction mixture was vacuum filtered, affording a magenta-red colored filtrate and grey tin powder that was retained by the sinter. The filtrate was transferred to a RBF and was concentrated to about 25\% of volume in vacuo. The product was isolated by vacuum filtration of the concentrated filtrate. The product was isolated as a fine bright-orange powder in 17.3\% yield. Characterization by \textsuperscript{1}H NMR showed the presence of mostly a mononuclear molybdenum complex, with the presence of some dinuclear molybdenum as well, both of which are paramagnetic in nature. \textsuperscript{1}H NMR (CD}_2\text{Cl}_2): \delta 65.04 \text{ (broad), } \delta 54.92 \text{ (broad), } \delta 25.10 \text{ (broad), } \delta 18.01 \text{ (broad).}
\end{align*}
\]
Synthesis of 2,6-bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine-MoCl₃.

Previously prepared [MoCl₃(THF)₃] (0.703 g, 1.68 mmol) and 2,6-Bis[1-(2,6-diisopropylphenylimino)-ethyl]pyridine (0.808 g, 1.68 mmol) were combined in dry THF (40 mL). The suspension was set to reflux at 70 °C for 12 hours, which afforded a blue colored reaction mixture. Characterization by ¹H NMR in CDCl₃ revealed the presence of broad chemical shifts, indicative of a paramagnetic molybdenum-centered complex. The solution was concentrated in vacuo and was allowed to crystallize for better characterization and analysis.
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