Spring 2005

Mechanistic studies in carbene and polyurethane chemistry

Susanne M. Lewis

University of New Hampshire, Durham

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Mechanistic studies in carbene and polyurethane chemistry

Abstract
The chemistry of benzylchlorocarbene was investigated through both theory and experiment. Photolysis of a phenanthrene-based precursor in an NMR tube gave evidence for isomeric beta-chlorostyrenes but not the alpha-isomer. Computations showed that insertion into the aromatic ring should have a barrier smaller than that for 1,2-hydrogen migration.

Attempts were made to confirm the structure of a novel "ene" product that appears to result from addition of photogenerated cyclopentyne to cyclohexene. DFT calculations explored the energetics of these reactions and showed that Gilbert’s bis-carbene mechanism is an unlikely route to the ene product. A variety of photochemical vinylidene precursors were prepared based on the phenanthrene and pyrene frameworks.

Several substituted triazinanetriols were investigated and tested to determine catalytic ability and were successfully polymerized with difunctional isocyanates, p-tolyldiisocyanate (TDI) and poly-4,4'-methylenedis(phenylisocyanate) (pMDI).

Computational and NMR studies of a DABCO-isocyanate complex were performed and it was concluded that the equilibrium concentration of this complex was too low to measure.

Preliminary results were acquired using a reaction calorimeter in the mechanistic studies of the reaction between an alcohol and an isocyanate. These results indicate that the reaction follows Farkas and Strohm's proposed mechanism and that the rate-determining step is the activation of the alcohol with an amine base.

The lowest energy pathway for the interconversion of axial-methylcyclohexane to equatorial-methylcyclohexane was calculated at two Hartree-Fock levels of theory (HF/3-21G and HF/6-31G*) and at the Moller-Plesset level of theory (MP2/6-31G). Through the Hartree-Fock and Moller-Plesset levels of theory, we have determined that there is one lowest energy pathway for the interconversion of axial-methylcyclohexane to equatorial-methylcyclohexane. Calculations were attempted at a higher level of theory (density functional theory), however this level of theory caused the individual transition states to converge into one, not allowing us to determine a lowest energy pathway at that level of theory.*

Keywords
Chemistry, Organic

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MECHANISTIC STUDIES IN CARBENE AND POLYURETHANE CHEMISTRY

BY

SUSANNE M LEWIS
B.A. Regis College, 1996

DISSERTATION

Submitted to the University of New Hampshire in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
In
Chemistry

May, 2005
This dissertation has been examined and approved.

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May 5, 2005
Date
DEDICATION

This is dedicated to my husband, David, without whom I might never have gotten this far in pursuing my dream and to my father, who always wanted me to do my very best at whatever I did.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>iv</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF SCHEMES</td>
<td>xii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xvi</td>
</tr>
<tr>
<td>I. PHOTOGENERATION OF REACTIVE CARBENES BY FRAGMENTATION OF CYCLOPROPA NATED PHENANTHRENES</td>
<td>1</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>6</td>
</tr>
<tr>
<td>Conclusion</td>
<td>50</td>
</tr>
<tr>
<td>II. SYNTHESIS AND USE OF A NOVEL CATALYST FOR POLYURETHANE FORMATION AND ATTEMPTED MECHANISTIC DETERMINATION OF THE DABCO CATALYZED REACTION BETWEEN 1-HEXANOL AND P-TOLYL-ISOCYANATE</td>
<td>52</td>
</tr>
<tr>
<td>Introduction</td>
<td>52</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>56</td>
</tr>
<tr>
<td>Conclusion</td>
<td>79</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Molar Ratios of Reagents Used in Reaction Calorimetry Study</td>
<td>74</td>
</tr>
<tr>
<td>2. Rate Constants for Activated Isocyanate and Activated Alcohol Model Rate Laws</td>
<td>77</td>
</tr>
<tr>
<td>3. Experimental Error Determined from Using Average Rate Constants. Shaded areas indicate lower error</td>
<td>78</td>
</tr>
<tr>
<td>4. Energies Calculated Using HF/3-21G Level of Theory</td>
<td>88</td>
</tr>
<tr>
<td>5. Energies Calculated Using HF/6-21G* Level of Theory</td>
<td>89</td>
</tr>
<tr>
<td>6. Energies Calculated Using MP2/6-21G* Level of Theory</td>
<td>90</td>
</tr>
<tr>
<td>7. Difference Between Adjusted Relative Energies for HF/6-31G* and HF/3-21G</td>
<td>95</td>
</tr>
<tr>
<td>8. Difference between Adjusted Relative Energies for MP2/6-31G* and HF/6-21G*</td>
<td>96</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Stabilization of Carbene by Electron Donating Groups</td>
<td>2</td>
</tr>
<tr>
<td>2. Examples of Nucleophilic, Ambiphilic and Electrophilic Carbenes</td>
<td>3</td>
</tr>
<tr>
<td>3. Computational Results for the Possible Mechanistic Pathways of Benzylchlorocarbene</td>
<td>10</td>
</tr>
<tr>
<td>4. Comparison of NMR Spectra for Photolysis of 7 in CDCl$_3$ (top) and CD$_3$CN (bottom)</td>
<td>11</td>
</tr>
<tr>
<td>5. Symmetric and Antisymmetric Singlet Ground State Cyclopentene Diradical</td>
<td>16</td>
</tr>
<tr>
<td>6. Coupling Spin Systems for 3-Cyclopentenyl-1-cyclohexane (16)</td>
<td>23</td>
</tr>
<tr>
<td>7. Correlation Spectroscopy (COSY) for diene 16 at 360 MHz</td>
<td>25</td>
</tr>
<tr>
<td>8. Correlation Spectroscopy (COSY) for diene 16 at 500 MHz</td>
<td>26</td>
</tr>
<tr>
<td>9. Two Possible Intermediates for Cyclopropanation of Dicarbenic Cyclopentene</td>
<td>28</td>
</tr>
<tr>
<td>10. MP2 Geometry Optimized 15</td>
<td>31</td>
</tr>
<tr>
<td>11. MP2 Geometry Optimized 16</td>
<td>31</td>
</tr>
<tr>
<td>12. Transition State from 24a to 16</td>
<td>32</td>
</tr>
<tr>
<td>13. Transition State from 24a to 16</td>
<td>32</td>
</tr>
<tr>
<td>14. Transition State from 24b to 15</td>
<td>33</td>
</tr>
<tr>
<td>15. Unsaturated Carbenes (from left to right): Vinylidene (alkylidene), Vinylidenecarbene, $C_2$, $C_3$</td>
<td>34</td>
</tr>
<tr>
<td>16. Transition State Proposed by Bacaloglu, Cotarcă, Marcu and Tőlgyi</td>
<td>55</td>
</tr>
</tbody>
</table>

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36. Pathway for the Interconversion of 64 to 65.................................................................93
37. HF/3-21G Adjusted Relative Energies for the Interconversion of 64 to 65.............37
38. HF/6-21G* Adjusted Relative Energies for the Interconversion of 64 to 65.........95
39. MP2/6-21G* Adjusted Relative Energies for the Interconversion of 64 to 65.......96
## LIST OF SCHEMES

<table>
<thead>
<tr>
<th>SCHEME</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Examples of Carbene Generation by Extrusion of Small Molecules</td>
<td>4</td>
</tr>
<tr>
<td>2. Photogeneration of Dichlorocarbene (2) from 7,7-Dichlorodibenzo[a,c]-bicyclo[4.1.0]heptane (1)</td>
<td>5</td>
</tr>
<tr>
<td>3. Rearrangement of Benzylchlorocarbene (4) to (E)- and (Z)-β-Chlorostyrenes through 1,2-Hydrogen Migration</td>
<td>7</td>
</tr>
<tr>
<td>4. Synthesis of Benzylchlorocarbene Precursor 7 from 1</td>
<td>7</td>
</tr>
<tr>
<td>5. Possible Pathway for Formation of α-Chlorostyrene</td>
<td>8</td>
</tr>
<tr>
<td>6. Reported Synthesis of Cyclopentyne by Wittig</td>
<td>13</td>
</tr>
<tr>
<td>7. Reaction of Carbon-14 Labeled 1-Chlorocyclopentene with Phenyllithium. Percentages are Abundance of Carbon-14 Label</td>
<td>13</td>
</tr>
<tr>
<td>8. Product Mixture from Reaction of 1-Chlorocyclohexene-6-(^{14})C and 1-Chlorocyclohexene-2-(^{14})C with Phenyllithium</td>
<td>14</td>
</tr>
<tr>
<td>9. Fitjer’s Synthesis and Trapping of Cyclopentyne</td>
<td>15</td>
</tr>
<tr>
<td>10. Synthesis of Cyclobutylidenecarbene Precursor 12</td>
<td>17</td>
</tr>
<tr>
<td>11. Irradiation of Cyclobutylidenecarbene Precursor 12 to Form Cyclopentyne (14)</td>
<td>18</td>
</tr>
<tr>
<td>12. Synthesis of 1-Bromocyclopentane (19)</td>
<td>19</td>
</tr>
<tr>
<td>13. Attempted Synthesis of 3-Cyclopentenyl-1-cyclohexene (16) from Copper Coupling of 1-Bromocyclopentene and 3-Bromocyclohexene</td>
<td>19</td>
</tr>
<tr>
<td>14. Formation of 1-Iodocyclopentene (22)</td>
<td>20</td>
</tr>
</tbody>
</table>
15. Attempted Synthesis of 3-Cyclopentenyl-1-cyclohexene (16) from Copper Coupling of 1-Iodocyclopentene (23) and 3-Bromocyclohexene (20) .............................................. 21
17. Proposed Reaction Pathways for Formation of 3-Cyclopentenyl-1-cyclohexene (16) by Hernandez ................................................................................................................... 27
18. B3LYP/6-31G* Computational Results for a Possible Pathway for Cyclopentyne Addition to Cyclohexene ................................................................................................................................... 30
19. Examples of α-Elimination to Form Vinylidenes .......................................................................................................................... 35
20. Nitrosation of a Primary Vinylamine to Form Vinylidenes .................................................................................................................. 35
21. Examples of Thermal and Photochemical Generation of Vinylidenes .............................................................................................. 36
22. Synthesis of 7-Methylenedibenzo[a,c]bicycle[4.1.0]heptane (26) .................................................................................................................. 37
23. Synthesis of d7-7-Methylenedibenzo[a,c]bicycle[4.1.0]heptane (28) ........................................................................................................... 38
24. Formation of 9,9-Dichloro-9H-cyclopropa[e]pyrene (30) and dicyclopropanated adduct 30a ........................................................................................................................................ 39
25. Photolysis of Dichloro-9H-cyclopropa[e]pyrene (30) .......................................................................................................................... 40
26. Formation of Vinylidene Cyclopropapyrene Precursor 32 .................................................................................................................. 41
27. Photolysis of Vinylidene Cyclopropapyrene Precursor 32 at 254 nm .................................................................................................. 41
28. Synthesis of 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa-[l]phenanthrene (35) ................................................................................................................................. 43
29. Photolysis of 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa-[l]phenanthrene (35) at 254 nm .................................................................................................................. 44

xiii

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30. Photolysis of 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa[1]phenanthrene (35) at 300 nm ........................................................................................................... 45

31. Synthesis of (1-Chloro-1a,9b-dihydro-1H-cyclopropa[1]-phenanthren-1-yl)(phenyl)methanol (37) ........................................................................................................... 46

32. Synthesis of (1-Chloro-1a,9b-dihydro-1H-cyclopropa[1]-phenanthren-1-yl)(phenyl)methanone (38) ........................................................................................................... 47

33. Photolysis of (1-Chloro-1a,9b-dihydro-1H-cyclopropa[1]-phenanthren-1-yl)(phenyl)methanone (38) ........................................................................................................... 48

34. Synthesis of 1a,9b-Dihydro-1-(nonan-5-ylidene)-1H-cyclopropa[1]phenanthrene (41) ....................................................................................................................................................... 49

35. Photolysis of 1a,9b-Dihydro-1-(nonan-5-ylidene)-1H-cyclopropa[1]phenanthrene (41) ....................................................................................................................................................... 50

36. Mechanism of Reaction for Base Catalyzed Isocyanate Formation as Proposed by Baker and Holdsworth ........................................................................................................... 52

37. Mechanism of Reaction for Base Catalyzed Isocyanate Formation as Proposed by Farkas and Strohm ........................................................................................................... 53

38. Synthesis of 3-[Bis-(3-hydroxypropyl)-amino]-propan-1-ol (44) ........................................................................................................... 57

39. Synthesis of 3-[4-(3-Hydroxypropyl)-piperazin-1-yl]-propan-1-ol (45) ........................................................................................................... 57

40. Synthesis of 3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46) ........................................................................................................... 58

41. Attempted Synthesis of Bis-analogue of 46 ........................................................................................................... 61

42. Attempted Synthesis of a Difunctional analogue of 46 ........................................................................................................... 61

43. Synthesis of 2-(2-{3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl}-ethoxy)-ethanol (54) ........................................................................................................... 63
<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>44</td>
<td>Attempted Synthesis of 3-[4,6-Bis-(3-hydroxy-propyl)-[1,3,5]triazin-2-yl]-propan-1-ol (56)</td>
<td>65</td>
</tr>
<tr>
<td>45</td>
<td>Second Attempted Synthesis of 3-[4,6-Bis-(3-hydroxy-propyl)-[1,3,5]triazin-2-yl]-propan-1-ol (56)</td>
<td>66</td>
</tr>
<tr>
<td>46</td>
<td>Synthesis of 1,3,5-Trihexyl-[1,3,5]triazinane (59)</td>
<td>67</td>
</tr>
<tr>
<td>47</td>
<td>Isocyanate Activated Model Reaction for Urethane Formation</td>
<td>74</td>
</tr>
<tr>
<td>48</td>
<td>Alcohol Activated Model Reaction for Urethane Formation</td>
<td>75</td>
</tr>
<tr>
<td>49</td>
<td>Interconversion of Cyclohexane Chair Conformers</td>
<td>81</td>
</tr>
</tbody>
</table>
ABSTRACT

MECHANISTIC STUDIES IN CARBENE AND POLYURETHANE CHEMISTRY

by

Susanne Marie Krauss Lewis

University of New Hampshire, May 2005

The chemistry of benzylchlorocarbene was investigated through both theory and experiment. Photolysis of a phenanthrene-based precursor in an NMR tube gave evidence for isomeric β-chlorostyrenes but not the α-isomer. Computations showed that insertion into the aromatic ring should have a barrier smaller than that for 1,2-hydrogen migration.

Attempts were made to confirm the structure of a novel “ene” product that appears to result from addition of photogenerated cyclopentyne to cyclohexene. DFT calculations explored the energetics of these reactions and showed that Gilbert’s bis-carbene mechanism is an unlikely route to the ene product. A variety of photochemical vinylidene precursors were prepared based on the phenanthrene and pyrene frameworks.

Several substituted triazinanetriols were investigated and tested to determine catalytic ability and were successfully polymerized with difunctional isocyanates, p-tolyl-diisocyanate (TDI) and poly-4,4′-methylenebis(phenylisocyanate) (pMDI).

Computational and NMR studies of a DABCO-isocyanate complex were performed and it was concluded that the equilibrium concentration of this complex was too low to measure.

Preliminary results were acquired using a reaction calorimeter in the mechanistic studies of the reaction between an alcohol and an isocyanate. These results indicate that the reaction follows Farkas and Strohm’s proposed mechanism and that the rate-determining step is the activation of the alcohol with an amine base.

The lowest energy pathway for the interconversion of axial-methylocyclohexane to equatorial-methylocyclohexane was calculated at two Hartree-Fock levels of theory (HF/3-21G and HF/6-31G*) and at the Møller-Plesset level of theory (MP2/6-31G). Through the Hartree-Fock and Møller-Plesset levels of theory, we have determined that there is one lowest energy pathway for the interconversion of axial-methylocyclohexane to equatorial-methylocyclohexane. Calculations were attempted at a higher level of theory (density functional theory), however this level of theory caused the individual transition states to converge into one, not allowing us to determine a lowest energy pathway at that level of theory.
CHAPTER 1

PHOTOGENERATION OF REACTIVE CARBENES BY FRAGMENTATION OF CYCLOPROPANATED PHENANTHRENES

Introduction

Carbenes are neutral, divalent, reactive intermediates that have been a source of research interest since the late 1800's. Methylene is the simplest carbene and its chemistry has been studied in great detail. Initially, chemists and theoreticians thought that methylene was a diradical because its chemistry was like that of radical intermediates. Skell proposed that singlet methylene would have a bent structure, $sp^2$ hybridization and an empty p orbital, much like a carbocation has an empty p orbital. He also proposed an explanation for the stereochemical differences between the two spin states of carbenes in their addition to olefins. The singlet state, in which the two nonbonding electrons share the same orbital, adds stereospecifically, while the triplet state, in which the two nonbonding electrons are in different orbitals, adds nonstereospecifically. Hammond was able to show through photosensitized decomposition of diazomethane in solution, that the triplet state of methylene can be generated and studied. He observed the stereochemistry predicted by Skell’s rule. Hammond also noted C – H insertion of methylene into C – H bonds on cyclohexene. This agreed with Doering’s observation of methylene reacting indiscriminately with various types of olefins.
The spin states of methylene have been a source of much discussion and research. It is now accepted that the triplet is the ground state while the singlet is an excited state. The energy difference between these two states is approximately 8.5 kcal/mol. Substituents on the carbene change this energy gap and may reverse the order. Electron donating groups usually serve to preferentially stabilize the singlet state through resonance (Figure 1).

\[ 
\begin{align*}
\ddot{\text{X}}\ddot{\text{C}}\dddot{\text{Y}} & \quad \leftrightarrow \quad \dddot{\text{X}}\dddot{\text{C}}\dddot{\text{Y}} \\
\dddot{\text{X}}\ddot{\text{C}}\dddot{\text{Y}} & \quad \leftrightarrow \quad \dddot{\text{X}}\dddot{\text{C}}\dddot{\text{Y}} \\
\end{align*}
\]

**Figure 1. Stabilization of Carbene by Electron Donating Groups**

Substituents also affect the reactivity of the carbene. Moss studied many different singlet carbenes and olefins to develop a reactivity index. This index describes carbenes as electrophilic, ambiphilic, or nucleophilic, depending on attached substituents (Figure 2). Moss has proposed an equation based on linear free energy correlation plots that can assist in deciding where a carbene should fit on the selectivity scale.
There are many ways to generate carbenes. Most involve extrusion of a small molecule by thermal or photochemical activation (Scheme 1). Griffin described in great detail photochemical cycloeliminations yielding carbenes from shelf-stable precursors. One common precursor is a cyclopropane derivative and the [3→2+1] cheletropic cycloelimination is known as a Griffin fragmentation. In 1965, Richardson and coworkers published a paper on the photochemical generation of singlet methylene (Eq. 5) from a cyclopropanated phenanthrene. The methylene was initially generated photochemically and added across the 9,10 double bond in phenanthrene. Upon photolysis, methylene was reformed and trapped with cyclohexene, while phenanthrene was cleanly regenerated. Results observed with this method of carbene generation agreed with those from photolysis of diazomethane in cyclohexene.

<table>
<thead>
<tr>
<th>Nucleophilic</th>
<th>Ambiphilic</th>
<th>Electrophilic</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₃CO-OCH₃</td>
<td>H₃CO-Cl</td>
<td>Cl-Cl</td>
</tr>
<tr>
<td>H₃CO-N(CH₃)₂</td>
<td>H₃CO-F</td>
<td>Ph-Cl</td>
</tr>
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<td></td>
<td></td>
<td>H₃C-Cl</td>
</tr>
</tbody>
</table>

Figure 2. Examples of Nucleophilic, Ambiphilic and Electrophilic Carbenes
Scheme 1. Examples of Singlet Carbene Generation by Extrusion of Small Molecules

In 1972, Joshi and coworkers reported that dichlorocarbene could be added across the 9,10-double bond of phenanthrene to form 7,7-dichlorodibenzo[a,c]bicyclo[4.1.0]-
heptane (1). This carbene is easily generated under phase-transfer conditions. Kirchhoff later showed that upon photolysis of 1, dichlorocarbene and phenanthrene are generated (Scheme 2).

Scheme 2. Photogeneration of Singlet Dichlorocarbene (2) from 7,7-Dichlorodibenzo[a,c]-bicyclo[4.1.0]heptane (1)

Photolysis of 1 provided the first photochemical route to singlet carbene 2 and the absolute kinetics of the reactivity of dichlorocarbene to several substituted olefins versus pyridine were also determined in collaboration with Chateaneuf. More recently Jones has used the dibromo analog of 1 to synthesize alkyl carbene precursors and showed that photolysis of phenanthrene-based carbene precursors generates singlet carbenes uncontaminated by excited nitrogen complexes produced from photolysis of nitrogen-based precursors. Our own research has used the method of lithium - halogen exchange and subsequent alkylation to form new carbene precursors. Kirchhoff began with the synthesis and trapping of dichlorocarbene and chlorocarbene as well as the previously mentioned kinetics of dichlorocarbene. The precursor to dibromocarbene was prepared but the carbene could not be cleanly trapped. Kirchhoff also attempted the synthesis of
cyclopropylidene precursors. Abbot continued this work by forming various alkylcarbene precursors and capturing the photogenerated carbenes. Among the carbenes formed were: benzylchlorocarbene, chlorocarbene, vinylcarbene, and vinylidene. Abbot was also involved with the laser flash photolytic generation of chlorocarbene, benzylchlorocarbene, and other alkylhalocarbenes. Hernandez continued this project by contributing work on photolysis of vinylcarbene and trapping of cyclopropene, synthesis and photolysis of precursors to straight-chain alkylidenes and three cycloalkylidenes.

As a continuation of this earlier work, this project included studies on benzylchlorocarbene and vinylidenecyclobutane, a precursor to cyclopentynne. The synthesis and photolysis of other novel vinylidene carbene precursors were also investigated.

Results and Discussion

Synthesis and Photolysis of a Benzylchlorocarbene Precursor for Attempted Formation of α-Chlorostyrene

Benzylchlorocarbene (4) has been very well studied. This reactive intermediate has been formed from 3-chloro-3-benzyldiazirine as well as by our method and is well known to rearrange via C-H insertion, resulting in both (Z)- and (E)-β-chlorostyrenes, 5 and 6 respectively (Scheme 3). Precursor 7 was prepared through lithium-halogen exchange of 1, followed by electrophilic quenching with benzyl bromide (Scheme 4), following the method of Kirchhoff and Abbot. Spectral data agreed with previous results.
Scheme 3. Rearrangement of Benzylchlorocarbene (4) to (E)- and (Z)-β-
Chlorostyrenes through 1,2-Hydrogen Migration

Scheme 4. Synthesis of Benzylchlorocarbene Precursor 7 from 1

Abbot was able to observe and characterize the formation of the β-chlorostyrenes
and phenanthrene by photolysis of 7 at 254 nm. Another possible product from this
reaction may be α-chlorostyrene. If the photogenerated carbene were to add to a π-bond
in the benzene ring, the resulting bicyclobutane (8) might open to give α-chlorostyrene
(9) (Scheme 5). The same substance can arise from a 1,2-phenyl shift in the carbene.
Reaction pathways for singlet carbene 4 were studied using density functional theory and Møller-Plesset theory. In addition to product structures, transition states were located for ring addition and the diastereomeric modes of 1,2-hydrogen shift. Unexpectedly, it was found that the transition state energy for addition into the benzene π-bond was lower in energy than of the 1,2-hydrogen shift (Figure 3). The transition state for the conversion of benzylchlorocarbene to the ring addition product was approximately 7 kcal/mol. The transition state for the conversion of benzylchlorocarbene to E-β-chlorostyrene through a 1,2-hydrogen shift was approximately 10 kcal/mol. The transition state for the conversion of benzylchlorocarbene to Z-β-chlorostyrene through a 1,2-hydrogen shift was approximately 11-12 kcal/mol.

In order to seek evidence for the product of ring addition, a small sample of 7 was photolyzed with 254 nm light in a quartz NMR tube with d-chloroform for 4.5 hr, 1.5 hr, and 45 min. Photolysis was also carried out in a quartz NMR tube with d$_3$-acetonitrile for 1 hr. Prior to and after each photolysis, the NMR spectrum was acquired and scrutinized for chemical shifts that might correspond to 9. An authentic sample of α-chlorostyrene was prepared by reacting acetophenone with phosphorous pentachloride. Figure 4 shows...
the resulting spectra. Resonances were observed for 5 and 6 but the spectra suggest a number of additional products. No chemical shifts were observed for α-chlorostyrene in any of the samples tested.

Further calculations were performed to determine the transition state energy for ring opening and rearomatization from 8 to α-chlorostyrene. The results showed that this energy was much higher than the energy for a hydrogen shift to the β-chlorostyrenes (approximately 40 kcal/mol vs. approximately 8 kcal/mol, respectively). Since we believe that the ring insertion transition may be reversible, it is possible that this process is occurring but the ring opening barrier is too large to overcome, so the 1,2-hydrogen shift pathway dominates. Moss has reported\textsuperscript{28} that through photolysis of benzylchlorodiazirine, α-chlorostyrene was formed in a small percentage of the reaction mixture. He attributes this product as being the result of a 1,2-phenyl shift. The barrier to this shift will need to be calculated and compared to the ring-addition process.

Our predicted barriers suggest that intramolecular addition to the aromatic ring should be faster than rearrangement by 1,2-hydrogen shift, but we see no evidence for this experimentally. It is likely that the 1,2-shift enjoys a substantial advantage from quantum mechanical tunneling. This is well documented in hydrogen shifts.\textsuperscript{30}
Figure 3. Computational Results for the Possible Mechanistic Pathways of Benzylchlorocarbene
Figure 4. Comparison of NMR spectra for photolysis of 7 in CDCl₃ (top) and CD₃CN (bottom)
Synthesis of Cyclobutylidenecarbene Precursor and Characterization of the Addition Products of Cyclopentyne and Cyclohexene

Cyclopentyne may have been first generated by Favorskii in 1936. Upon reaction of 1,2-dibromocyclopentene with sodium metal, Favorskii observed the formation of trindane as one of the reaction products. He assumed that this was the result of a polymerization process during the course of the reaction.

![Trindane](image)

In 1960, Wittig reported trapping cyclopentyne through reaction of 1,2-dibromocyclopentene with magnesium metal, in the presence of 1,3-diphenylisobenzofuran. The Diels-Alder product was identified through catalytic hydrogenation, followed by dehydration to form 2,3-dihydro-4,9-diphenyl-1H-cyclopenta[b]naphthalene (Scheme 6).
Wittig published several more papers on cyclopentyne through the early 1970’s.\textsuperscript{33-36} Not long after Wittig’s communication, Montgomery and his group described how cyclopentyne could be an intermediate in the reaction between 1-chlorocyclopentene-1-\textsuperscript{14}C and phenyllithium (Scheme 7).\textsuperscript{37}

\textbf{Scheme 6. Reported Synthesis of Cyclopentyne by Wittig}

\textbf{Scheme 7. Reaction of Carbon-14 Labeled 1-Chlorocyclopentene with Phenyllithium}

Percentages are Abundance of Carbon-14 Label
A full paper was published in 1965\textsuperscript{38} and described in more detail the mechanistic rationalizations of the product mixture. Additional experiments with \textsuperscript{14}C-labeled 1-chlorocyclohexene and phenyllithium were also performed (Scheme 8) to verify the method of degradation used with the products formed from the reaction of 1-chlorocyclopentene-1-\textsuperscript{14}C and phenyllithium and to further analyze the reaction mechanism. Since the 1-chlorocyclohexene had the label in the 2- or 6-position on the ring, they were able to determine that the reaction did not go through direct substitution of the phenylide anion with the chloride on the ring. If this were the case, 1-phenylcyclohexene-3-\textsuperscript{14}C or 1-phenylcyclohexene-1-\textsuperscript{14}C should not have been formed. Montgomery’s group postulates that through a cyclohexyne intermediate this could be possible.

\[
\begin{align*}
\text{Scheme 8. Product Mixture from Reaction of 1-Chlorocyclohexene-6-\textsuperscript{14}C and 1-Chlorocyclohexene-2-\textsuperscript{14}C with Phenyllithium}
\end{align*}
\]
Fitjer's group formed cyclopentyne from dibromomethylene cyclobutane as shown in Scheme 9. They were attempting to cyclopropanate cyclohexene with cyclobutylidenecarbene and serendipitously discovered this new route to cyclopentyne. It is not known whether this involves a free carbene intermediate.

Scheme 9. Fitjer's Synthesis and Trapping of Cyclopentyne

Fitjer and Modaressi later observed that cycloadditions of cyclopentyne with cis- and trans-2-butene occurs stereospecifically and there is a strong preference for 1,2-addition to 1,3-butadiene. The Woodward and Hoffmann orbital symmetry rules dictate that a thermal [2+2] cycloaddition is "forbidden" unless it occurs stepwise or with antarafacial stereochemistry. Because of the cis-stereospecificity of the [2+2] cycloaddition of cyclopentyne to alkenes and the preference for this cycloaddition to [2+4] cycloaddition, Fitjer and Modaressi suggested that cyclopentyne exists as a diradical with an antisymmetric singlet ground state (Figure 5).
To explain these results, Gilbert and Baze suggested that cyclopentene might be the equilibration of two π-complexes. However, Olivella et al. were quick to dismiss this by carrying out calculations that would accurately describe these singlet diradicals. Through these calculations, they were able to find a $C_{2v}$ symmetric minimum for cyclopentene. Not to be dissuaded, Gilbert and Kirschner introduced the concept of a "lumomer," a species in which the HOMO and LUMO are inverted. Johnson and Daoust studied a series of cycloalkyldenedecarbenes and the rearrangement to cycloalkynes using various \textit{ab initio} levels of theory and determined that cyclobutylidenecarbene should readily rearrange to cyclopentene. They determined that the "lumomer" of Gilbert and Kirschner was an anomaly caused by the semiempirical AM1 wavefunction. Gilbert has continued work in the area of cyclopentene and recently described computational and experimental results which suggest that norbornyne and cyclopentene may act like a dicarbene.

Following the method of Hernandez, which was the first photochemical route to cyclopentene, the cyclobutylidenecarbene precursor was synthesized by reacting dichlorocarbene adduct with n-butyllithium followed by quenching with cyclobutanone (Scheme 10). The resulting chlorohydrin was treated with pyridine or imidazole and TMSCl to give TMS-ether. The 1,2-elimination of TMSOLi was completed by
reacting TMS-ether 11 with tert-butyl lithium at -90°C in THF/pentane. Purification of cyclobutylidenecarbene adduct 12 was performed through radial chromatography followed by preparative TLC.

Scheme 10. Synthesis of Cyclobutylidenecarbene Precursor 12

Cyclobutylidenecarbene adduct 12 was then irradiated at 254 nm for 2 hours in the presence of cyclohexene (Scheme 11). As observed by Hernandez, this afforded [2+2] cycloaddition product 15, as a major product, along with “ene”-like product 16. When Hernandez originally performed this research, the product 16 was completely unexpected. The object of the current research is to confirm the structure that Hernandez had proposed. The structure is isolated in minute quantity and is not known in the literature so a comparison of spectral evidence through literature sources is not a possibility. There are
several ways to perform structural identification: independent synthesis of the proposed molecule, 2-dimensional NMR correlation spectroscopy, or high-resolution mass spectrometry to determine fragmented ions from the parent structure.

Scheme 11. Irradiation of Cyclobutylidenecarbene Precursor 12 to Form Cyclopentyne (14)

The first attempt to prepare 16 began with synthesizing 1-bromocyclopentene (19) through reacting cyclopentene (17) with elemental bromine to form trans-1,2-dibromocyclopentane (18) in 97% yield (Scheme 12). The $^1$H-NMR spectrum agreed with literature data. A dehydrohalogenation was then performed by reacting 18 with a mixture of morpholine, DMSO and potassium hydroxide in refluxing 95% ethanol. After removing the solvent, the crude product was vacuum distilled and pure 1-
bromocyclopentene (19) was collected in 6% yield. The $^1$H-NMR spectrum agreed with literature data\textsuperscript{55} (Scheme 12).

\textbf{Scheme 12. Synthesis of 1-Bromocyclopentene (19)}

This route to 3-cyclopentenyl-1-cyclohexene was based on well known cuprate chemistry.\textsuperscript{56} 1-Bromocyclopentene (19) was reacted with \textit{tert}-butyllithium at $-78^\circ$C followed by copper(I) iodide to form a cuprate. 3-Bromocyclohexene (20) was then added slowly with the expected formation of 3-cyclopentenyl-1-cyclohexene (16) (Scheme 13).

\textbf{Scheme 13. Attempted Synthesis of 3-Cyclopentenyl-1-cyclohexene (16) from Copper Coupling of 1-Bromocyclopentene (19) and 3-Bromocyclohexene (20)}

This reaction did not result in a species that had the same $^1$H-NMR resonances of the product isolated by Hernandez. It was thought that the $S_N2$ or $S_N2'$ reactions weren’t happening due to the lack of a cuprate being formed from the bromopentene. To improve
reactivity, 1-iodocyclopentene (23) was synthesized through the oxidation of hydrazone 22 with iodine.\textsuperscript{57} The hydrazone (22) was formed by the reaction of cyclopentanone (21) with hydrazine monohydrate at 100°C for 1 hour (Scheme 14). The hydrazone was formed in 90% yield and the $^1$H-NMR spectrum correlated with the literature data. The hydrazone was then reacted with an ethereal solution of iodine in the presence of triethylamine (Scheme 14). A second product of this reaction was 1,1-diiodocyclopentane (24), which was separated by vacuum distillation, followed by chromatography through Florisil with hexane as the eluent.

![Scheme 14. Formation of 1-Iodocyclopentene (22)](image)

Pure 1-iodocyclopentene (23) was then used in the copper coupling reaction. 1-Iodocyclopentene was reacted with tert-butyllithium at $-78^\circ$C (Scheme 15). Copper(I) chloride was added and once fully dissolved, 3-bromocyclohexene was added slowly. After aqueous workup and solvent removal, the $^1$H-NMR spectrum was acquired and compared with the spectrum of 16 from Hernandez’s dissertation. The mixture was complex but there were no matching resonances.
Our second approach was based on Heck coupling. Triethylamine was added to a mixture of 1-iodocyclopentene and a catalytic amount of tetrakis(triphenylphosphine)palladium(0) in THF at room temperature. After this was allowed to stir for 30 min, cyclohexene was added and the solution was stirred overnight (Scheme 16). Upon workup, the $^1$H-NMR spectrum indicated that the reaction had not proceeded and there were only starting materials present. The reaction was repeated with catalytic palladium(II) chloride and triphenylphosphine to generate tetrakis(triphenylphosphine)palladium(0) in situ. This also yielded only starting materials. The reaction was repeated a third time using the same reactants as the second attempt but the reaction mixture was refluxed for approximately 40 h. After workup and removal of solvent, the $^1$H-NMR spectrum showed that the starting materials had disappeared, but there were no distinguishable resonances for the desired target product.
Scheme 16. Attempted Synthesis of 3-Cyclopentenyl-1-cyclohexene (16) through Heck Palladium Coupling

At this point, NMR studies were undertaken to determine the structure of the compound. Compound 16 was isolated by chromatography in small quantities from the reaction mixture of photolysis of carbene precursor 12 in the presence of cyclohexene and showed spectra that compared well to those of Hernandez. The first correlation experiment that was carried out was a gradient 2-dimensional COSY (Correlation Spectroscopy), which allows a researcher to determine the connectivity of a molecule by determining which protons are spin-spin coupled. Off-diagonal peaks in the spectrum denote splitting between protons on adjacent carbons. In the structure that was proposed to be 16, there should be two major spin systems connected by allylic coupling ($^{4}J \sim 2$ Hz) (Figure 6).
Figure 6. Coupling Spin Systems for 3-Cyclopentenyl-1-cyclohexene (16)

The first spectrum was acquired on a Brucker 360 MHz NMR (Figure 7). After acquiring and processing the COSY, it was determined that the compound tested did have two separate spin systems. One of the vinyl protons was in one spin system and the other two vinyl protons were in the second spin system. The two vinyl protons at 5.6-5.7 ppm correlate with a saturated proton at 1.9-2.0 ppm. The vinyl proton at 5.3 ppm correlates with a saturated proton at 2.3 ppm, which in turn correlates with another saturated proton at 1.8-1.9 ppm. Unfortunately the sample slowly degraded. The sample had been dissolved in deuterated chloroform, which often contains a small amount of acid, and the vinyl proton signals began to change. It is possible that one of the double bonds migrated into conjugation with the other one. The signals identified as the vinyl protons on the desired product began to decrease while a new signal grew in. It was not determined if this new signal was due to a conjugated diene system. A second COSY was acquired and processed on a fresh sample on a higher field NMR spectrometer (500 MHz). The second COSY confirmed the first spectrum (Figure 8). The higher field magnet also gave some additional detail into the saturated region. The saturated proton at 1.9-2.0 ppm correlates
with another proton at 2.8-2.9 ppm and the protons between 1.5-1.8 ppm. The saturated proton at 2.3 ppm correlates with a proton just to the right between 2.1-2.2 ppm and the other that was seen before at 1.8-1.9 ppm. With this knowledge, a Heteronuclear Single Quantum Coherence (HSQC) spectroscopy was performed to determine the hydrogen-carbon coupling. This could not be done previously due to the resolution of the spectrometer and the amount of sample available. Unfortunately, with the limited sample the solvent signal overpowered the spectrum. Many attempts were made to suppress the solvent signal but there was no success. Further work needs to be done in acquiring more of the compound in question to complete the 2-dimensional NMR studies or to send the sample for high resolution mass spectrometry.
Figure 7. $^1$H-NMR Correlation Spectrum (COSY) for diene 16 at 360 MHz.
Figure 8. $^1$H-NMR Correlation Spectrum (COSY) for diene 16 at 500 MHz.
Computational Studies on the Reaction Mechanism

It is of interest to determine what common intermediate might lie on the pathways toward the [2+2] addition product 15 and the putative “ene” product 16. Hernandez had proposed two possible pathways: a concerted ene reaction pathway and a stepwise diradical pathway\(^\text{19}\) (Scheme 17). It has been pointed out\(^\text{58}\) that there is an absence of an ene product in previously reported reactions of cyclopentene. This was explained as being due to the increased diradical character of cyclopentene and the inversion of the HOMO and LUMO states, which led Gilbert to the concept of the “lumomer”.

Scheme 17. Proposed Reaction Pathways for Formation of 3-Cyclopentenyl-1-cyclohexene (16) by Hernandez

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Gilbert's recent suggestion of a "dicarbene"-like cyclopentyne led us to consider a similar intermediate. There are two intermediates that could be formed from the initial cyclopropanation of cyclohexene with the "dicarbene"-like cyclopentyne, as shown in Figure 9. Both intermediates can undergo a 1,2-carbon shift to give the apparent [2+2] product 15. Intermediate 24a is arranged nicely to perform a 1,5-hydrogen shift to give 16.

![Figure 9. Two Possible Intermediates for Cyclopropanation of Dicarbenic Cyclopentyne](image)

Computations were performed using density functional theory (B3LYP) and a 6-31G* basis set to determine the energetics of some of the proposed pathways. For the dicarbenic system, the "ene"-like product is about 20 kcal/mol lower in energy than the expected 2+2 product (Scheme 18).
B3LYP energies are given in hartrees
Relative Energies (kcal/mol)
are in parentheses

Scheme 18. B3LYP/6-31G* Computational Results for a Possible Pathway for
Cyclopentene Addition to Cyclohexene

B3LYP energies are given in hartrees
Relative Energies (kcal/mol)
are in parentheses

24b
-428.686678
(-34.9)

TS 24b-15
-428.66282
(-32.4)
($E_a = 2.5$ kcal/mol)

TS 24a-15
-428.65662
(-28.5)
($E_a = 7.5$ kcal/mol)

TS 24a-16
-428.63859
(-17.2)
($E_a = 18.8$ kcal/mol)

15
-428.74670
(-84.7)

16
-428.77841
(-104.9)
Figures 10 and 11 show the geometry optimized structures of the products (15 and 16). Figure 12 shows the transition state structure for the 1,2-shift of 24a to 15. Figure 13 shows the transition state structure for the 1,2-shift of 24b to 15. Figure 14 shows the transition state structure for the intramolecular hydrogen abstraction within 24a in the pathway to 16. The atom labels have been assigned to assist in comparing the structures to each other and to the transition states leading to the products. These results indicate that 24a should not be a precursor to 16 since that barrier is much higher than for rearrangement to 15.

Figure 10. B3LYP Optimized 15

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Figure 11. B3LYP Geometry Optimized 16

Figure 12. Transition State from 24a to 15
Figure 13. Transition State from 24b to 15

Figure 14. Transition State from 24a to 16
In these preliminary calculations, we were unable to locate a transition state for the concerted ene-mechanism. Models of the ene-mechanism using acetylene and propene or acetylene and cyclohexene were successfully calculated but when cyclopentyne was used with propene or cyclohexene, the wavefunction would not converge. Spartan does not handle singlet diradicals effectively and Gaussian will be needed to perform this calculation.

Synthesis and Selected Photochemical Experiments of Novel Vinylidene Precursors

Vinylidenes are of a class of carbenes where the carbenic center is located on an unsaturated carbon (Figure 15). Unsaturated carbenes (C₂ and C₃) have been detected extraterresterially⁵⁹, but in the laboratory have not been detected outside of a carbon arc. Most of the vinylidenes described in current literature are those involved in metal complexes.⁶⁰ These types of vinylidenes will not be described here.

![Figure 15. Unsaturated Carbenes (from left to right): vinylidene (alkylidene), vinylidene carbene, C₂, C₃](image)

Vinylidenes can be prepared through a variety of methods. α-Elimination methods proceed via base decomposition of a primary vinyl halide⁶¹-⁶³, primary vinyl triflate⁶⁴,⁶⁵, or nitrosooxazolidones⁶⁶-⁷⁰; treatment of a 1,1-dibromoalkene with an alkyllithium⁷¹ or through fluoride decomposition of an α-chlorovinylsilane⁷² (Scheme 19). Treatment of primary vinylamines with isoamyl nitrite also shows evidence of
formation of vinylidenes through a diazonium salt intermediate (Scheme 20). Thermal and photochemical methods include decomposition of diazoethenes, photoelimination of hydrogen chloride from primary vinyl chlorides and photofragmentation of methylenecyclopropanes (Scheme 21). It is this last method that we are implementing in our methodology for the photolysis of cyclopropanated phenanthrenes.

**Scheme 19. Examples of α-Elimination to form Vinylidenes**

\[ R \ce{C=CH} X \rightarrow R \ce{C=CH} \]

\[ \text{base (KOTBu, PhLi, KNH}_2\text{)} \]

\[ X = \text{Cl, Br, OTf} \]

\[ R \ce{C=CH} \]

\[ \text{CH}_3\text{Li} \]

\[ R \ce{C=CH} \]

\[ \text{OH}^- \]

\[ R \ce{C=CH} \]

\[ \text{Me}_4\text{N}^+\text{F}^- \]

\[ R \ce{C=CH} \]
Scheme 20. Nitrosation of a Primary Vinlamine to form Vinylidenes

Scheme 21. Examples of Thermal and Photochemical Generation of Vinylidenes

Vinylidenes are predicted to have a singlet ground state and the singlet-triplet gap is calculated to be 20 – 46 kcal/mol.\textsuperscript{77,78} The singlet ground state has also been demonstrated experimentally through the observation of stereospecific products from the reaction of vinylidenes with trans-2-butene.\textsuperscript{79}

Vinylidenes undergo both intramolecular and intermolecular reactions. Rearrangements to alkynes\textsuperscript{77,80} and carbon-hydrogen insertion reactions (both [1,5]\textsuperscript{61,81-84} and [1,3]\textsuperscript{61} C-H insertions have been observed) are the most common intramolecular
reactions seen experimentally. Vinylidenes react intermolecularly, as saturated carbenes do, through insertion reactions into O-H\textsuperscript{61,65,71,72} and Si-H\textsuperscript{67} bonds, although the only intermolecular C-H insertions that have been observed were through photogenerated vinylidenes\textsuperscript{76}. Vinylidenes also undergo addition reactions to alkenes\textsuperscript{65-69,71,72,85}, alkynes\textsuperscript{77}, allenes\textsuperscript{86} and cumulenes\textsuperscript{77}.

Using the framework developed by Abbot\textsuperscript{15}, a series of substituted vinylidene precursors were synthesized. The parent vinylidenecarbene precursor, 7-methylenedibenzo[a,c]bicyclo[4.1.0]heptane (26) was synthesized (Scheme 22) by reacting dichlorocarbene adduct 1 with \textit{n}-butyllithium followed by quenching with methyl iodide. The resulting chloromethylcyclopropane (25) was then subjected to elimination conditions using potassium \textit{tert}-butoxide in DMSO, followed by purification through chromatography on a silica rotor using an ether/hexane mixture (2:100) as the eluent. Further purification was completed through recrystallization from ethyl acetate.

\begin{center}
\begin{tikzpicture}
  \node at (0,0) {1};
  \node at (2,0) {a. \textit{n}-BuLi, THF, -78 °C};
  \node at (2,2) {b. CH\textsubscript{3}I};
  \node at (0,-2) {25};
  \node at (2,-2) {26};
  \node at (2,-4) {KOTBu};
  \node at (2,-5) {DMSO, 50 - 55 °C};
\end{tikzpicture}
\end{center}

**Scheme 22. Synthesis of 7-Methylenedibenzo\{}a,c\{}bicyclo[4.1.0]heptane (26)\**
Abbot had briefly studied the photochemistry of 26, but the kinetics of carbene reactions had not been determined. A sample was prepared and sent to our collaborator, David Modarelli, at the University of Akron to see if the kinetics could be determined using laser flash photolysis (LFP) and trapping the resulting carbene with pyridine. Unfortunately, the rearrangement process for conversion to acetylene was too fast to be trapped by pyridine and Modarelli’s group saw no transients.

We wondered if replacing the hydrogens with deuterium would slow the process down enough for these detection methods. A deuterium analog to 26, d$_2$-7-methylenedibenzo[a,c]bicyclo[4.1.0]heptane (28), was synthesized using the same procedure (Scheme 23). Dichlorocyclopropane 1 was reacted with n-butyllithium, followed by quenching with d$_3$-methyl iodide. The resulting deuterated carbene precursor (27) was then subjected to elimination conditions using potassium tert-butoxide in DMSO followed by purification through rotary chromatography on silica, using an ether/hexane mixture (2:100) as the eluent. Further purification was completed through recrystallization from ethyl acetate. This precursor will be sent to our collaborator for further study.
Scheme 23. Synthesis of d$_2$-7-Methylenedibenzo[a,c]bicyclo[4.1.0]heptane (28)

Another avenue to assist our collaborators in detecting the vinylidene was to change the platform that the carbene is generated from. By using pyrene (29) as the platform for cyclopropanation, we could modify the absorbance spectrum of the precursor which may allow for the use of a different laser source in the LFP. The methodology for building the pyrene-based vinylidene precursor is the same as the methodology for using the phenanthrene platform. Dichlorocarbene was generated through $\alpha$-elimination of chloroform with saturated sodium hydroxide in the presence of a phase transfer catalyst. The resulting carbene was trapped by pyrene (29) to give both mono- and bis-cyclopropanated pyrene, 30 and 30a respectively (Scheme 24).
Scheme 24. Formation of 9,9-Dichloro-9H-cyclopropa[e]pyrene (30) and dicyclopropanated adduct 30a

This mixture was separated by silica gel column chromatography using hexanes as the eluent, followed by purification by rotory chromatography using toluene as the eluent. 9,9-Dichloro-9H-cyclopropa[e]pyrene (30) was isolated and photolyzed to confirm that pyrene could be regenerated under photochemical conditions (Scheme 25). A solution of 30 in cyclohexane was placed into a quartz tube and photolyzed at 254 nm and room temperature for two hours. It was determined by TLC that pyrene was being generated, but there was still a significant amount of starting material present. It is possible that the pyrene was as an internal filter since its UV-absorbance spectrum has five main absorbances in the ultra-violet region (239 nm, 263 nm, 272 nm, 320 nm, 335 nm). This would result in the newly generated pyrene acting as a filter and preventing enough energy to reach molecules of 30. However, it was reassuring to know that 30 would react to release the carbene and regenerate pyrene.
Scheme 25. Photolysis of Dichloro-9H-cyclopropa[e]pyrene (30)

The next step in the sequence toward the formation of a vinylidene precursor from pyrene was to make the chloromethylcarbene adduct. To this end, 30 was reacted with n-butyllithium to generate a lithium carbenoid, which was quenched with methyl iodide (Scheme 26). Purification of the residue through recrystallization from hexanes gave 31 in 64% yield. Base elimination of 31 through reaction with potassium tert-butoxide gave vinylidene precursor 32 in 93% crude yield. Purification by rotor chromatography using hexane as the eluent gave 32 in 65% yield. Vinylidene precursor 32 was added to hexanes in a quartz tube and photolyzed at 254 nm and room temperature for four hours with additional samples taken after one and two hours (Scheme 27). The quartz tube developed a yellow film as the reaction progressed. Thin layer chromatography and $^1$H-NMR confirmed that pyrene was being regenerated upon photolysis of 32. This compound will also be sent to our collaborator for further study.
Scheme 26. Synthesis of Vinylidene Precursor 32

Scheme 27. Photolysis of vinylidene precursor 32 at 254 nm

Synthesis and Photochemistry of Substituted Vinylidene Precursors
We next sought to prepare a series of precursors to substituted vinylidenes. These should rearrange more slowly and might be suitable for kinetic studies. Other questions in vinylidene chemistry might also be answered. We were interested to see if we could determine experimentally whether a methyl group or a phenyl group would migrate preferentially in a substituted vinylidene. The ultimate goal was to build a carbon labeled substituted vinylidene and monitor which group migrated relative to the labeled carbon. First, the precursor was synthesized without an isotopic label to refine the method and ensure that irradiation would be successful.

Racemic \(1\text{a},9\text{b}-\text{Dihydro-1-}(1\text{-phenylethylidene})\text{-1H-cyclopropa[1]-phenanthrene}\) (35) was synthesized by reacting 1 with \(n\text{-butyllithium}\) followed by quenching with acetophenone (Scheme 28). This step also created some monochlorocarbene adduct because of the acidity of the \(\alpha\)-protons on the acetophenone and the basicity of the lithium carbenoid that is formed in this process. The product was purified by removing excess acetophenone under vacuum, followed by recrystallization from ethanol. Formation of carbene adduct 33 also introduced a stereogenic center into the molecule which can be seen through the proton signals for the bridgehead protons. In an achiral precursor, these two protons are chemically and magnetically equivalent. In the presence of a stereocenter, these two protons are now diastereotopic and couple to one another. This intermediate was converted to 34 by treatment with trimethylsilyl chloride in the presence of pyridine. After removing the pyridine under vacuum, the silyl ether product (34), in a mixture of THF and pentane, was subjected to \textit{tert}-butyllithium. Upon purification by chromatography over Florisil, 35, as yellow crystals, was collected in 12% yield. Spectral data were consistent with the unsymmetrical structure.
Scheme 28. Synthesis of Racemic 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa-[l]phenanthrene (35)

Methylenecyclopropane 35 was placed into a quartz tube with hexane and irradiated at 254 nm at room temperature over a period of 90 min with samples taken at 30 minute intervals (Scheme 29). After 30 minutes, the solution became turbid and after 60 minutes, a yellow solid began to collect at the bottom of the quartz tube. The reaction was monitored by TLC for generation of phenanthrene and analyzed by gas chromatography to determine the generation of 1-phenylpropyne (36). Phenanthrene (3) and authentic 1-phenylpropyne (36) standards were both analyzed by gas chromatography to determine the retention times for comparison with experimental results. Retention times were 19.6 and 9.3 minutes, respectively.
Scheme 29. Photolysis of Racemic 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa-[l]phenanthrene (35) at 254 nm

1-Phenylpropyne (36) and phenanthrene (3) were initially observed after 30 minutes of irradiation. Other peaks at 5.5 and 8.1 minutes were observed and these increased in relative intensity with further irradiation of the sample. These results suggest that these additional products were the result of 1-phenylpropyne (36) reacting at this wavelength, so a control experiment was carried out. 1-Phenylpropyne (36), in hexane, was placed in a quartz tube and irradiated at 254 nm, with samples taken at 30 minute intervals and analyzed by gas chromatography. After 30 minutes, there were additional peaks occurring at approximately the same times as in the irradiation samples of 35. At 60, 90 and 120 minutes, these peaks became larger as well as many more additional peaks developing. NMR spectra were acquired after concentration of the reaction mixture at 120 minutes. This showed a complex mixture and it was clear that there was additional unwanted chemistry happening at this wavelength. Another test reaction was carried out with irradiation of 1-phenylpropyne (36) at 300 nm in a Pyrex tube. After 2 hours, the reaction mixture was concentrated and NMR spectra were measured. There was no change apparent in the spectra after irradiation.
Another problem that occurred in analyzing the experimental results was during analysis of the reaction mixture taken at 0 minutes; it appeared that degradation was occurring on the gas chromatography column due to a peak that occurred at the same retention time as 1-phenylpropyne (36). Repeated samples were analyzed at various times and temperatures to determine if a suitable method could be developed for complete analysis of this experiment. It was concluded that regardless of the temperature in the gas chromatographic analysis method, the starting carbene precursor still degraded on the column. Since alkyne carbon peaks are very recognizable in the carbon NMR spectrum, it was decided that characterization would be performed through NMR spectroscopy.

Compound 35, in hexane, was placed in a Pyrex tube and irradiated at 300 nm for 180 minutes (Scheme 30). The sample was concentrated by rotary evaporation and NMR spectra were collected. Phenanthrene (3) was present as the major component which indicates that the carbene was generated. However, there were no peaks that matched those of the authentic sample of 1-phenylpropyne (36). Further work is needed to determine if additional chemistry is occurring in the reaction mixture under these conditions.

Scheme 30. Photolysis of Racemic 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa-[l]phenanthrene (35) at 300 nm
Another carbene precursor we studied, racemic (1-chloro-1a,9b-dihydro-1H-cyclopropa[l]-phenanthren-1-yl)(phenyl)methanol (37), similar to 33, was formed through the addition of benzaldehyde to the lithium carbenoid of 1 (Scheme 31). This process did not have any side reactions occurring because there are no acidic protons present in the electrophile. The product was purified through recrystallization from ethyl acetate to give 37 as a pale yellow solid in 25% yield. As with 33, spectral data were consistent with an unsymmetrical structure. This substance might also be converted to a vinylidene precursor following the same method as the synthesis of 35, however this wasn’t completed at this time.

![Scheme 31. Synthesis of Racemic (1-Chloro-1a,9b-dihydro-1H-cyclopropa[l]-phenanthren-1-yl)(phenyl)methanol (37)](image)

Unlike the others, precursor 37 contains a secondary alcohol and we wondered what type of rearrangements we could observe if we oxidized the secondary alcohol and then irradiated the resulting ketone (Scheme 32). Compound 37 was reacted with pyridinium chlorochromate in methylene chloride and the resulting yellow solid was recrystallized from hexanes to give (1-chloro-1a,9b-dihydro-1H-cyclopropa[l]-
phenanthren-1-yl)(phenyl)methanone (38) in quantitative yield as yellow prism-like crystals. In principle, photolysis of 38 might provide a route to chlorophenylketene.

Scheme 32. Synthesis of (1-Chloro-1a,9b-dihydro-1H-cyclopropa[l]-phenanthren-1-yl)(phenyl)methanone (38)

Compound 38 was irradiated in the presence of cyclohexene, as a trap, for 4 hours (Scheme 33). Samples were collected during this time to monitor the progress of the reaction by TLC. The solution was then concentrated under reduced pressure in an ice bath to prevent any loss of possible products. The resulting residue was separated into four fractions by preparative TLC using a mixture of 2% diethyl ether in hexanes as the eluent. Although phenanthrene was clearly formed in good yield, we saw no evidence for the formation of a ketene adduct. The first fraction showed some resonances in the aromatic region, but on closer inspection, they had the same values as phenanthrene. The second and third fractions showed only solvent peaks. The fourth fraction was phenanthrene.
Another substituted vinylidene precursor that was synthesized was 1a,9b-dihydro-1-(nonan-5-ylidene)-1H-cyclopropa[l]phenanthrene (41) through the addition of 5-nonanone to the lithium carbenoid of 1 (Scheme 34). The resulting alcohol (39) was converted to the silyl ether (40) through reaction with trimethylsilyl chloride in the presence of pyridine. Methylene cyclopropane 41 was formed by reacting silyl ether 40 with tert-butyllithium at very low temperatures.
Scheme 34. Synthesis of (1aS,9bR)-1a,9b-Dihydro-1-(nonan-5-ylidene)-1H-cyclopropa[1]phenanthrene (41)

Photolysis of 41 at 254 nm and rearrangement of the resulting substituted vinylidene carbene via a [1,2]-alkyl shift should yield 5-decyne (42) as shown in Scheme 35. Preliminary photochemical experiments showed formation of phenanthrene but we were unable to characterize 42 as a product. Further purification and characterization of the product mixture is needed.
Scheme 35. Photolysis of 1a,9b-Dihydro-1-(nonan-5-ylidene)-1H-cyclopropa[l]phenanthrene (41)

Conclusions

The chemistry of benzylchlorocarbene was investigated through both theory and experiment. Photolysis of a phenanthrene-based precursor in an NMR tube gave evidence for isomeric β-chlorostyrenes but not the α-isomer. Computations showed that insertion into the aromatic ring should have a barrier smaller than that for 1,2-hydrogen migration. This is not observed experimentally, perhaps because hydrogen migration proceeds through tunneling.

Attempts were made to confirm the structure of a novel “ene” product that appears to result from addition of photogenerated cyclopentyno to cyclohexene. Several attempts at independent synthesis failed. COSY spectra supported the putative structure but more work needs to be done here. DFT calculations explored the energetics of these
reactions and showed that Gilbert’s bis-carbene mechanism is an unlikely route to the ene product.

The dichlorocarbene adduct to pyrene was prepared and showed to undergo fragmentation. This may be a useful substrate for future LFP studies.

A variety of photochemical vinylidene precursors were prepared based on the phenanthrene and pyrene frameworks. More work is needed to established the photochemistry of these substances.

We have shown through experimentation that phenanthrene, as well as pyrene, is an excellent “solid support” for building carbene precursors. Photolysis of these carbene precursors also generates a carbene that is free from excited nitrogen complexes.
CHAPTER 2

SYNTHESIS AND USE OF A NOVEL CATALYST FOR POLYURETHANE FORMATION AND ATTEMPTED MECHANISTIC DETERMINATION OF THE DABCO CATALYZED REACTION BETWEEN 1-HEXANOL AND P-TOLYLISOCYANATE

Introduction

Tertiary amines have long been used in the catalysis of polyurethane formation. It has been found that the less hindered the amine, the greater the catalytic ability. 1,4-Diaza[2.2.2]bicyclooctane, DABCO, is a very good catalyst because the nitrogen lone electron pair is very unhindered. There is also a catalytic trend that follows the basicity of tertiary amines: the stronger the base, the greater the catalytic ability. DABCO has greater catalytic ability than its basicity would predict. How these nitrogen bases catalyze the reaction, and even the order of the reaction, has been a subject of great debate. In 1947, Baker and Holdsworth proposed that the amine catalyzes the reaction through complexation with the electrophilic carbon in the isocyanate moiety as shown in Scheme 36. This would presumably result in a second order rate expression.

\[
\begin{align*}
\text{ArNCO} + \text{Base} & \xrightarrow{k_1} \text{Complex} \\
\text{Complex} + \text{MeOH} & \xrightarrow{k_3} \text{ArNHCO}_2\text{Me} + \text{Base}
\end{align*}
\]

Scheme 36. Mechanism of Reaction for Base Catalyzed Isocyanate Formation as Proposed by Baker and Holdsworth

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Pestemer and Lauerer\textsuperscript{96} reported a study using infrared-spectroscopy to detect this complex between the tertiary amine and the isocyanate. The study involved comparing spectra of phenylisocyanate in paraffin oil, triethylamine in paraffin oil and a mixture of the two in paraffin oil. In the mixture, they observed new bands in the region between 1500\,cm\textsuperscript{-1} and 1800\,cm\textsuperscript{-1} as well as the disappearance of bands that were present in the single component spectra. They attributed these changes to the formation of the complex. Contrary to Baker and Holdsworth's proposal, Farkas and Strohm\textsuperscript{97} put forth the idea that the amine interacts with the alcohol through hydrogen bonding as shown in Scheme 37. The resulting complex then reacts with the isocyanate.

\[
\text{ROH} + \text{Base} \quad \xrightarrow{k_1} \quad \text{Complex} \quad \xrightarrow{k_2} \quad \text{Complex} + \text{ArNCO} \quad \xrightarrow{k_3} \quad \text{ArNHCO}_2\text{R} + \text{Base}
\]

Scheme 37. Mechanism of Reaction for Base Catalyzed Isocyanate Formation as Proposed By Farkas and Strohm

They also attempted to repeat Pestemer and Lauerer's work and found that, in the complete absence of water, no new infrared bands are observed. Baker and Holdworth's rate expression can be modified by the use of the hydrogen bonded complex as a replacement for the amine-isocyanate complex in Baker's scheme. Entelis and Nesterov also concur with the hydrogen-bonded complex model.\textsuperscript{98} The major driving force for this mechanistic rationalization is that the amine-alcohol "complex" can be seen spectroscopically (IR and NMR) and the amine-isocyanate complex cannot.\textsuperscript{90} Sacher\textsuperscript{99} states that simply changing how the complex is formed does not keep the same rate
expression. Rather than having the concentration of alcohol playing a role in \( k_{obs} \), as given in Baker's rate expression, the concentration of the isocyanate plays that role. He also points out that neither Farkas nor Entelis tested this experimentally. Sacher raises other interesting points in the discussion of the reaction of isocyanates with alcohols, catalyzed and uncatalyzed. Using Hammett \( \sigma - \rho \) plots for substituted aryl isocyanates, large \( \rho \) values were found (>1.5) which suggests that substituents that are electron-withdrawing enhance the rate of reaction. This also implies that the electrophilic carbon of the isocyanate moiety plays a role in the rate-determining step. Another point made is that all of the solvents used in these kinetic experiments have low dielectric constants that promote complex formation either between the alcohol and the amine or the alcohol and the isocyanate. The choice of solvent can also affect the reaction order and control nucleophilicity by itself complexing with the amine base. Bacaloglu, *et al.*, have looked at the linear relationship between the second order rate constants and tertiary amine concentration. They conclude that the tertiary amine has a nucleophilic role, with attack at the electrophilic carbon atom in the isocyanate. A kinetic deutero-isotope experiment was also performed with phenylisocyanate and deuterated methanol. A primary isotope effect was observed which indicates that a proton transfer is occurring during the rate-determining step. They put these observations together to propose the transition state shown in Figure 16.
Figure 16. Transition State Proposed by Bacaloglu, Cotarcă, Marcu and Tőrgyi

In this study, a low influence of solvent polarity was observed. These researchers believe that this is an indication of a small difference in solvation between reactants and transition state. Sacher also points out that the mechanism of urethane formation has not been determined with certainty. Much of the kinetic work to date has only measured the decrease in concentration of isocyanate over time, which is considered a measure of integral properties and, depending on the method of measurement, may not be an in situ method. Often, if direct chemical sampling is used as the method of measurement of concentration, the integrity of the sample may be compromised by exposure to the atmosphere. This may not always give an accurate account of what is occurring within the reaction mixture.

In the present work, we have used reaction calorimetry to study the mechanism of catalyzed polyurethane formation. Reaction calorimetry, a direct measurement of differential properties, may provide a more accurate determination of the kinetics of this reaction. Reaction calorimeters measure the heat flow transferred into or out of the reactor, while keeping a user-controlled temperature profile. When the temperature profile is isothermal, the measure of heat flow rate is “directly proportional to a summation of the rate of each reaction step, as weighted by heat of reaction $\Delta H_i$ of the
corresponding step” as shown in Equation 1.\(^{101}\) The heat flow rate, which is measured in Joules per second, is equal to the power output of the reaction calorimeter. By knowing the power output of the reactor, the volume of the contents in the reactor and the overall heat of reaction, the overall reaction rate can be calculated.

\[
q_r = V_r \sum_i \Delta H_i \frac{dC_i}{dt}
\]

\(q_r\) = Heat flow rate (J/s)  \(\Delta H_i\) = Heat of reaction for the \(i\)th step (J/mol)  \(V_r\) = Volume of contents in reactor (L)  \(dC_i/dt\) = Reaction rate (mol/Ls)

**Equation 1. Measure of Heat Flow Rate**

Blackmond has been successful in using reaction calorimetry in optimizing efficiency of asymmetric catalysis for a variety of reactions.\(^{101-106}\) One disadvantage of reaction calorimetry is that no information is provided on the identity of the chemical species within the reaction mixture, something that can only be obtained through direct chemical sampling. However, the advantages of obtaining “real-time” data may outweigh this disadvantage.

Our goal for this research was to develop a new catalyst that would increase the rate of polymer formation. Knowledge of the mechanism of tertiary amine catalysis is essential to this task.

**Results and Discussion**

**Catalyst Development**

In order to include both the functionality of the alcohol and the tertiary amine catalyst, dendrimeric aminoalcohols were investigated as possible target compounds.
Ideally, only one catalytic center is required for many reactive hydroxyl groups. The initial compounds considered were 3-[bis-(3-hydroxypropyl)-amino]-propan-1-ol (44) and 3-[4-(3-hydroxypropyl)-piperazin-1-yl]-propan-1-ol (45). Aminoalcohol 44 was synthesized by the method of Franczyk et al.\textsuperscript{107} A mixture of 3-amino-1-propanol, 3-chloro-1-propanol and sodium carbonate in absolute ethanol was heated to reflux for 24 hours (Scheme 38). The reaction mixture was cooled and chloroform was added. This mixture was filtered and concentrated. The product of reaction of these two liquids reported in the literature should be a viscous liquid however the product collected here was a white solid. NMR spectroscopy indicated that the product had formed but there was significant starting material and solvent still present. Structure 45 was synthesized using a modification of the method used to synthesize 44. A mixture of 3-chloro-1-propanol, piperazine and sodium carbonate in absolute ethanol was heated to reflux for 24 hours (Scheme 39). The reaction mixture was cooled and chloroform was added. This mixture was filtered and concentrated. NMR spectroscopy indicated that the product, a white solid, had formed with minor impurities. This agrees with literature.\textsuperscript{108,109}

\begin{equation}
\text{HO-} - \text{NH}_2 + \text{HO-} - \text{Cl} \xrightarrow{\text{Na}_2\text{CO}_3} \text{EtOH (dry)} \xrightarrow{\text{reflux}} \text{EtOH (dry)} \xrightarrow{24 \text{ h}} \text{HO-} - \text{N} \text{C} \text{H}_2 \text{OH} \ 
scheme{38. Synthesis of 3-[Bis-(3-hydroxypropyl)-amino]-propan-1-ol (44)}
\end{equation}

\begin{equation}
\text{NH} - \text{N} + \text{HO-} - \text{Cl} \xrightarrow{\text{Na}_2\text{CO}_3} \text{EtOH (dry)} \xrightarrow{\text{reflux}} \text{EtOH (dry)} \xrightarrow{24 \text{ h}} \text{HO-} - \text{N} \text{C} \text{H}_2 \text{OH} \ 
scheme{39. Synthesis of 3-[4-(3-Hydroxypropyl)-piperazin-1-yl]-propan-1-ol (45)}
\end{equation}
Following the same theme, we chose a structure which had one catalytic center for each hydroxyl group. A synthetic scheme was identified from the literature and carried out. Paraformaldehyde was added slowly to a mixture of propanolamine and absolute ethanol (Scheme 40). After stirring overnight, the product, 3-[3,5-bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46), was isolated as a viscous liquid. This was formed in quantitative yield and did not solidify upon cooling. These results agreed with the literature. A polymer foam was formed by mixing 3.7 mmol of 46 with 5.2 mmol of 2,4-tolylenediisocyanate (TDI) and 1% water. After 14 seconds, a hard polymer formed nearly instantly, accompanied by a puff of steam. The approximate expansion of the foam was 4X - 5X and the foam had a slight amine odor. This foam proved to be very brittle and unhomogeneous so a surfactant was added to determine if this might decrease cell size. The rate of reaction appeared to increase and the foam was more evenly formed but still quite brittle.

Scheme 40. Synthesis of 3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46)

Flushed with success, we set out to synthesize a series of analogues to determine if any of them might increase the flexibility of the resulting urethane polymer than polymer foams formed using 46 as the alcohol precursor. By using aminoalcohols of varying carbon-chain lengths and the same synthetic methodology as in the formation of
we were able to complete the synthesis of four additional compounds with the identical central core to 46. These were identified as 2-[3,5-bis-(2-hydroxy-ethyl)-[1,3,5]triazinan-1-yl]-ethan-1-ol (47), 4-[3,5-bis-(3-hydroxy-butyl)-[1,3,5]triazinan-1-yl]-butan-1-ol (48), 5-[3,5-bis-(3-hydroxy-pentyl)-[1,3,5]triazinan-1-yl]-pentan-1-ol (49), and 6-[3,5-bis-(3-hydroxy-hexyl)-[1,3,5]triazinan-1-yl]-hexan-1-ol (50) (Figure 17). With the exception of 47, these compounds were not known in the literature. The NMR spectra for these viscous liquids were all very similar. The only difference between them was the number of methylene units in the branching chain off the triazinane ring system. Polymer foams were made in the same fashion as described above with 47 and 49 as a comparison to 46. Triol 47 is known and has been used commercially in catalytic amounts during the production of polyurethane foams, in addition to applications as an antimicrobial. Both of the new compounds compared favorably with 46 in foam formation. The polymer formed from 49 and TDI was slightly more flexible than the polymer foam from 46 and TDI. All of these polymers were formed so rapidly that the polymer walls collapsed before curing was complete. To minimize polymer cell wall collapse, and to possibly prevent the water from escaping as steam, compounds 46 and 47 were polymerized with TDI in the presence of two separate surfactants, DABCO DC193 and DABCO LK-443. Although the name suggests that 1,4-Diazabicyclo[2.2.2]octane (DABCO) might be present in these surfactants, the formulations were proprietary and therefore were unknown to us. After polymerization, surfactant DABCO DC-193 appeared to be the better surfactant of the two and maintained polymer cell wall integrity.
Additional compounds were designed to increase the elasticity of the resulting polyurethane foam. The previous set of compounds (46 – 50) was thought to be possibly too brittle due to the short carbon chains and central ring structure. Having a longer carbon chain connecting two of the ring systems was discussed and the synthesis put into action. Paraformaldehyde was added to a mixture of propanolamine, 1,6-diaminohexane and ethanol (Scheme 41).
Scheme 41. Attempted Synthesis of Bis-analogue of 46

The desired product, 51, was not the major product of this reaction. The NMR spectrum of the product mixture was very complicated and inconclusive as to the number of products formed. The major product was 46 based on the correlation of the $^{13}$C-NMR resonances with pure 46. The synthesis of a difunctional analogue to 46 (52) was also attempted (Scheme 42). Again, the major product in the complex mixture was 46 based on the $^{13}$C-NMR spectrum. Separation of these mixtures has not been attempted. Reaction of these mixtures with a monofunctional isocyanate may prove to be the only way to separate the components within. By using an isocyanate with a benzene ring, separation methods that utilize ultraviolet detection may be adequate to perform the separation by chromatographic means.

Scheme 42. Attempted Synthesis of a Difunctional analogue of 46
Chemical stability tests were performed on 46 to determine if the ring structure would revert back to starting components. Mechanistically this is possible if water is present since water molecules are generated in the process of ring forming. Thermogravimetric analysis (TGA) showed that triol 46 begins to lose mass at 90 °C and was completely vaporized at 150 °C. Variable temperature NMR studies were performed at temperatures between 60°C and 100°C to determine what was actually happening. Triol 46 was not reverting back to starting materials but to a compound that incorporates the oxygen and nitrogen into a single ring. Linde and coworkers reported that 46 will convert to [1,3]oxazinane (53) upon heating to 125 °C at atmospheric pressure.\textsuperscript{111} [1,3]Oxazinane, upon sitting at room temperature for several weeks, will convert to 46 (Figure 18). This interconversion is problematic for long-term storage of this component. [1,3]Oxazinane is not polyfunctional and makes an undesired component for polyurethane formation.

Figure 18. Equilibrium between 1,3-Oxazinane (53) and triol 46

Due to this unforeseen chemical stability issue a different analogue was required. Compound 49 did not suffer from the same chemical stability issues as 46 did, but the initial starting aminoalcohol was slightly more expensive. Another compound was proposed and the cost for the aminoalcohol precursor was comparable to the
aminoalcohol used to synthesize 46 and is readily available. 2-({2-[3,5-bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl]-ethoxy})-ethanol (54) was synthesized through the addition of paraformaldehyde to a mixture of 2-(aminoethoxy)-ethanol and ethanol (Scheme 43) and proved to be the best component as yet synthesized.

Scheme 43. Synthesis of 2-({2-[3,5-bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl]-ethoxy})-ethanol (54)

Thermogravimetric analysis showed that 54 began to lose mass at 168°C. Thus, there is much greater stability than 46. The polymer foams that were formed from this compound and TDI were superior to those formed from TDI and 46. With and without the presence of a surfactant, they expanded to a greater extent and were slightly more flexible. Polymers were also formed from 54 and poly-4,4'-methylenebis(phenylisocyanate) (pMDI) (55). These foams were found to expand the greatest of all the polymers tested.

Figure 19. poly-4,4'-Methylenebis(phenylisocyanate) (pMDI) (55)
The reaction conditions were also modified because the original solvent system, ethanol, was very difficult to remove from the final product, especially on a large scale. Changing the solvent to tetrahydrofuran proved to be quite effective and the yields were unchanged. The exothermicity of the reaction may cause problems with bulk scale if the reactor is not cooled due to the lower boiling point of the aprotic solvent used.

One problem that was discovered in the wake of completely removing the solvent from 54 was the apparent release of formaldehyde gas upon polymerization. Researchers in our collaborator’s laboratory used the ethanol-free 54 in a larger scale reaction and were driven from the laboratory due to a burning sensation in their eyes, nose and throat. Because water is used as the blowing agent and because polymerization results in high temperatures of reaction, 54 is believed to partially revert back to starting materials and exude small amounts of formaldehyde gas. This poses an undesirable hazard. Either another blowing agent needs to be used or the temperature of reaction needs to be better controlled.

Attempts were made to synthesize an aromatic analogue of 46. Having additional bonding in the ring core will prevent thermal degradation or chemical instability. The synthesis of 3-[4,6-bis-(3-hydroxy-propyl)-[1,3,5]triazin-2-yl]-propan-1-ol (56), was attempted by two methods. The first method (Scheme 42) was through addition of a Grignard reagent to cyanuryl chloride (57). There is literature precedent for Grignard addition to cyanuryl chloride.\textsuperscript{112} The hydroxyl group was first protected. \textit{tert}-Butyldimethylsilylchloride (TBDMSCl) was added to a mixture of imidazole and 3-chloropropanol in tetrahydrofuran. The reaction was judged complete upon inspection of the $^1$H-NMR spectrum, which showed that the alcoholic proton was no longer present.
The Grignard reagent was made by adding the silyl ether to a mixture of magnesium metal in dry ether. After the Grignard reagent was judged to be formed by apparent decrease in magnesium, cyanuryl chloride, dissolved in ether, was added slowly (Scheme 44). After an aqueous work-up, it was determined that the Grignard never formed. The $^1$H-NMR spectrum was identical to that of the silyl ether starting material. Since chlorides are known to be slower to form Grignard reagents, activated magnesium was used. Gilman has written a number of treatises on the preparation of activated magnesium for Grignard reagents. Iodine was added to magnesium in dry benzene and stirred until the color disappeared. The mixture was distilled to dryness and allowed to cool. The residue was then used as magnesium would be used in the preparation of the Grignard reagent. Unfortunately, as with the previous synthesis, the Grignard reagent never formed and the silyl ether was recovered.

Scheme 44. Attempted Synthesis of 3-[4,6-Bis-(3-hydroxy-propyl)-[1,3,5]triazin-2-yl]-propan-1-ol (56)
Another method was attempted that involved the hydrochlorides of cyclic iminoethers.\textsuperscript{116} 4-Hydroxybutyronitrile was prepared (Scheme 43) following the method of Bliche and Brown.\textsuperscript{117} An aqueous solution of potassium cyanide was added to an ethanolic solution of 3-bromo-1-propanol. The reaction mixture was then refluxed and then stirred at room temperature. After distillation, a solution of dry hydrogen chloride in ether was added. The yellow-white crystals that formed, the hydrochloride salt of 2-iminotetrahydrofuran (58), were collected and then subjected to triethylamine in tetrahydrofuran (Scheme 45). After filtration, the recovered product was a white solid. The desired product is reported to be a viscous liquid with a boiling point of 196-198°C at 0.1 mmHg.\textsuperscript{116} \textsuperscript{1}H- and \textsuperscript{13}C-NMR spectroscopic data were inconclusive and supported the presence of a mixture. Work was not continued on this aspect of the project due to time constraints.

\[ \text{HO} - CH_2CH_2 - CH_2CH_2 - Br \xrightarrow{\text{KCN}_{(aq)}, \text{ethanol}} \xrightarrow{\text{reflux 8 h}} \text{HO} - CH_2CH_2 - CH_2CH_2 - CN \xrightarrow{\text{HCl in ether}} \xrightarrow{\text{2 d}} \text{HO} - CH_2CH_2 - CH_2CH_2 - CN + \text{HCl} \]

\[ \xrightarrow{\text{Et}_3\text{N, THF}} \xrightarrow{\text{several days}} \]

\[ \text{HO} \quad \text{N} \quad \text{N} \quad \text{N} \quad \text{N} \quad \text{HO} \quad \text{OH} \]

\[ \text{HO} \quad \text{N} \quad \text{N} \quad \text{N} \quad \text{N} \quad \text{HO} \quad \text{OH} \]

\[ \text{Scheme 45. Second Attempted Synthesis of 3-[4,6-Bis-(3-hydroxy-propyl)-[1,3,5]triazin-2-yl]-propan-1-ol (56)} \]

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One compound that may have potential use as a nucleophile and catalyst is 1,3,5-trihexyl-[1,3,5]triazinane (59). This compound has been previously synthesized similar in manner as described below and has also been patented for use as a bactericide and fungicide. This compound was formed by adding paraformaldehyde to a mixture of hexylamine in ethanol (Scheme 46).

The structure of 59 is of interest. Computational studies, using density functional theory (pBP/DN*), were performed to determine the preferred conformation of 59. If all three lone pair electrons on the nitrogens in the ring occupy an axial position on the triazinane ring, it may act as a "catcher's mitt" (Figure 22). At this level of theory, the structure with two of the electron pairs axial and one pair equatorial (Figure 21) proved to be lower in energy than the structure with all electron pairs axial by 6.3 kcal/mol. These results correlate with calculations performed by Bushweller's group on othertrialkylated triazinanes. It has not yet been determined if placing an electrophilic or acidic compound near the lone pair electrons will alter these energetics.

Scheme 46. Synthesis of 1,3,5-Trihexyl-[1,3,5]triazinane (59)
Figure 20. 1,3,5-Trihexyl-[1,3,5]triazinane (59) with two hexyl groups in equatorial positions and one hexyl group in axial position.

Figure 21. 1,3,5-Trihexyl-[1,3,5]triazinane (59) with hexyl groups in all equatorial positions.
Mechanistic Studies

Computational studies were first performed to determine the energetic feasibility of a DABCO-isocyanate complex. Three isocyanates were chosen based on their electronic properties. Adamantylisocyanate (60) was used to mimic a standard hydrocarbon isocyanate. p-Tolylisocyanate (61) was used to mimic the commonly used difunctional tolylenediisocyanate. 4-Nitrophenylisocyanate (62) was used to see if having a strong electron-withdrawing group on the aromatic ring would favorably affect the complexation. 1,4-Diazabicyclo[2.2.2]octane (DABCO) (63) was chosen because it is a commercially used catalyst in polyurethane production.

![Figure 22. Adamantylisocyanate (60), p-Tolylisocyanate (61), 4-Nitrophenylisocyanate (62) and 1,4-Diazabicyclo[2.2.2]octane (DABCO) (63)](image)

Each isocyanate structure was built within the program (Spartan 02, Wavefunction) with the DABCO complexed to the carbon atom of the isocyanate moiety. The computations were run at a Møller-Plesset level of theory (MP2/6-31G*) to determine the energetics of each complex. Figures 23-25 show the minimized structure with the change in electrostatic charge for the atoms that are participating in the complexation. The computational analysis showed that all of the complexes were energetically favored over the uncomplexed components. The adamantylisocyanate-
DABCO complex was 1.4 kcal lower in energy than the starting components. The p-tolylisocyanate-DABCO complex was 6.1 kcal lower in energy than the starting components. The 4-nitrophenylisocyanate-DABCO complex was 10.9 kcal lower in energy than the starting components. The more electron-withdrawing the substituent on the isocyanate moiety, the more favored the complex. The 4-nitrophenylisocyanate complex is favored over the p-tolylisocyanate complex, which is favored over the adamantylisocyanate complex. The bond lengths also support complexation because the double bonds in the isocyanate moieties increased.

![Adamantylisocyanate and DABCO Complex with Changes in Electrostatic Charge and Complex Bond Length](image)

Figure 23. Adamantylisocyanate and DABCO Complex with Changes in Electrostatic Charge and Complex Bond Length

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NMR spectroscopy was next used to explore the existence of the same isocyanate/DABCO complex. Complexation should result in changes in the NMR spectrum. For example, when DABCO is complexed with the isocyanate, the nitrogen participating in the complexation would now bear a positive charge and the hydrogens
attached to the carbons adjacent to this nitrogen should display a downfield shift toward 10 ppm on the $\delta$ scale in the spectrum due to the deshielding effect of the positive charge on the adjacent nitrogen atom.

DABCO and each isocyanate were separately dissolved into CDCl$_3$ for NMR analysis. The $^1$H-NMR spectrum was acquired for each sample. To each of the isocyanate NMR samples, solid DABCO was added and mixed thoroughly. The $^1$H-NMR spectrum for each mixture was then compared to the reference spectrum for DABCO and the isocyanate in question. There were no visible shifts in resonances for any of the mixtures. The proton spectrum for each mixture appeared to be just a mixture of two compounds and no evidence for complexation was observed. It is possible that there is a very low concentration of complex that is not visible on the NMR spectroscopy timescale.

A reaction calorimeter enables us to determine the kinetics of a reaction by monitoring heat transfer from the reaction vessel to the bath. The acquisition of data is in real time and, in most cases, is more accurate than other methods used to determine reaction kinetics (NMR, IR, UV-VIS). The reaction calorimeter allows for the ability to directly acquire the change in concentration of product versus time rather than calculating it from the concentration of product sampled at various time intervals. A Chemisens CPA200 calorimeter was used in the present study. This instrument has the capability of collecting data on the heat output which is measured through a sensor that is sandwiched between the interior of the reaction vessel and a Peltier element. This thermocouple has one side facing the heat flow sensor and the other side facing the thermostatted exterior of the reaction vessel. By collecting and modeling this data we should be able to determine which kinetic model predominates for our reaction.
Our rationale for this study was that we should be able to determine which species, isocyanate or alcohol, associates with the tertiary amine. By varying the molar ratios of the two reactants while maintaining a constant molar amount of catalyst, we should be able to determine which mechanism is operative in these reactions. If the mechanism is preassociation of alcohol with DABCO, then the rate should increase as the concentration of alcohol increases since the concentration of alcohol is part of that rate law (Figure 17). If the rate limiting step is preassociation of isocyanate with DABCO, the rate should increase as the concentration of isocyanate increases since the concentration of isocyanate is part of that rate law (Scheme 36).

The reagents used in this reaction were anhydrous 1-hexanol, p-tolylisocyanate, and DABCO. DABCO and dry tetrahydrofuran were placed in the reactor which was sealed to prevent any contamination from the circulating water bath. After the reactor was assembled and all of the data gathering probes were connected, the reactor and circulating bath were allowed to equilibrate to 25°C. After 30 minutes, 1-hexanol and p-tolylisocyanate were injected through a septum. After one hour, the reaction was stopped by removing the data acquisition probes and the reactor was emptied, rinsed with dry tetrahydrofuran and recharged with another sample of DABCO and fresh, dry tetrahydrofuran. These steps were repeated using the molar ratios shown in Table 1. Total power data from each experiment were downloaded from the instrument interface to an Excel spreadsheet.
<table>
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<th>Experiment</th>
<th>Reagent</th>
<th>Molar Ratio</th>
</tr>
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<td></td>
<td>1-Hexanol</td>
<td>$p$-Tolylisocyanate</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
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</tr>
<tr>
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</tr>
<tr>
<td>6</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1. Molar ratios of reagents used in reaction calorimetry study.

In order to process the acquired data, two model rate laws were needed. The first model rate law that was used was based on Baker and Holdsworth’s model, the equilibrium of an isocyanate and a catalyst with an activated complex and this activated complex reacting with an alcohol to form a urethane (Scheme 47). The steady-state approximation can be used to simplify our rate law (Equation 2) because as soon as a molecule of activated complex is formed, it will react immediately with the alcohol resulting in zero concentration of the activated complex in the reaction mixture.

$$R—\text{NCO} + \text{Catalyst} \xrightleftharpoons[k_c]{} k_c^{-1} R—\text{NCO}^+$$

$$R—\text{NCO}^+ + R'—\text{OH} \xrightarrow{k_{oc}} R—\text{NCO}^+ + R'—\text{OH}$$

Scheme 47. Isocyanate Activated Model Reaction for Urethane Formation

$$\frac{d[\text{Urethane}]}{dt} = \frac{k_c [\text{catalyst}] [R—\text{NCO}]}{1 + \frac{k_c}{k_{oc} [R'—\text{OH}]}}$$

Equation 2. Isocyanate Activated Model Rate Law for Urethane Formation

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The second model rate law that was used was based on Farkas and Strohm’s model, the equilibrium of an alcohol and a catalyst with an activated complex and this activated complex reacting with an isocyanate to form a urethane (Scheme 48). Again, the steady-state approximation can be used to simplify the rate law (Equation 3).

\[
\begin{align*}
R'\text{--OH} + \text{Catalyst} & \xrightleftharpoons[k_{-c}']{k_c'} R'\text{--OH}^+ \\
R'\text{--OH}^+ + R\text{--NCO} & \rightarrow R'\text{--NCO} \\
\end{align*}
\]

Scheme 48. Alcohol Activated Model Reaction for Urethane Formation

\[
\frac{d[\text{Urethane}]}{dt} = \frac{k_c' \text{[catalyst]} [R'\text{--OH}]}{1 + \frac{k_{oc}'}{k_{oc'} [R\text{--NCO}]}}
\]

Equation 3. Alcohol Activated Model Rate Law for Urethane Formation

For each experiment, the power was sampled from the calorimeter at two second time intervals. These power data were then used to determine the heat of reaction at each time interval. By integrating these data, the overall heat of reaction, as well as the reaction conversion, was determined. From the power and the heat of reaction, the change in product over time (\(d[\text{Urethane}] / dt\)) was determined for each time interval.

The experimental rate (\(d[\text{Urethane}] / dt\)) versus conversion was plotted between 30% and 90% conversion. This allowed for any error associated with the calorimeter not keeping up with the heat of mixing due to the methodology of the sample input. The model rate laws for both the isocyanate activated reaction and the alcohol activated reaction were then plotted against the experimental values for reaction conversion, and minimized rate constants were calculated using the least square sum method based on a
best-fit to the experimental reaction rate. Table 2 shows the individual rate constants calculated for the two model rate laws as well as the averaged values for these rate constants. Review of this data shows that neither of the model rate laws fit any of the experiments using a 1:1:0.5 ratio of alcohol:isocyanate:catalyst. There is also no consistency as to the areas of the experimental data where the model rate laws overlap for these three experiments. The reason for this is still unclear. The rate constants $k_c$ and $k_c/k_{oc}$, for the activated isocyanate model, were averaged over all the experiments and placed back into the model rate law. This process was repeated for the activated alcohol model with the rate constants $k_c'$ and $k_c'/k_{oc}'$. The error associated for each of these average rate constants was then assessed to determine, for each experiment, which model rate law had the lowest error, or the closest fit to the experimental data. Table 3 shows the error values for these models when the averaged rate constants were used.

By looking at the error values after applying the average rate constants to the respective model rate laws, the activated alcohol model rate law seems to have a smaller overall error. Twelve out of the eighteen experiments show the alcohol model rate law having the smaller value. Out of these twelve, eight of these values appear to be significantly lower to support the hypothesis that the activated alcohol model rate law is the predominant model for this solvent system at this given temperature. It is possible that both mechanisms coexist under these conditions. The solvent chosen will also activate both the alcohol and the isocyanate due to the presence of oxygen lone electron pairs. Ideally, this experiment should be retested in a solvent that will not participate in the rate as well as changes to the methodology of reagent introduction.
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<th>Experiment Log Number</th>
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<th>Activated Alcohol</th>
</tr>
</thead>
<tbody>
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<td>$k_c/k_{oc}$ (L/mol) $(10^3)$</td>
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<td>106</td>
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<td>0632B</td>
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<td>0632C</td>
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<td>0632D</td>
<td>1.71</td>
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Table 2. Rate Constants for Activated Isocyanate and Activated Alcohol Model Rate Laws

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<table>
<thead>
<tr>
<th>Experiment Log Number</th>
<th>Activated Isocyanate Error ($10^{12}$)</th>
<th>Activated Alcohol Error ($10^{12}$)</th>
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</table>

Table 3. Experimental Error Determined from Using Average Rate Constants. Shaded areas indicate lower error.
Conclusions

Our goals in this project were to develop a new catalyst that would increase the rate of polymer formation and to develop a more complete understanding of the mechanism of tertiary amine catalysis. Triol 46 was the first compound investigated and tested to determine its catalytic ability. Thermogravimetric analysis determined that this compound would not remain stable under the high reaction temperatures. Triol 54 was then investigated and was found to have much better thermal stability. The cost and availability of the aminoalcohol precursor to 54 was comparable to the aminoalcohol precursor of 46. Both of these triols were successfully polymerized with difunctional isocyanates, \( p \)-tolyldiisocyanate (TDI) and poly-4,4' -methylenebis(phenylisocyanate) (pMDI). Synthesis of an aromatic analog to 46 was attempted to prevent the thermal degradation seen in triol 46. Intermediates to triol 56 were formed but the desired product was never isolated.

In the computational and NMR studies of the DABCO-isocyanate complex, it was concluded that the equilibrium concentration of this complex was too low to measure.

Although much has been learned, there are still many unanswered questions. The chemical stability of triol 54 and its integration into a working model for rigid foam formation should be studied further. The mixtures of the difunctional ring systems as well as the multi-ring compounds will require adequate separation before characterization can be completed. Additionally, alternate means of synthesis should be explored. Further computational work will also be needed to determine how the solvent affects the reactants and mechanistic pathway. Hydrogen bonding studies should be performed to determine if DABCO has a stabilizing effect on the alcohol and how that compares to the
isocyanate-DABCO complexes previously looked at. Insight has been given to a possible model rate law for determining the reaction kinetics of 1-hexanol with p-tolylisocyanate in the presence of DABCO. Preliminary results indicate that the reaction follows Farkas and Strohm's proposed mechanism and that the rate-determining step is the activation of the alcohol with the amine base. Further work is needed in this area to confirm the preliminary data as well as expanding on the system studied.
CHAPTER 3

COMPUTATIONAL STUDIES OF THE INTERCONVERSION OF AXIAL TO EQUATORIAL METHYLCYCLOHEXANE

Introduction

Interconversion of the two chair forms of cyclohexane is a classic textbook process. As shown in Scheme 48, the process proceeds through the half-chair transition state to the twist boat. A second boat transition state interconnects the twist boats. This has been well studied both computationally and spectroscopically. The two equilibrium forms of cyclohexane have been studied either through low temperature spectroscopic methods\textsuperscript{122-124} or through determination of heat of vaporization and combustion analyses\textsuperscript{125}. Computational studies on this interconversion range across all levels of theory,\textsuperscript{126-134} including very early work using molecular hand models and mathematical calculations.\textsuperscript{135}

Scheme 49. Interconversion of Cyclohexane Chair Conformers
For monosubstituted cyclohexanes, much effort has focused on accurately determining the free energy difference, or the A-value, between the axial-substituted chair form and the equatorial-substituted chair form.\textsuperscript{136-141} In the case of methylcyclohexane, the equatorial-substituted chair form is lower in energy of the two. The accepted energy difference is 1.8 kcal/mol. However, the precise pathway between these two species remains unknown. Freeman and coworkers\textsuperscript{141} have studied axial- and equatorial-substituted methylcyclohexane, focusing on the energetics of rotation of the methyl group with respect to the axial hydrogens on the cyclohexane ring. Wiberg and coworkers\textsuperscript{140} have performed spectroscopic and computational studies to determine the equilibrium constant for this system.

The goal of this present work was to determine what the lowest energy pathway is for the interconversion of axial-methylcyclohexane to equatorial-methylcyclohexane.

Results and Discussion

Computational models were constructed starting with stationary points for the ring-inversion of cyclohexane. Figure 28 shows the four cyclohexane starting points and, excluding enantiomers, the number of unique substitution points on each structure. All of the methylcyclohexane structures were constructed and the geometries of these structures optimized; in practice not all resulted in unique structures. Figures 29-32 contain line structures for all of the molecules we identified as possible structures within the pathway.
Figure 28. Analysis of Substitution Sites on Cyclohexane Stationary Points

Figure 29. Chair and Twist-Boat Minima for Methylcyclohexane
Figure 30. Boat Transition States for Methylcyclohexane

Figure 31. Equatorial Half-Chair Transition States for Methylcyclohexane

Figure 32. Axial Half-Chair Transition States for Methylcyclohexane
Once these models were constructed, they were subjected to either geometry optimization (for the minima) or transition-state geometry search (for the transition-states). These calculations were completed at the 3-21G and 6-31G* Hartree-Fock levels of theory. The MP2 calculations were attempted through geometry optimization and transition-state geometry searches, however each of the three sets of transition-state geometry searches converged to one structure. Therefore the MP2 calculations were completed by calculating single point energies and thermodynamic data of the geometry optimizations and transition-state geometries from the HF/6-31G* calculations. Tables 4 – 6 show the results of these calculations. Once these calculations were completed, the transition-state structures imaginary vibrations were inspected to determine to which minima the transition states connected. This was done by observing the vibrational movement of the structure in Spartan and looking at the first and last structure and comparing its structure to one of the minima to determine the pathway from one minimum to another. Once all the transition states had been connected to two minima, a pathway connecting 64 to 65 was constructed (Figure 33).

By our calculations, it appears that there is one low energy pathway that goes from 64 to 73 to 67 to 80 to 65. Figures 37, 38 and 39 show, respectively, the HF/3-21G, HF/6-31G* and MP2/6-31G* adjusted relative total energies for the minima and transition states and although many of the energies are very close, it shows that there is one pathway that is the lowest. At the HF/3-21G level of theory (Figure 34), the energy difference between 64 and 73 is 12.89 kcal/mol; between 73 and 67 is 6.12 kcal/mol; between 67 and 80 is 7.35 kcal/mol; and between 80 and 65 is 12.41 kcal/mol. At this level of theory, transition state 79 is 0.14 kcal/mol lower in energy than transition state
This does change the low energy pathway for this lower level of theory. At the HF 6-31G* level of theory (Figure 35), the energy difference between 64 and 73 is 12.33 kcal/mol; between 73 and 67 is 5.51 kcal/mol; between 67 and 80 is 6.49 kcal/mol; and between 80 and 65 is 11.22 kcal/mol. At the MP2/6-31G* level of theory (Figure 39), the energy difference between 64 and 73 is 12.19 kcal/mol; between 73 and 67 is 5.19 kcal/mol; between 67 and 80 is 6.08 kcal/mol; and between 80 and 65 is 10.99 kcal/mol.

Table 7 shows the difference in adjusted relative energies between HF/3-21G and HF/6-31G* levels of theory. There does not appear to be an obvious trend in the increase or decrease in energy between the two levels of theory. Structures 64 through 72, with the exception of 69, have slightly higher energies at the HF/6-31G* level of theory while structures 73 through 80, with the exception of 78, have slightly lower energies at the HF/6-31G* level of theory. These energy differences, with the exception of 76, are all under 1 kcal/mol.

Table 8 shows the difference in adjusted relative energies between HF/6-31G* and MP2/6.31G* levels of theory. There does not appear to be an obvious trend in the increase or decrease in energy between the two levels of theory. Structures 64 through 72 have slightly higher energies at the MP2/6-31G* level of theory while structures 73 through 80 have slightly lower energies at the MP2/6-31G* level of theory. The energy differences between HF/6-31G* and MP2/6-31G* are very small and may be considered insignificant.

Conclusions

We completed calculations at two Hartree-Fock levels of theory (HF/3-21G and HF/6-31G*) and at the Møller-Plesset level of theory (MP2/6-31G*). Total energies as
well as the thermodynamic data including zero-point vibrational energy were calculated through either geometry optimizations or transition-state optimizations. At the MP2 level of theory, the values calculated were obtained through single-point energy calculations of the optimized structure from the HF/6-31G* level of theory. The energies calculated from the higher Hartree-Fock level of theory are a little higher than reported data but are still within reason.

Through the Hartree-Fock and Møller-Plesset levels of theory, we have determined that there is one lowest energy pathway for the interconversion of axial-methylcyclohexane to equatorial-methylcyclohexane. Calculations were attempted at a higher level of theory (density functional theory), however this level of theory caused the individual transition states to converge into one, not allowing us to determine a lowest energy pathway at that level of theory.
<table>
<thead>
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<th>Minima</th>
<th>Energy (hartrees)</th>
<th>Adjusted Energy (hartrees)</th>
<th>Rel E (kcal/mol)</th>
<th>Adjusted Rel E (kcal/mol)</th>
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Table 4. Energies calculated using HF/3-21G level of theory
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Table 5. Energies calculated using HF/6-31G* level of theory
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Table 6. Energies calculated using MP2/6-31G* level of theory

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Figure 33. Pathway for the Interconversion of 64 to 65
Figure 34. HF/3-21G Adjusted Relative Energies for the Interconversion of 64 to 65

Relative energy values are given in kcal/mol and have been adjusted for zero point vibrational energy.
Figure 35. HF/6-31G* Adjusted Relative Energies for the Interconversion of 64 to 65
Figure 36. MP2/6-31G* Adjusted Relative Energies for the Interconversion of 64 to 65
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Table 7. Difference between Adjusted Relative Energies for HF/6-31G* and HF/3-21G
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Table 8. Difference between Adjusted Relative Energies for MP2/6-31G* and HF/6-21G*
CHAPTER 4

EXPERIMENTAL SECTION

General Experimental

Instrumentation:

$^1$H NMR Spectra were recorded on a Bruker AM-360 NMR spectrometer, a Varian Mercury NMR spectrometer, or a Varian Unity INova NMR spectrometer. All Spectra were measured in CDCl$_3$ as solvent and Me$_4$Si as internal reference unless otherwise noted. Chemical shifts ($\delta$) are reported in parts per million (ppm) relative to Me$_4$Si and coupling constants (J values) are in hertz (Hz).

$^{13}$C NMR Spectra were recorded on the same instruments described above. All Spectra were measured in CDCl$_3$ as solvent and Me$_4$Si as internal reference unless otherwise noted. Chemical shifts ($\delta$) are reported in parts per million (ppm) relative to Me$_4$Si.

Melting Points (mp) were recorded on a Mel-Temp capillary melting point apparatus and a Thomas Hoover capillary melting point apparatus and are uncorrected.

Infrared Spectra (IR) were recorded on a Nicolet MX-1 FT-IR spectrometer and a Perkin-Elmer 283 B grating spectrometer. Absorptions are reported in wavenumbers (cm$^{-1}$).

Ultraviolet Spectra (UV) were recorded on a UV/Visible, CARY-5 spectrophotometer.
Analytical Gas Chromatography (GC) was performed with a Hewlett-Packard 6890 instrument equipped with a flame ionization detector (FID), connected to a Hewlett-Packard 3395 integrator. A 25 meter crosslinked methyl silicone capillary column was used.

Molecular Modeling was performed using Spartan '02 or Gaussian '98 on a Dell Workstation (Windows 2000) or a Dell Dimension Desktop (Windows XP).

Reaction Calorimetry was performed with a ChemiSens CPA 200 calorimeter with a 0.2L reactor running in isothermal mode. Data sets were collected using the included Human Machine Interface software package and exported to MS Excel.

Photochemical Experiments:
In all photochemical experiments, quartz tubes and spectroquality solvents were used unless otherwise specified. All solutions were degassed with nitrogen prior to irradiation. The light source was a Rayonet RPR-100 reactor fitted with 254 nm or 300 nm lamps.

Solvents:
n-Pentane, n-hexane and cyclopentane used in photochemical experiments were spectroquality grade, purchased from Fisher Scientific. The following chromatographic solvents (Reagent/ACS grade) were obtained from Fisher Scientific or VWR Scientific and used without further purification: ethyl acetate, n-pentane, n-hexane, dichloromethane, and diethyl ether. The following solvents used for experimentation were freshly distilled from sodium benzophenone ketyl under a nitrogen atmosphere and used immediately: diethyl ether (Et₂O), tetrahydrofuran (THF) and n-pentane. Anhydrous dimethyl sulfoxide (DMSO), tetrahydrofuran (THF) and 1,4-dioxane were purchased from Aldrich and used without further purification. Anhydrous ethanol (EtOH) was

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purchased from Pharmaco and used without further purification. Chloroform was used as obtained from Fisher Scientific. Pyridine was distilled from potassium hydroxide and stored over 4Å sieves prior to use. The following deuterated solvents for NMR analysis were purchased from Cambridge Isotope Laboratories and stored over 4Å sieves: chloroform-d (CDCl₃), benzene-d₆ and acetonitrile-d₃.

Reagents:

All reagents purchased were of sufficient quality and used as obtained from the following companies: Sigma-Aldrich, Lancaster, Fisher (Acros), Farchan, and VWR (Alfa Asar).

Column Chromatography and Adsorbants:

Silica Gel: 60-200 mesh Fisher Scientific silica gel was used as obtained from the company. Where necessary, the silica get was doped with Sylvania 2282 green phosphor to allow observation with ultraviolet light in quarts chromatography columns.

Preparative Thin Layer Chromatography (TLC): Silica gel (1 mm) preparative TLC plates were purchased from Analtech. When necessary, these plates were oven dried for 24 h prior to use.

Florisil: 100-200 mesh Fisher Scientific was used as obtained from the company.

Thin Layer Chromatography (TLC) was performed using Whatman polyester plates coated with 250 μm layer silica gel doped with phosphor. Visualization was accomplished through the use of ultraviolet light or an iodine vapor stain.

Radial Chromatography was performed on a Chromatotron apparatus purchased from Harrison Research, under a nitrogen atmosphere (15 mL/min). The rotors (1 mm, 2 mm, and 4 mm thickness), precoated with gypsum bound silica made by Analtech, were purchased from Alltech, Fisher Scientific or VWR Scientific. Where necessary these
rotors were oven dried for 24 hours prior to use. The typical chromatography procedure was to dissolve the prepurified sample in a minimum amount of dichloromethane and then to introduce the solution onto a rotor (thickness given in following procedures) that had been completely wetted with dichloromethane. Once all the mixture had been introduced and the inlet rinsed with a minimum amount of solvent, the nitrogen flow was increased to 1500 mL/min and the rotor was completely dried for 1 to 2 hours. The nitrogen flow was then reduced to 15 mL/min and the dried mixture eluted with a solvent combination which provided the best separation of the mixture’s components. Visualization was accomplished through the use of ultraviolet light.

Experimental

Synthesis of 7,7-dichlorodibenz[a,c]bicyclo[4.1.0]heptane (1)

Following Todd’s procedure,142 phenanthrene (36.0 g, 0.202 mol), sodium hydroxide pellets (160 g, 4.0 mol), and benzyltriethylammonium chloride (0.7 g, 3 mmol) were placed into a 1000 mL, three-neck, round bottom flask equipped with a mechanical stirrer. A room-temperature water bath was placed under the apparatus. Water (160 mL) was added and the mixture was slowly stirred until all the sodium hydroxide had dissolved. Chloroform (400 mL) was then added and the mixture was allowed to stir vigorously for 3 – 4 days. At the end of this period, the brown suspension was diluted with ice water (500 mL) and neutralized with concentrated hydrochloric acid. An additional amount of chloroform (500 mL) was added and the solution was vacuum filtered through a layer of Celite in a large Büchner funnel to assist in breaking the emulsion. The resulting solution was placed into a 2 L separatory funnel and the organic layer was separated from the aqueous layer. The organic layer was then dried over

100

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sodium sulfate, filtered, and concentrated on a rotary evaporator. The resulting brown crystals were recrystallized from hexane. The mother liquor was reduced and a second crop of crystals was collected. Yellow crystals (40.7 g, 77%) were isolated. m.p. 132-133 °C 1H-NMR (360 MHz) 8.02 (dd, 2H, J = 1.2 Hz, J = 7.9 Hz), 7.49 (dd, 2H, J = 1.7 Hz, J = 7.3 Hz), 7.43-7.32 (m, 4H), 3.41 (s, 2H).

Synthesis of 7-exo-benzyl, 7-endo-chlorodibenzo [a,c] bicyclo [4.1.0] heptane (7)

Following Abbot’s procedure15, 7,7-dichlorodibenzo [a,c] bicyclo [4.1.0] heptane (1) (1.48 g, 5.67 mmol) was placed in a 100 mL, three-neck, round bottom flask equipped with a magnetic stir bar, a rubber septum, a glass stopper, and a nitrogen inlet. THF and diethyl ether (25 mL, 3:2, v:v, freshly distilled) were injected into the flask, and the flask was cooled to -78 °C (dry ice/ acetone). n-Butyllithium (6.9 mL of a 1.6 M solution in hexanes, 11 mmol) was injected drop wise into the flask. Upon injection, the solution became a dark teal-green. After 1h, benzyl bromide (2.1 mL, 18 mmol) was injected into the flask. The reaction mixture then became an orange-brown color. The reaction was kept at -78 °C for another hour then allowed to warm slowly to room temperature and continued to be stirred overnight. The reaction mixture was then quenched with brine (4 mL). The organic layer was washed with brine (2 X 4 mL) then dried over magnesium sulfate. The solution was filtered and concentrated on a rotary evaporator. The resulting solid was dissolved in dichloromethane (25 mL) and vacuum filtered through a frit of silica into a round-bottom flask. The filtrate was then placed on a silica rotor that had been previously wetted with dichloromethane. The rotor was then dried completely over and increased nitrogen flow for approximately 1.5 hours. The mixture was eluted with dichloromethane:hexane in a 1:4, v:v mixture. The resulting solid was recrystallized...
twice from hexanes yielding white crystals (0.60 g, 33%). \(^1\)H-NMR CDCl\(_3\) (360 MHz) 8.01, (d, 2H, \(J = 8.34\) Hz), 7.42-7.27 (m, 13H), 3.37 (s, 2H), 2.91 (s, 2H). \(^1\)H-NMR CD\(_3\)CN (360 MHz) 8.07 (dd, 2H, \(J = 1.8\) Hz, \(J = 7.4\) Hz), 7.45-7.30 (m, 13H), 3.35 (s, 2H), 3.11 (s, 2H).

**Photolysis of 7-exo-benzyl, 7-endo-chlorodibenzo[a,c] bicyclo[4.1.0] heptane (7)**

A sample of 7-exo-benzyl, 7-endo-chlorodibenzo[a,c] bicyclo[4.1.0] heptane (7) (5.0 mg, 0.016 mmol) was placed into a quartz NMR tube and diluted with \(d\)-chloroform. The tube was placed into a Rayonet photoreactor with a lamp wavelength of 254 nm. \(^1\)H-NMR spectra were acquired at reaction times of 45 minutes, 1.5 hours and 4.5 hours. Spectral data showed a complex mixture, however the production of phenanthrene was evident by observation of peaks at the following ppm: 8.71 (d, 2H, \(J = 8.4\) Hz), 7.90 (dd, 2H, \(J = 1.5\) Hz, \(J = 7.8\) Hz), 7.75 (s, 2H), 7.69-7.58 (m, 4H).

In a second experiment, 7-exo-benzyl, 7-endo-chlorodibenzo[a,c] bicyclo[4.1.0] heptane (7) (6.0 mg, 0.019 mmol) was placed into a quartz NMR tube and diluted with \(d\)_3-acetonitrile. The tube was placed into a Rayonet photoreactor with a lamp wavelength of 254 nm. The reaction was allowed to proceed for 1 hour before the \(^1\)H-NMR spectrum was measured. Spectral data showed a complex mixture, however the production of phenanthrene was evident by observation of peaks at the following ppm: 8.77 (d, 2H, \(J = 8.0\) Hz), 7.96 (dd, 2H, \(J = 1.6\) Hz, \(J = 7.5\) Hz), 7.81 (s, 2H), 7.72-7.62 (m, 4H).

**Attempted Synthesis of \(\beta\)-Chlorostyrene (5 and 6)**

\(\beta\)-Chlorostyrene was first attempted by addition of phenylacetaldehyde (1.30 g, 10.8 mmol), phosphorous pentachloride (2.86 g, 13.3 mmol), and benzene (50 mL, dried over calcium sulfate) were placed into a round-bottomed flask equipped with a condenser.
and heated under reflux for 1.5 hours. The reaction mixture was then cooled in an ice bath. Crushed ice (20 g) was carefully added to the reaction mixture. The layers were then separated and the organic layer was quickly washed with water (2 X 10 mL) and then immediately dried with calcium chloride. The solution was then filtered and concentrated on a rotary evaporator. The $^1$H-NMR spectrum gave no evidence for formation of either β-chlorostyrene (cis- or trans-) based on literature values.

A second approach was taken through the use of the Wittig reaction. (Chloromethyl) triphenylphosphonium chloride (164 mg, 0.471 mmol) and diethyl ether (15 mL) were added to a three-necked, round-bottom flask equipped with a stir bar, nitrogen inlet, and rubber septa and cooled to 0 °C. Phenyllithium (0.262 mL of a 1.8 M solution in hexanes, 0.471 mmol) was injected drop wise. The reaction was then allowed to come to room temperature and stir for 3 hours. The flask was again cooled to 0 °C and benzaldehyde (0.050 mL, 0.47 mmol) was injected slowly. The reaction was allowed to slowly come to room temperature and allowed to stir overnight. The reaction was quenched with water and placed into a separatory funnel. The organic layer was washed with water (3 X 10 mL). The combined aqueous layers were washed with diethyl ether. The combined organic layers were dried over magnesium sulfate, filtered, and concentrated on a rotary evaporator. As with the previous approach, the $^1$H-NMR spectrum gave no evidence for formation of either β-chlorostyrene (cis- or trans-) based on literature values.

Synthesis of α-Chlorostyrene (9)

Acetophenone (1.16 mL, 10.0 mmol), phosphorous pentachloride (2.76 g, 12.9 mmol) and benzene (50.0 mL, dried over calcium sulfate) were placed into a round-
bottomed flask equipped with a condenser and heated under reflux for 1.5 hours. The reaction mixture was then cooled in an ice bath. Crushed ice (20 g) was carefully added to the reaction mixture. The layers were then separated and the organic layer was quickly washed with water (2 X 10 mL) and then immediately dried with calcium chloride. The solution was then filtered and concentrated on a rotary evaporator. A yellow liquid (3.56 g) was recovered. ¹H-NMR showed a mixture that included acetophenone, benzene, and α-chlorostyrene. Spectral evidence for α-chlorostyrene was determined by the following peaks: 5.60 (d, J = 1.8 Hz) and 5.49 (d, J = 1.8 Hz) which correlate with literature values.¹⁴⁵

**Synthesis of 7-Cyclobutylidenedibenzo[a,c]bicyclo[4.1.0]heptane (12)**

The procedure of Hernandez¹⁹ was followed with slight modification. To a solution of 1 (1.00 g, 3.8 mmol) in dry THF (30 mL) at −78°C was added drop wise n-butyllithium (2.0 mL of a 2.5 M solution in hexane, 5.0 mmol). After 1 h of stirring at −78°C, cyclobutanone (0.5 mL, 6.7 mmol) was added drop wise and the reaction mixture was stirred at −78°C for 1 h, then gradually warmed to room temperature. Stirring was continued overnight. After 12-20 h, brine (5 mL) was injected into the flask. The organic layer was separated and washed with brine (2 X 5 mL), dried with magnesium sulfate (MgSO₄), filtered and concentrated yielding adduct 10 (1.1831 g, 4.0 mmol, 96%). Spectral data agreed with Hernandez¹⁹.

To a solution of adduct 10 (2.77 g, 9.27 mmol) in dry pyridine (30 mL) under nitrogen at room temperature was added drop wise TMSCl (3.0 mL, 23.6 mmol). After stirring for 3 h at room temperature, the reaction mixture was slowly quenched with cold water (10 mL). The organic layer was separated and the aqueous layer was extracted with
ether (2 X 20 mL). The extracts were combined, washed with 10% NaOH (20 mL), water (20 mL), brine (20 mL), dried (MgSO₄), filtered and concentrated. The excess of pyridine was removed by use of the vacuum pump to give a pale yellow solid, silyl ether adduct 11 (2.4074 g, 6.5 mmol, 70%). Spectral data agreed with Hernandez¹⁹.

A solution of silyl ether adduct 11 (500 mg, 1.3 mmol) in dry THF (10 mL) under nitrogen was cooled (hexane/liquid N₂) to −90°C. tert-Butyllithium (2 mL of a 1.7 M solution in pentane, 3 mmol) was added drop wise. After stirring for 1 h at −90°C, the reaction mixture was allowed to slowly warm to −4°C and quenched with water (2 mL). The organic layer was washed with brine (2 X 3 mL), dried (MgSO₄), filtered and concentrated. Radial chromatography (silica gel rotor, 1 mm, hexane) afforded a white solid which was then further purified by preparative TLC (silica gel, hexane) to yield 12 (144.8 mg, 0.58 mmol, 45 %) as a white solid. Spectral data agreed with Hernandez¹⁹.

Photolysis of 7-Cyclobutylidenedibenzo[a:c]bicyclo[4.1.0]heptane (12)

7-Cyclobutylidenedibenzo[a;c]bicyclo[4.1.0]heptane (12) (0.0502 g, 0.204 mmol) pentane (30 mL, distilled, degassed) and cyclohexene (20 mL, distilled) were combined in a quartz tube and sealed with a rubber septum. The solution was irradiated at 254 nm for 2 h at room temperature. The sample was cooled in the freezer overnight then concentrated on an ice bath with a rotary evaporator. The residue spectral data agreed with Hernandez.¹⁹ The residue was then purified through column chromatography using quartz column (Florisil with phosphor, 2.5 cm X 20 cm, pentane) and monitored by TLC (15 Rf= 0.76, 16 Rf= 0.69). Product 16, the desired product, was isolated in a very small quantity and the spectral data agreed with Hernandez.¹⁹

Synthesis of 1,2-dibromopentane (18)²³
Cyclopentene (32.3 mL, 0.367 mol) was placed into a round bottom flask equipped with a stir-bar and an addition funnel. The flask was placed on ice and bromine (20 mL, 0.39 mol) in methylene chloride (25 mL) was transferred slowly through the addition funnel. Upon completion of addition, the reaction stirred for an additional hour at 0°C then allowed to warm slowly to room temperature. The reaction mixture was washed with sodium bisulfite then brine. The organic layer was dried (MgSO₄), filtered and concentrated by rotary evaporation. Dibromide 18 was collected in 97% yield (81.29 g, 0.357 mol). ¹H-NMR (360 MHz) 4.56-4.53 (m, 2H), 2.66-2.55 (m, 2H), 2.15-2.07 (m, 2H), 1.99-1.91 (m, 2H).

Synthesis of 1-Bromocyclopentene (19)₅⁵

A mixture of 1,2-dibromocyclopentane (18) (81.3 g, 0.357 mol), morpholine (95.0 mL, 1.09 mol), DMSO (165 mL, 2.33 mol), and potassium hydroxide (10.0 g, 0.179 mol) in 95% ethanol (350 mL) was stirred at 85°C for 2 d. After cooling, the mixture was diluted with water (700 mL) and extracted with ether (4 X 400 mL). The combined ether extracts were washed with the following: dilute HCl (3 X 400 mL), water (700 mL), sat’d sodium bicarbonate solution (900 mL), water (700 mL) and brine (400 mL). The organic layer was dried (Na₂SO₄), filtered and carefully concentrated on a rotary evaporator. The residue was purified by reduced pressure distillation and 19 was collected in 6% yield (1.6489 g, 22.0 mmol). Spectral data agreed with literature.₅⁵

Attempted Synthesis of 3-(Cyclopentenyl)-cyclohexene (16) through copper coupling₅⁶

1-Bromocyclopentene (19) (1.65 g, 22.0 mmol) and THF (5 mL, dry) were placed in a 100-mL, 3-neck, round-bottom flask equipped with a stir bar, nitrogen inlet, septum and stopper. After the reaction mixture was cooled to -78°C for 0.5 h, tert-butyllithium
(29.0 mL, 44.0 mmol) was added slowly and the solution was stirred for 1 h at this temperature. Copper (I) iodide (2.1 g, 11 mmol) was added all at once. The reaction mixture was kept stirring until all the solid had dissolved (warming slowly to room temperature if necessary to completely dissolve the solid). 3-Bromocyclohexene (20) (2.5 mL, 22 mmol) was added drop wise and the reaction mixture was stirred at -78°C for an additional hour. The reaction mixture was warmed slowly to room temperature then quenched with brine (5 mL). The organic layer was washed with brine (2 X 5 mL), dried (Na₂SO₄), filtered and concentrated on an ice bath with rotary evaporation. Spectral data of the collected residue did not match any peaks of the proposed photolysis product (16).¹⁹

Synthesis of 1-Iodocyclopentene (23) through hydrazone 22

Cyclopentanone (10.0 mL, 0.133 mol) was added very slowly to hydrazine monohydrate (20.0 mL, 0.412 mol) with vigorous stirring. The resulting mixture was then heated on a steam bath for 1 h. The cooled solution was extracted with chloroform and the chloroform layer was washed with water, dried (anh K₂CO₃), filtered and concentrated by rotary evaporation. Hydrazone 22 was isolated in 90% yield (9.95 g, 0.101 mol) and spectral data agreed with literature.

Iodine (30.1 g, 0.199 mol) was placed in an Erlenmeyer flask and ether was added just to dissolve the solid (appr. 150 mL). This solution was added slowly to a solution of hydrazone 22 (9.95 g, 0.101 mol), ether (30 mL) and triethylamine (70 mL, 0.502 mol). The reaction was judged complete by the cessation of evolution of nitrogen and persistence of iodine color. The mixture was diluted with ether (200 mL) and washed with 5% sodium thiosulfate (150 mL), 3M HCl (150 mL), 5% sodium bicarbonate (150
mL) and brine (150 mL). The organic layer was dried (anh. K₂CO₃), filtered and concentrated by rotary evaporation. The residue was purified by vacuum distillation (0°C – 30°C, 0.04 mm Hg) followed by column chromatography (Florisil, hexane). 1-Iodocyclopentene (23) was isolated as a pink liquid in 43% yield (5.30 g, 0.027 mol). Spectral data of pure 23 agreed with literature.⁵⁷

Attempted Synthesis of 3-(Cyclopentenyl)-cyclohexene (16) through copper coupling⁵⁶

1-Iodocyclopentene (23) (0.682 g, 3.50 mmol) and THF (5 mL, dry) were placed in a 100-mL, 3-neck, round-bottom flask equipped with a stir bar, nitrogen inlet, septum and stopper. After the reaction mixture was cooled to -78°C for 0.5 h, tert-butyllithium (2.30 mL, 3.85 mmol) was added slowly and the mixture was stirred for 1 h at this temperature. Copper (I) iodide (0.173 g, 1.75 mmol) was added all at once. The reaction mixture was kept stirring until all the solid had dissolved (warming slowly to room temperature if necessary to completely dissolve the solid). 3-Bromocyclohexene (0.7 mL, 6.2 mmol) was added drop wise by syringe and the reaction mixture was stirred at -78°C for an additional hour. The reaction mixture was warmed slowly to room temperature then quenched with brine (5 mL). The organic layer was washed with brine (2 X 5 mL), dried (Na₂SO₄), filtered and concentrated on an ice bath with rotary evaporation. Spectral data of the collected residue did not match any peaks of the proposed photolysis product (16).¹⁹

Attempted Synthesis of 3-(Cyclopentenyl)-cyclohexene (16) through Heck Coupling

1-Iodocyclopentene (23) (2.01 g, 10.3 mmol), tetrakis(triphenylphosphine)-palladium(0) (0.10 g, 0.090 mol) and THF (20 mL) were added to a 50-mL round-bottomed flask equipped with a stir bar, nitrogen line and septa. Triethylamine (3.0 mL, "Reproduced with permission of the copyright owner. Further reproduction prohibited without permission."
22 mmol) was added and the solution stirred for 30 min. Cyclohexene (1.1 mL, 11 mmol) was added and the reaction stirred overnight. The reaction was quenched with brine (5 mL) and the organic layer washed with 1M HCl (10 mL) followed by brine (2 X 5 mL), dried (MgSO₄), filtered and concentrated carefully by rotary evaporation. The residue was passed through Florisil with pentane. The spectral data of the resulting yellow liquid was the spectra of a mixture of the two starting materials.

**Attempted Synthesis of 3-(Cyclopentenyl)-cyclohexene (16) through Heck Coupling (in situ generation of tetrakis(triphenylphosphine)palladium(0))**

1-Iodocyclopentene (23) (2.01 g, 10.3 mmol), palladium(II) chloride (0.0179 g, 0.101 mol), triphenylphosphate (0.105 g, 0.400 mmol) and triethylamine (5.0 mL) were added to a 100-mL round-bottomed, three-necked flask equipped with a stir bar, nitrogen line and septa. The mixture stirred for 1 h then cyclohexene (1.06 mL, 10.5 mmol) was added and the reaction stirred overnight. The reaction was quenched with brine (5 mL) then pentane (5 mL) was added. The organic layer was washed with water (4 X 5 mL) followed by brine (5 mL), dried (K₂CO₃), filtered and concentrated carefully by passing nitrogen over the liquid. The spectral data of the resulting liquid was the spectra of a mixture of the two starting materials.

**Attempted Synthesis of 3-(Cyclopentenyl)-cyclohexene (16) through Heck Coupling (in situ generation of tetrakis(triphenylphosphine)palladium(0))**

Palladium(II) chloride (18 mg, 0.10 mol), triphenylphosphine (52 mg, 0.20 mol), acetonitrile (5 mL) and triethylamine (5 mL) were added to a round-bottomed flask equipped with a stir bar, nitrogen line and condenser. The mixture stirred for 1 h then 1-iodocyclopentene (1 g, 5 mmol) and cyclohexene (1.5 mL, 15 mmol) were added and the
reaction refluxed for 40 h. The cooled reaction was quenched with brine (5 mL) then pentane (5 mL) was added. The organic layer was washed with water (4 X 5 mL) followed by brine (5 mL), dried (K₂CO₃), filtered and concentrated carefully by rotary evaporation. Spectral data of the collected residue did not match any peaks of the proposed photolysis product (16).¹⁹

**Synthesis of 7-exo-Methyl-7-endo-chlorodibenzo[a,c]bicycle[4.1.0]heptane (25)**

Following Abbot’s procedure¹⁵, 7,7-dichlorodibenzo [a,c] bicyclo [4.1.0] heptane (1) (1.5 g, 5.8 mmol) was placed in a 100 mL, three-neck, round bottom flask equipped with a magnetic stir bar, a rubber septum, a glass stopper, and a nitrogen inlet. THF and diethyl ether (25 mL, 3:2, v:v, freshly distilled) were injected into the flask, and the flask cooled to -78 °C (dry ice/ acetone). n-Butyllithium (4.4 mL of a 2.5 M solution in hexanes, 11 mmol) was injected drop wise into the flask. After 1h, methyl iodide (1.1 mL, 18 mmol) was injected into the flask. The reaction was kept at -78 °C for another hour then allowed to warm slowly to room temperature and continued to be stirred overnight. The reaction mixture was then quenched with brine (4 mL). The organic layer was washed with brine (2 X 4 mL), dried (MgSO₄), filtered and concentrated by rotary evaporation. Radial chromatography (silica gel rotor, ether:hexane (2:100, v:v)) afforded mg of a white solid which was then further purified by recrystallization from hexane to yield 25 (0.557 mg, 2.30 mmol, 40%) as a white solid. Spectral data agreed with Abbot’s.¹⁵

**Synthesis of 7-Methylenedibenzo[a,c]bicycle[4.1.0]heptane (26)**

Following Abbot’s procedure¹⁵, potassium tert-butoxide (0.533 g, 4.75 mmol) was placed into a 100 mL, three-necked round bottom flask equipped with a stir bar,
nitrogen inlet, reflux condenser, addition funnel and septum. DMSO (25 mL, dry) was injected into the flask and the mixture was warmed with a 50 - 55°C oil bath. 7-exo-Methyl-7-endo-chlorodibenzo[a,c]bicycle[4.1.0]heptane (25) (0.374 g, 1.50 mmol) was mixed with DMSO (20 mL) and placed into the addition funnel. This mixture was added, drop wise, to the flask over a period of 30 min. After this time, the mixture was allowed to cool to room temperature and continue stirring for an additional 20 minutes. The mixture was then quenched with water and washed with ether (3 X 25 mL). The combined ether layers were washed with water (3 X 10 mL), dried (MgSO₄), filtered and concentrated by rotary evaporation. Radial chromatography (silica gel rotor, ether:hexane (2:100, v:v)) afforded 0.237 g of a white solid which was then further purified through recrystallization from hexanes to yield 26 (0.158 g, 0.772 mmol, 51%) as a white solid. Spectral data agreed with Abott's.¹⁵

Synthesis of 7-exo-d₃-Methyl-7-endo-chlorodibenzo[a,c]bicycle[4.1.0]heptane (27)

Following Abbot's procedure with slight modification, 7,7-dichlorodibenzo [a,c] bicyclo [4.1.0] heptane (1) (1.05 g, 4.01 mmol) and THF (10 mL, dry) were placed in a 100 mL, three-neck, round bottom flask equipped with a magnetic stir bar, a rubber septum, a glass stopper, and a nitrogen inlet. The flask was cooled to −78 °C (dry ice/acetone). n-Butyllithium (2.0 mL of a 2.5 M solution in hexanes, 5.0 mmol) was injected drop wise into the flask. After 30 min, d₃-iodomethane (1.0 mL, 16 mmol) was injected into the flask. The reaction was kept at −78 °C for another hour then allowed to warm slowly to room temperature and continued to be stirred overnight. The reaction mixture was then quenched with brine (4 mL). The organic layer was washed with brine (2 X 4 mL), dried (MgSO₄), filtered and concentrated by rotary evaporation. Radial

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chromatography (silica gel rotor, ether:hexane (2:100, v:v)) afforded 27 (0.628 g, 1.70 mmol, 42%) as a white solid. m.p. = 118-120°C. $^1$H-NMR (360 MHz) 8.05 (d, 2H, J = 7.8Hz), 7.35 (dddd, 8H, J = 1.5 Hz, J = 7.2 Hz, J = 14.4 Hz, J = 15.9 Hz), 2.74 (s, 2H).

Synthesis of 7-d$_2$-Methylene[benzo[a,c]bicycle[4.1.0]heptane (28)

Following Abbot’s procedure$^{15}$ with slight modification, potassium tert-butoxide (1.00 g, 8.67 mmol) was placed into a 100 mL, three-necked round bottom flask equipped with a stir bar, nitrogen inlet, reflux condenser, addition funnel and septum. DMSO (25 mL, dry) was injected into the flask and the mixture was warmed with a 50 – 55°C oil bath. 7-exo-d$_3$-Methyl-7-endo-chlorodibenzo[a,c]bicycle[4.1.0]heptane (27) (0.652 g, 2.70 mmol) was mixed with DMSO (20 mL) and placed into the addition funnel. This mixture was added, drop wise, to the flask over a period of 30 min. After this time, the mixture was allowed to cool to room temperature and continue stirring for an additional 20 minutes. The mixture was then quenched with water and washed with ether (3 X 25 mL). The combined ether layers were washed with water (3 X 10 mL), dried (MgSO$_4$), filtered and concentrated by rotary evaporation. Radial chromatography (silica gel rotor, ether:hexane (2:100, v:v)) afforded 28 as a white solid. m.p. = 120-123°C. $^1$H-NMR (360 MHz) 7.99-7.94 (m, 2H), 7.41-7.36 (m, 2H), 7.29-7.24 (m, 4H), 3.14 (s, 2H).

Synthesis of 9,9-Dichloro-9H-cyclopropa[e]pyrene (30)

Following the general procedure from Todd$^{141}$, pyrene (29) (24.9 g, 0.123 mol), NaOH pellets (100 g, 2.5 mol) and benzyltriethylammonium chloride (0.025 g, 0.11 mmol) were placed into a 500 mL, three-neck, round bottom flask equipped with an overhead mechanical stirrer and ice bath. Water (100 mL) was added with moderate stirring. Upon complete dissolution of the NaOH, chloroform (250 mL) was added and
the mixture stirred rapidly for several days. The solution was neutralized with HCl (conc) until neutral to pH paper. The resulting mixture was filtered through Celite and the layers separated. The aqueous layer was washed with methylene chloride and the organic layer separated and combined with the organic layer from the filtrate. The combined organic layers were dried (Na$_2$SO$_4$), filtered and concentrated by rotary evaporation. The residue was purified by first extraction with hexane to yield a yellow-orange solid that was further purified by recrystallization from hexane followed by column chromatography (silica gel, hexanes as eluent) to yield dichloro-9H-cyclopropa[e]pyrene (30). $^1$H-NMR (360 MHz) 7.87 (dd, 2H, J=1.3Hz, J=7.8Hz), 7.77 (s, 2H), 7.73 (dd, 2H, J=1.3Hz, J=7.2Hz), 7.67-7.63 (m, 2H), 3.66 (s, 2H).

**Photolysis of Dichloro-9H-cyclopropa[e]pyrene (30)**

Dichloro-9H-cyclopropa[e]pyrene (30) (0.0100 g, 0.0350 mmol) and cyclohexane (5 mL, HPLC grade) were added to a quartz tube. The solution was irradiated at 254 nm for two hours. $R_f$ (pyrene standard) = 0.27, $R_f$ (30 standard) = 0.16, $R_f$ (pyrene exp.) = 0.25.

**Synthesis of Vinylidene cyclopropapyrene precursor 32**

Dichloro-9H-cyclopropa[e]pyrene (30) (0.500 g, 1.75 mmol) was added to a three-neck, round bottom flask equipped with a nitrogen line, stir bar, and septa. THF and diethyl ether (25 mL, 3:2, v:v) were injected into the flask and cooled to -78°C (Dry Ice/acetone bath). n-Butyllithium (1.3 mL of a 2.5 M solution in hexanes, 3.3 mmol) was injected drop wise into the flask. After 1 h, methyl iodide (0.4 mL, 5 mmol) was injected into the flask. The reaction mixture was kept at -78°C for an additional hour then warmed slowly to room temperature overnight. The reaction was quenched with brine (5 mL) and...
the layers separated. The organic layer was washed with brine (2 X 5 mL), dried 
(MgSO₄), filtered and concentrated by rotary evaporation. The pale yellow solid was 
recrystallized from hexanes to give 0.194 g (0.728 mmol) of 31 in 42% yield. m.p. = 135-
138°C. ¹H-NMR (360MHz) 7.83 (dd, 2H, J=1.9Hz, J=7.3Hz), 7.77 (s, 2H), 7.67-7.60 (m,
4H); 3.03 (s, 2H), 2.02 (s, 3H).

Potassium tert-butoxide (1.41 g, 12.6 mmol) was placed in a 100 mL, three-neck, 
round bottom flask equipped with a nitrogen line, stir bar, addition funnel, condenser, and 
septa. DMSO (20 mL, dry) was injected into the flask and warmed to 50 – 50°C. A 
solution of 31 (0.836 g, 3.15 mmol) in DMSO (20 mL, dry) was added drop wise via the 
addition funnel over 30 min. The solution was then cooled to room temperature and 
stirred for an additional 20 min. The reaction was quenched with water (20 mL) and the 
resulting solution was washed with ether (3 X 20 mL). The combined ether layers were 
washed with water (3 X 10 mL), dried (MgSO₄), filtered and concentrated by rotary 
evaporation. The residue was purified by rotor chromatography (hexane) to give 0.434 g 
(1.88 mmol) of 32 in 65% yield. m.p. = 168-171°C. ¹H-NMR (360 MHz) 7.76 (dd, 4H,
J= 1.4Hz, J=9.1Hz), 7.66-7.57 (m, 4H), 5.41 (t, 2H, J=2.1Hz), 3.48 (t, 2H, J=2.1Hz). 

Photolysis of Vinlylidene cyclopropapryrene precursor (32)

32 (0.0200 g, 86.8 μmol) and hexane (50 mL, purged) were added to a quartz tube 
and fitted with a septum. The tube was placed into the photolysis chamber and irradiated 
at 254 nm for 4 h. After 2 h, a 10 mL sample was removed, concentrated by rotary 
evaporation and the ¹H-NMR spectrum showed production of pyrene by observation of 
peaks at the following ppm: 8.21 (d, 4H, J=7.6Hz), 8.10 (s, 4H), 8.03 (dd, 2H, J=7.2Hz,
J=8.0Hz). After 4 h, the solution was concentrated by rotary evaporation and the ¹H-

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NMR spectrum showed increased production of pyrene as compared to the sample after 2 h.

**Synthesis of 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa[1]-phenanthrene (35)**

THF (20 mL, dry) and 1 (2.0 g, 7.6 mmol) were placed into a 3-neck, round bottom flask equipped with a stir bar, nitrogen line, and septa. The mixture was cooled to -78 °C and after 1 h, n-butyllithium (4.0 mL of a 2.5 M solution in hexanes, 10 mmol) was added drop wise and the mixture stirred for 1 h. Acetophenone (1.3 mL, 11 mmol) was added drop wise and the mixture stirred at -78 °C for 1 h and then warmed slowly to room temperature overnight. The reaction was quenched with brine and the layers separated. The organic layer was washed with brine (4 X 5 mL), dried (MgSO₄), filtered and concentrated by rotary evaporation. The residual acetophenone was removed by vacuum. The resulting residue was purified by filtering through Florisil with a mixture of ether and hexane (2:100, v:v) and concentrated to afford the intermediate alcohol (33) (2.17 g, 6.23 mmol) in 82% yield.

Alcohol 33 (0.918 g, 2.63 mmol) and pyridine (10 mL, dry) were added to a round bottom flask equipped with a stir bar and septum which was placed on an ice bath. TMSCl (4.0 mL, 0.032 mol) was added and the mixture allowed to stir for an hour. The mixture was then quenched with cold water and the organic layer was washed with additional water. The combined aqueous layers were washed with ether and the organic layer separated and combined with the initial organic layer. The combined organic layers were dried (MgSO₄), filtered and concentrated by rotary evaporation. The resulting residue was purified by filtering through Florisil with methylene chloride and concentrated by rotary evaporation to yield the silyl ether (34) in quantitative yield.
The silyl ether (34) (0.112 g, 1.70 mmol) and a mixture of THF and pentane (10 mL, 1:1, dry) were added to a three necked, round bottom flask equipped with a stir bar, argon line, low temperature thermometer and septum. The flask was cooled to -90 °C (hexane/liq N$_2$). tert-Butyllithium (2.2 mL of a 1.7M solution in pentane, 3.7 mmol) was added drop wise. The mixture stirred at -90 °C for 1 h and upon warming slowly to -4 °C was quenched with water (5 mL). The organic layer was washed with brine, dried (MgSO$_4$), filtered and concentrated by rotary evaporation. Radial chromatography (silica gel rotor, ether:hexane (2:100, v:v)) afforded 0.0615 mg of a white solid which was then further purified through recrystallization from hexane to yield 12% of 35 (60.1 mg, 0.204 mmol) as yellow crystals. $^1$H-NMR (360 MHz) 8.00-7.95 (m, 2H), 7.59-7.56 (m, 2H), 7.40-7.18 (m, 9H), 3.35 (dd, 2H, J=9.7Hz, J=151.3Hz), 1.98 (s, 3H). $^{13}$C-NMR (360 MHz) 145.01, 132.14, 131.24, 130.89, 130.01, 129.95, 127.74, 127.51, 127.45, 126.83, 122.67, 122.57, 77.13, 50.02, 27.94, 27.02, 24.97.

**Photolysis of 1a,9b-Dihydro-1-(1-phenylethylidene)-1H-cyclopropa[l]-phenanthrene (35)**

35 (0.012 g, 0.039 mmol) and hexane (50 mL, purged with nitrogen) were added to a quartz tube and irradiated for 90 min at 254 nm and room temperature. Samples were taken at 0, 30, 60, and 90 minutes and the progression of the reaction was monitored by TLC (silica gel, hexanes) at these time intervals to determine completion. The samples were also monitored by gas chromatography ($T_i$ = 70 °C for 5 min, Ramp = 25 °C/min. $T_f$ = 200 °C for 9.8 min). Retention times (min): Phenanthrene (3) (19.6), 1-phenylpropyne (36) (9.3), 35 (degrades on column).
Synthesis of (1-chloro-1a,9b-dihydro-1H-cyclopropa[l]-phenanthren-1-yl)(phenyl)-methanol (37)

1 (1.0 g, 3.8 mmol) and THF (10 mL, dry) were added to a three neck, round bottom flask equipped with a stir bar, nitrogen line and septa. The flask was cooled to -78°C and after 1 h, n-butyllithium (2.0 mL of a 2.5 M solution in hexanes, 5 mmol) was added drop wise. After 1 h, benzaldehyde (0.5 mL, 4.9 mmol, distilled) was added drop wise. The mixture stirred for 1 h at -78°C and then warmed slowly to room temperature overnight. The reaction was quenched with brine (5 mL) and the layers separated. The organic layer was washed with brine, dried (Na₂SO₄), filtered and concentrated by rotary evaporation. Recrystallization from ethyl acetate (2X) afforded 37 (0.32 g, 0.95 mmol) as a pale yellow solid in 25% yield. m.p. = 173-175°C. ¹H-NMR (d₆-acetone, 360 MHz) 8.10 (d, 2H, J = 7.7 Hz), 7.67-7.65 (m, 2H), 7.49 (dd, 1H, J = 1.9 Hz, J = 7.2 Hz), 7.41-7.25 (m, 9H), 3.80 (s, 1H), 3.44 (d, 1H, J = 9.4 Hz) 3.36 (d, 1H, J = 9.4 Hz). ¹³C-NMR (d₆-acetone, 360 MHz) 143.87, 134.06, 132.53, 132.22, 132.09, 129.62, 129.37, 129.24, 129.05, 128.90, 128.86, 124.51, 79.19, 79.08, 129.35, 30.54.

Oxidation of (1-chloro-1a,9b-dihydro-1H-cyclopropa[l]-phenanthren-1-yl)(phenyl)-methanol (37)

Pyridinium chlorochromate (100 mg, 0.5 mmol) and methylene chloride (1.0 mL) were added to a three neck, round bottom flask equipped with a stir bar, nitrogen line and septa. 37 (101 mg, 0.300 mmol) in methylene chloride (2 mL) was added to the flask rapidly. After 2 h, diethyl ether (5 mL) was added and the solvent decanted into an Erlenmeyer flask. The black residue was washed with diethyl ether (2 X 3 mL) and the combined ether layers were filtered through Florisil and concentrated by rotary
evaporation. The resulting yellow solid was purified by recrystallization from hexanes to afford 38 in quantitative yield as yellow prism-like crystals. m.p. = 136-137°C. \(^1\)H-NMR (360 MHz) 8.14 (dd, 2H, J = 1.1 Hz, J = 7.7 Hz), 7.95-7.93 (m, 2H), 7.60-7.54 (m, 3H), 7.50-7.40 (m, 6H), 3.73 (s, 2H). \(^13\)C-NMR (360 MHz) 197.05, 135.81, 132.77, 132.39, 130.72, 129.30, 128.45, 128.16, 128.05, 122.93, 43.99, 32.95.

Photolysis of (1-chloro-1a,9b-dihydro-1H-cyclopropa[l]-phenanthren-1-yl)(phenyl)-methanone (38)

38 (0.0509 g, 0.153 mmol), cyclohexene (15 mL, 0.15 mol, distilled) and hexane (50 mL, purged) were added to a quartz tube and irradiated at 254 nm and room temperature. 1 mL samples were taken at 0, 1, 2.5, 3 and 4 h and the reaction progress monitored by TLC (silica gel, hexanes). After 4 hours, it was determined that the reaction would proceed no further. The reaction mixture was then concentrated by rotary evaporation at 0°C. The residue was separated by preparative TLC (silica gel) using diethyl ether:hexane (2:100, v:v) as the eluent. Spectral data indicated a complex mixture but the production of phenanthrene was apparent.

Synthesis of dibutylvinylidene precursor (41)

Dichlorocyclopropane 1 (0.499 g, 1.90 mmol) and THF (20 mL, dry) were added to a round bottom flask equipped with a stir bar, nitrogen line, and septa. The mixture was cooled to -78°C and after 1 h, \(n\)-butyllithium (1.7 mL of a 2.63 M solution in hexanes, 4.2 mmol) was added drop wise and the mixture allowed to stir for 1 h. 5-nanonanone (0.7 mL, 4 mmol) was slowly added drop wise and the mixture kept at -78°C for an additional hour before warming slowly to room temperature and continued stirring overnight. The reaction was quenched with brine (5 mL) and the organic layer washed
with brine (3 X 10 mL), dried (MgSO₄), filtered and concentrated by rotary evaporation. The residue was purified by filtration through a plug of Florisil with methylene chloride to give adduct 39.

The intermediate alcohol (39) (0.996 g, 2.70 mmol) and dry pyridine (10 mL) were added to a flask equipped with a stir bar, argon line, and septum. TMSCI (4.0 mL, 0.032 mol) was added and the mixture stirred overnight. The reaction flask was cooled in an ice bath and quenched with water. Ether was added to the mixture and organic layer separated and washed with water, dried (MgSO₄), filtered and concentrated by rotary evaporation. The residue was placed under vacuum to remove excess pyridine then purified by filtering through Florisil with methylene chloride to give 0.9435 g of silyl ether 40 (79% yield, 2.13 mmol).

Silyl ether 40 (0.931 g, 2.10 mmol) and a mixture of dry THF and dry pentane (20 mL, 1:1) were added to a three-necked, round bottom flask equipped with a stir bar, argon line, low-temperature thermometer and septum. The flask was cooled to -90°C (liq N₂/hexane slurry) and t-butyllithium (2.7 mL of a 1.7 M solution in pentane, 4.6 mmol) was added slowly and kept at -90°C for 1 h. The flask was allowed to warm slowly to -4°C and then the reaction was quenched with water. The organic layer was washed with brine, dried (MgSO₄), filtered and concentrated by rotary evaporation. The residue was filtered through Florisil with pentane then recrystallized from hexane to give 0.397 g of 41 in 59% yield (1.24 mmol). m.p. = 107-108.5°C. ¹H-NMR (360 MHz) 8.04 (d, 2H, J = 7.5 Hz), 7.38-7.29 (m, 6H), 3.02 (s, 2H), 2.03-1.96 (m, 2H), 1.64-1.55 (m, 6H), 1.31 (qd, 4H, J = 7.2 Hz, J = 14.6 Hz), 0.98 (t, 6H, J = 7.3 Hz). ¹³C-NMR (360 MHz) 131.21, 130.11, 127.39, 126.79, 122.62, 132.44, 78.92, 41.02, 26.51, 26.05, 23.29,
14.29, 2.16. IR (cm⁻¹) 3853.7, 2955.5, 2931.5, 2872.0, 1260.9, 1251.1, 1071.7, 908.60, 840.04, 754.16, 727.93, 618.31, 586.96, 491.08, 465.24, 446.52, 419.44.

**Photolysis of dibutyl vinylidene precursor (41)**

41 (0.0047 g, 0.016 mmol) and cyclopentane (50 mL, dry) were added to a quartz test tube. The solution was purged with nitrogen then irradiated at 254 nm and room temperature for 15 min. TLC analysis indicated that phenanthrene was generated but 5-decyne was not. \(^{R_f}(41 \text{ standard}) = 0.2, \) \(^{R_f}(\text{phenanthrene standard}) = 0.39, \) \(^{R_f}(5-\text{decyne standard}) = 0.59, \) \(^{R_f}(41 \text{ photolyzed}) = 0.38. \) The reaction mixture was concentrated by rotary evaporation. \(^{1}H\)-NMR spectrum showed production of phenanthrene by observation of peaks at the following ppm: 8.71 (d, 2H, \(J = 8.4 \text{ Hz}\)), 7.90 (dd, 2H, \(J = 1.5 \text{ Hz}, J = 7.8 \text{ Hz}\)), 7.75 (s, 2H), 7.69-7.58 (m, 4H).

**Synthesis of 3-[Bis-(3-hydroxypropyl)-amino]-propan-1-ol (44)**

A mixture of 3-amino-1-propanol (0.41 mL, 5.4 mmol), 3-chloro-1-propanol (1.1 mL, 13 mmol) and sodium carbonate (1.25 g, 11.8 mmol) in absolute ethanol (6 mL) was heated to reflux for 24 hours. The reaction mixture was cooled and chloroform (10 mL) was added. The mixture was filtered and concentrated by rotary evaporation. Spectral data shows a mixture of starting materials as well as 3-[Bis-(3-hydroxypropyl)-amino]-propan-1-ol (44). \(^{1}H\)-NMR (360 MHz) 4.69 (br s), 3.73-3.64 (m), 2.76 (t, \(J = 6.6 \text{ Hz}\)), 2.58 (t, \(J = 6.8 \text{ Hz}\)), 2.01-1.94 (m), 1.75-1.68 (m). \(^{13}C\)-NMR (360 MHz) 77.35, 77.00, 76.64, 60.98, 58.07, 51.52, 47.24, 41.42, 34.75, 31.06, 28.40.

**Synthesis of 3-[4-(3-Hydroxypropyl)-piperazin-1-yl]-propan-1-ol (45)**

A mixture of 3-chloro-1-propanol (1.1 mL, 13 mmol), piperazine (0.453 g, 5.30 mmol), and sodium carbonate (1.25 g, 11.8 mmol) in absolute ethanol (6 mL) was heated...
to reflux for 24 hours. The reaction mixture was cooled and chloroform (15 mL) was added. The mixture was filtered and concentrated by rotary evaporation. 3-[4-(3-Hydroxypropyl)-piperazin-1-yl]-propan-1-ol (45) was collected in 89% yield (0.9544 g). 

$^1$H-NMR (360 MHz) 5.01 (br s, 2H), 3.79-3.76 (m, 4H), 2.60-2.57 (m, 4H), 2.51 (br s, 8H), 1.69 (dt, 2H, J = 5.5 Hz, J = 10.5 Hz). $^{13}$C-NMR (360 MHz) 64.60, 58.65, 53.22, 26.97.

**Synthesis of 3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46)**

Paraformaldehyde (2.65 g, 88.4 mmol) was added slowly to a stirred mixture of 3-aminopropanol (6.0 mL, 78 mmol) and absolute ethanol (30 mL), followed by stirring overnight. The mixture was filtered and the ethanol was initially removed by rotary evaporation and completed with removal by higher vacuum (to ca. 0.1 torr). The resulting product, a viscous liquid, was formed in quantitative yield. NMR spectral data are consistent with literature values.

**Polymerization of 3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46) with tolylenediisocyanate (TDI)**

3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46) (0.987 g, 3.74 mmol) and water (0.05 mL, 2.5 mmol) were mixed together with a stirbar. Tolylenediisocyanate (0.75 mL, 5.2 mmol) was added all at once and the mixture stirred until foaming began approximately 1 minute later. Steam was observed during the polymerization process and after 2 minutes, the resulting polymer foam (1.75 g total weight) was brittle and hard.
Synthesis of 2-[3,5-Bis-(2-hydroxy-ethyl)-[1,3,5]triazinan-1-yl]-ethan-1-ol (47)

Paraformaldehyde (11.8 g, 0.390 mol) was added slowly to a stirred mixture of ethanolamine (20 mL, 0.33 mol) in absolute ethanol (75 mL), followed by stirring overnight. The mixture was filtered and the ethanol was initially removed by rotary evaporation and completed with removal by higher vacuum (to ca. 0.1 torr). The resulting viscous liquid appeared to be a complex mixture by the $^1$H-NMR spectrum but the $^{13}$C-NMR spectrum showed that the expected product was the major product. $^1$H-NMR (360 MHz) 3.62-3.60 (m, 6H, OCH$_2$CH$_2$), 2.58-2.56 (m, 6H, CH$_2$C$_7$/2N). $^{13}$C-NMR (360 MHz) 73.51, 58.98, 54.82.

Synthesis of 4-[3,5-Bis-(3-hydroxy-butyl)-[1,3,5]triazinan-1-yl]-butan-1-ol (48)

Paraformaldehyde (2.02 g, 0.067 mol) was added slowly to a stirred mixture of 4-amino-1-butanol (5.02 g, 0.056 mol) in absolute ethanol (100 mL), followed by stirring overnight. The mixture was filtered and the ethanol was initially removed by rotary evaporation and completed with removal by higher vacuum (to ca. 0.1 torr). The resulting product, a viscous liquid, was formed in quantitative yield. The NMR spectrum was consistent with the expected product. $^1$H-NMR (400 MHz) 4.84 (br s, 3H), 3.61-3.58 (m, 6H), 3.39 (br s, 6H), 2.51-2.48 (m, 6H), 1.66-1.58 (m, 12H). $^{13}$C-NMR (400 MHz) 73.47, 62.06, 51.99, 31.19, 24.38.

Synthesis of 5-[3,5-Bis-(3-hydroxy-pentyl)-[1,3,5]triazinan-1-yl]-pentan-1-ol (49)

Paraformaldehyde (1.84 g, 0.0610 mol) was added slowly to a stirred mixture of 5-amino-1-pentanol (5.3 mL, 0.049 mol) in absolute ethanol (100 mL), followed by stirring overnight. The mixture was filtered and the ethanol was initially removed by rotary evaporation and completed with removal by higher vacuum (to ca. 0.1 torr). The
resulting product, a viscous liquid, was formed in quantitative yield. The NMR spectrum was consistent with the expected product. $^1$H-NMR (400 MHz) 4.27 (br s, 3H), 3.61-3.58 (m, 6H), 3.29 (br s, 6H), 2.45-2.41 (m, 6H), 1.60-1.36 (m, 18H) $^{13}$C-NMR (400 MHz) 74.54, 62.52, 52.59, 32.52, 27.21, 23.72.

Synthesis of 6-[3,5-Bis-(3-hydroxy-hexyl)-[1,3,5]triazinan-1-yl]-hexan-1-ol (50)

Paraformaldehyde (1.42 g, 0.0470 mol) was added slowly to a stirred mixture of 6-amino-1-hexanol (5.00 g, 0.0430 mol) in absolute ethanol (100 mL), followed by stirring overnight. The mixture was filtered and the ethanol was initially removed by rotary evaporation and completed with removal by higher vacuum (to ca. 0.1 torr). The resulting product, a viscous liquid, was formed in quantitative yield. The NMR spectrum was consistent with the expected product. $^1$H-NMR (400 MHz) 4.23 (br s, 3H), 3.59-3.56 (m, 6H), 3.26 (br s, 6H), 2.39-2.35 (m, 6H), 1.54-1.32 (m, 24H). $^{13}$C-NMR (400 MHz) 74.39, 62.52, 52.51, 32.60, 27.32, 27.14, 25.54.

Polymerization of 2-[3,5-Bis-(2-hydroxy-ethyl)-[1,3,5]triazinan-1-yl]-ethan-1-ol (47) with tolylenediisocyanate (TDI)

2-[3,5-Bis-(2-hydroxy-ethyl)-[1,3,5]triazinan-1-yl]-ethan-1-ol (47) (5.2 g, 0.024 mol) and water (0.3 mL, 0.02 mol) were mixed together with a stirbar. Tolylenediisocyanate (5.0 mL, 0.035 mol) was added all at once and the mixture stirred until foaming began approximately 5 seconds later. Steam was observed during the polymerization process and after 24 seconds, the foaming ceased. Upon cooling the resulting polymer foam was brittle and hard.
Polymerization of 5-[3,5-Bis-(3-hydroxy-pentyl)-][1,3,5]triazinan-1-yl]-pentan-1-ol (49) with tolylenediisocyanate (TDI)

5-[3,5-Bis-(3-hydroxy-pentyl)-][1,3,5]triazinan-1-yl]-pentan-1-ol (49) (10 g, 0.026 mol) and water (0.05 mL, 2.5 mmol) were mixed together with an overhead mechanical paddle. Tolylenediisocyanate (5.6 mL, 0.039 mol) was added all at once and the mixture stirred until foaming began approximately 5 seconds later. Steam was observed during the polymerization process and after 24 seconds, the foaming ceased. Upon cooling the resulting polymer foam was brittle and hard in some places and spongy in others.

 Attempted Synthesis of 51

Paraformaldehyde (10.3 g, 0.340 mol) was added, portion wise, to a solution of 3-amino-1-propanol (16 mL, 0.21 mol) and 1,6-diaminohexane (6.2 g, 0.050 mol) in absolute ethanol (100 mL) and stirred overnight. The solution was filtered and concentrated on a rotary evaporator. Spectral data showed a complex mixture with 46 as a major product. Separation was not attempted.

 Attempted Synthesis of 52

Paraformaldehyde (9.11 g, 0.303 mol) was added, portion wise, to a solution of 3-amino-1-propanol (13.8 mL, 0.180 mol) and hexylamine (12 mL, 0.090 mol) in absolute ethanol (100 mL) and stirred overnight. The solution was filtered and concentrated on a rotary evaporator. Spectral data showed a complex mixture with 46 as a major product. Separation was not attempted.
Variable Temperature NMR Study (400 MHz) of 3-[3,5-Bis-(3-hydroxypropyl)-1,3,5-triazinan-1-yl]-propan-1-ol (46) in DMSO

A small amount of 46 was placed into an NMR tube and d6-DMSO was added. An initial \(^1\)H-NMR spectrum was acquired prior to heating the sample while spinning in the spectrometer. \(^1\)H-NMR spectra were acquired between 60 - 100°C at 10° intervals and at 100°C at 10 min intervals for 1 h. The multiplets at 2.40-2.38 (46) and 1.54-1.51 (impurity) were monitored because these peaks each both represented 6H. As the temperature increased, the relative integrations between the two multiplets showed that the multiplet representing 46 was decreasing while the multiplet representing the impurity was increasing. We believe that this experiment showed that 46 was degrading with increasing temperature to 1,3-oxazinane (53) as was previously shown in the literature.\(^{11}\)

Synthesis of 2-(2-{3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]}}-1,3,5-triazinan-1-yl)-ethoxy)-ethanol (54) in absolute ethanol

Paraformaldehyde (5.39 g, 0.179 mol) was added, portion wise, to a mixture of 2-(2-aminoethoxy)ethanol (15 mL, 0.150 mol) and absolute ethanol (250 mL) and stirred overnight. The solution was filtered and concentrated on a rotary evaporator. The sample was placed under vacuum to completely remove the solvent. Triazinane 54 was collected in quantitative yield. \(^1\)H-NMR (400 MHz) 4.38 (br s, 3H), 3.69-3.56 (m, 24H), 2.72-2.69 (m, 6H). \(^13\)C-NMR (400 MHz) 74.46, 72.63, 69.28, 61.83, 52.04.
Polymerization of 2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl)-ethoxy)-ethanol (54) with tolylenediisocyanate (TDI)

2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl)-ethoxy)-ethanol (54) (10.0 g, 0.026 mol) and water (1 drop) were mixed together with an overhead mechanical paddle. Tolylenediisocyanate (5.6 mL, 0.039 mol) was added all at once and the mixture stirred for approximately 5 seconds until the mixture foamed and stopped rising. Upon cooling the resulting polymer foam was hard and yellow colored at the top of the paddle shaft but white colored at the paddle.

Polymerization of 2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl]-ethoxy)-ethanol (54) with tolylenediisocyanate (TDI) and DC-193 surfactant

2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl]-ethoxy)-ethanol (54) (15.4 g, 0.0440 mol), water (0.5 mL, 3 mass %), and DC-198 (0.77 g, 5 mass %), with an initial combined volume of 15 mL, were mixed together with an overhead mechanical paddle. Tolylenediisocyanate (9 mL, 0.06 mol) was added all at once and stirred until the mixture foamed and stopped rising. Upon cooling the resulting polymer foam had expanded to a total water displacement volume of 1000 mL yielding an expansion ratio of 42.

Polymerization of 2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl]-ethoxy)-ethanol (54) with poly-4,4'-methylenebis(phenylisocyanate) (pMDI) and DC-193 surfactant

2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl]-ethoxy)-ethanol (54) (16.4 g, 0.0470 mol), water (0.7 mL, 2 mass %), and DC-193 (1.6 g, 4 mass
% were mixed together with an overhead mechanical paddle. Poly-4,4'-methylenebis(phenylisocyanate) (18.8918 g, 0.052 mol) was added all at once and stirred until the mixture foamed and stopped rising. Upon cooling the resulting polymer foam was hard not easily compressed or torn and yielded an expansion ratio of 21.

Large scale synthesis of 2-(2-{3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl}-ethoxy)-ethanol (54) in absolute ethanol

2-(2-aminoethoxy)ethanol (480 mL, 4.78 mol) and absolute ethanol (2 L) were placed into a reactor equipped with a jacket cooler, thermometer, and overhead mechanical stirrer. The jacket cooler was kept at 0°C with a refrigerated pump. Paraformaldehyde (158 g, 5.26 mol) was added portion wise and additional ethanol (0.83 L) was added. The reaction stirred for 2 days and then stood for 1 week. The solution was removed and the reactor rinsed with absolute ethanol which was collected and combined with the reaction mixture. The combined solutions were filtered and concentrated by rotary evaporation until the amount of ethanol reached approximately 8%. Hexane was then used as an azeotrope to assist in the removal of the last portion of ethanol. Triazinane 54 was produced in quantitative yield. \(^1\)H-NMR (500 MHz) 4.33 (br s, 3H), 3.63-3.41 (m, 24H), 2.65-2.64 (m, 6H). \(^13\)C-NMR (500 MHz) 74.20, 72.38, 68.91, 61.57, 51.76.

Synthesis of 2-(2-{3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-[1,3,5]triazinan-1-yl}-ethoxy)-ethanol (54) in tetrahydrofuran

Paraformaldehyde (11.0 g, 0.366 mol) was added, portion wise, to a chilled mixture of 2-(2-aminoethoxy)ethanol (32.5 mL, 0.324 mol) and tetrahydrofuran (100 mL) and stirred overnight. The solution was filtered and concentrated on a rotary
evaporator. The sample was placed under vacuum to completely remove the solvent. Triazinane 54 was formed in quantitative yield. $^1$H-NMR (500 MHz) 4.07 (br s, 3H), 3.63-3.48 (m, 18H), 3.42 (br s, 6H), 2.64-2.62 (m, 6H). $^{13}$C-NMR (500 MHz) 74.20, 72.36, 68.90, 61.52, 51.76.

**Attemped Synthesis of 3-[4.6-bis-(3-hydroxy-propyl)]triazin-2-yl]propan-1-ol (56) through Grignard reaction**

3-Chloropropanol (10 mL, 0.12 mol) and tetrahydrofuran (20 mL) were added to a 100 mL, dry round-bottom flask. Imidazole (8.18 g, 0.120 mol) and tert-butyl-dimethylsilyl chloride (18.2 g, 0.120 mol) were added sequentially and upon placing the reaction flask on ice, stirred overnight. The mixture was filtered through a silica plug which was washed repeatedly with ether. The combined rinses were placed on ice and carefully concentrated by rotary evaporation. The silyl ether product was recovered in quantitative yield. $^1$H-NMR (500 MHz) 3.63-3.60 (m, 4H), 1.83-1.82 (m, 2H), 0.87 (s, 9H), 0.03 (s, 6H). $^{13}$C-NMR (500 MHz) 59.32, 41.64, 35.39, 25.83, 18.22.

Magnesium (0.101 g, 4.15 mmol, dry) was placed into a dry, three-neck, round bottom flask equipped with a nitrogen inlet, a dry condenser, and a dry stir bar. Ether was added to cover the magnesium and a small crystal of iodine was added. The solution stirred until the color had disappeared. The silyl ether product (above) was mixed with ether (2 mL) and added drop wise to the flask. Upon addition, the color of the solution changed to a opaque yellow-orange that decreased over time. Upon complete addition, the solution refluxed for 15 min, after which cyanuryl chloride (57) (0.256 g, 1.39 mmol) in ether was added and continued to reflux overnight. Upon cooling, addition ether was added and the solution filtered, washed (sat’d NaHSO$_3$), dried (MgSO$_4$), filtered and
concentrated by rotary evaporation. Spectral data indicated that the residue is starting materials.

**Attempted Synthesis of 3-[4,6-bis-(3-hydroxy-propyl)-1,3,5']triazin-2-yl]-propan-1-ol (56) through Grignard reaction with activated magnesium**

Magnesium (1.00 g, 41.1 mmol) was placed in a round bottom flask equipped with a magnetic stirrer, addition funnel and reflux condenser with a drying tube (CaCl₂). Benzene (20 mL) and iodine (0.50 g, 2.0 mmol) were added and stirred. Ether (1.0 mL) was added drop wise to the stirred mixture. Upon disappearance of the iodine color, the reflux condenser was replaced with a distillation apparatus and the solution distilled to dryness over an oil bath which was maintained at 150-160°C for an additional 5 min to ensure complete removal of the benzene. The flask cooled for 10 min then the residue was quickly transferred to a dry vial.

Activated magnesium (0.1.29 g, 4.64) and tetrahydrofuran (5 mL, dry) were placed into a dry, three-neck, round bottom flask equipped with a condenser, stopper, septum and stir bar. The silyl ether product (above) (0.605 g, 2.90 mmol) in tetrahydrofuran (5 mL) was added and the mixture refluxed overnight. Additional tetrahydrofuran (5 mL) and cyanuric chloride (57) (0.255 g, 1.38 mmol) were added to the reaction mixture and allowed to reflux overnight. Upon cooling, the reaction mixture was quenched with mild acid (5% HCl). The organic layer was washed with sat’d sodium bicarbonate, brine, sat’d sodium bisulfite, and brine, dried (MgSO₄), filtered and concentrated by rotary evaporation. Spectral data indicated that no reaction had occurred.
Attempted Synthesis of 3-[4,6-bis-(3-hydroxy-propyl)-1,3,5-triazin-2-yl]-propan-1-ol (56)

A solution of potassium cyanide (7.33 g, 0.113 mol) in water (15 mL) was added, drop wise, to a stirred refluxing solution of 3-bromo-1-propanol (10 mL, 0.11 mol) in ethanol (60 mL). The mixture was stirred and refluxed for 8 hours and then stirred at room temperature for an additional 18 hours. The mixture was filtered and the residue rinsed with ethanol. The solvents were removed by rotary evaporation. The residue was dissolved in ether, dried with anhydrous magnesium sulfate, filtered and concentrated by rotary evaporation followed by vacuum distillation. 4-Hydroxybutyronitrile was formed in 47% yield and the $^1$H-NMR and $^{13}$C-NMR spectra are consistent with literature values.$^{146}$

The method of Nohira et al was followed with slight modification.$^{116}$ Hydrogen chloride dissolved in ether (30 mL of a 2.0 M solution, 60 mmol) was injected into a flask containing 4-hydroxybutyronitrile (4.22 g, 49.6 mmol) and ether (120 mL) on an ice bath. This tightly stoppered flask was allowed to stand at room temperature for 2 days. The crystals that formed were filtered, washed with ether, and dried in a desiccator. 2-Iminotetrahydrofuran hydrochloride was formed in 48% yield.

2-Iminotetrahydrofuran hydrochloride (2.89 g, 23.8 mmol), triethylamine (7.0 mL, 50 mmol) and tetrahydrofuran (30 mL, dry) were placed into a flask, which was then tightly closed with a stopper. The mixture was allowed to stand at room temperature, with intermittent shaking, for 3 days. The mixture was filtered and the solvent removed by rotary evaporation. The $^1$H-NMR and $^{13}$C-NMR spectra showed evidence of a complex mixture and no separation was attempted due to time constraints. $^1$H-NMR (500 MHz)
11.43 (br s), 10.35 (br s), 8.72-8.67 (m), 6.02 (br s), 5.92 (br s), 5.52-5.51 (m), 5.26 (s),
4.31 (t, J = 7.1 Hz), 4.16-4.09 (m), 3.89-3.87 (m), 3.66 (t, J = 6.0 Hz), 3.57 (t, J = 6.3 Hz),
2.92 (t, J = 7.1 Hz), 2.45 (t, J = 8.2 Hz), 2.37 (t, J = 7.2 Hz), 2.26-2.20 (m), 2.08-1.98 (m),
1.83-1.77 (m), 1.38-1.34 (m). $^{13}$C-NMR (500 MHz) 178.90, 107.94, 68.72, 67.67, 62.00,
44.55, 35.82, 32.45, 30.14, 30.11, 29.33, 28.04, 27.92, 27.83, 24.04, 22.27, 8.72.

Synthesis of 1,3,5-Trihexyl-1[1,3,5]triazinane (59)

Hexylamine (40.0 mL, 0.303 mol) and ethanol were placed into a round-bottomed
flask and mixed thoroughly. Paraformaldehyde (10.0 g, 0.333 mol) was added portion
wise and the mixture was stirred overnight. The solution was filtered and the ethanol
removed by rotary evaporation. The sample was placed under vacuum to completely
remove solvent. Triazinane 59 was formed as a viscous liquid in 98% yield (33.6 g, 98.9
mmol). $^{1}$H-NMR (400 MHz) 3.29 (br s, 6H), 2.41-2.38 (m, 6H), 1.49-1.42 (m, 6H), 1.31-
1.29 (m, 24H), 0.88 (t, J = 6.8 Hz). $^{13}$C-NMR (400 MHz) 74.62, 52.75, 31.66, 27.48,
27.09, 22.51, 13.92.

NMR Study on Mixtures of Adamantylisocyanate (60), p-Tollylisocyanate (61), and 4-
Nitrophenyl- isocyanate (62) each with 1,4-DiazaBicyclo[2.2.2]octane (DABCO) (63)

A small amount of each isocyanate and DABCO (10-25 mg) were each placed
into a separate NMR tube and CDCl$_3$ (1-2 mL) was added. Spectral data was acquired for
each one. $^{1}$H-NMR Adamantylisocyanate (360 MHz) 2.09 (br s, 6H), 1.88 (d, 6H,
J=2.5Hz), 1.65 (br s, 3H). $^{1}$H-NMR p-Tollylisocyanate (360 MHz) 7.08 (d, 2H, J = 8.3
Hz), 6.94 (d, 2H, J = 8.3 Hz), 2.30 (s, 3H). $^{1}$H-NMR 4-Nitrophenylisocyanate (360 MHz)
8.23 (d, 2H, J = 8.9 Hz), 7.24 (d, 2H, J = 8.9 Hz). $^{1}$H-NMR DABCO (360 MHz) 2.79 (s,
12H). DABCO (10-25 mg) was added to each of the NMR tubes that contained
isocyanates. Spectral data was acquired for each one. $^1$H-NMR Adamantylisocyanate/DABCO (360 MHz) 2.79 (s), 2.09 (br s), 1.88 (d, J = 2.7 Hz), 1.65 (d, J = 2.3 Hz). $^1$H-NMR p-Tolylisocyanate/DABCO (360 MHz) 7.08 (d, J = 8.4 Hz), 6.94 (d, J = 8.3 Hz), 2.76 (s), 2.30 (s). $^1$H-NMR 4-Nitrophenylisocyanate/DABCO (360 MHz) 8.21 (d, J = 8.0 Hz), 7.25 (d, J = 7.7 Hz), 2.79 (s). It was determined, based on this data, that no complex was visible by NMR spectroscopy.

Reaction Calorimetry with 2-[3,5-Bis-(2-hydroxy-ethyl)-[1,3,5]triazinan-1-yl]-ethan-1-ol (47) and p-Tolylisocyanate

2-[3,5-Bis-(2-hydroxy-ethyl)-[1,3,5]triazinan-1-yl]-ethan-1-ol (47) (1.45 g, 6.61 mmol) and tetrahydrofuran (100 mL) were added to the calorimetry reactor, which was sealed, placed into a temperature constant bath, and connected to the electronic sensors. The temperature was equilibrated to 25°C. p-Tolylisocyanate (2.50 mL, 19.8 mmol) was injected by pump at a rate of 5 mL/min and the reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. When the reaction was completed (no further change in total power) the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

Reaction Calorimetry with 3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46) and p-Tolylisocyanate

3-[3,5-Bis-(3-hydroxypropyl)-[1,3,5]triazinan-1-yl]-propan-1-ol (46) (1.72 g, 6.60 mmol) and tetrahydrofuran (100 mL) were added to the calorimetry reactor, which was sealed, placed into a temperature constant bath, and connected to the electronic sensors. The temperature was equilibrated to 25°C. p-Tolylisocyanate (2.50 mL, 19.8 mmol) was
injected by pump at a rate of 5 mL/min and the reaction was monitored for total power,
total heat transferred, reactor temperature and reference temperature by the calorimetry
software. When the reaction was completed (no further change in total power) the data
was collected and the integrated rate law was plotted to determine reaction order and rate
constant.

Reaction Calorimetry with 4-[3,5-Bis-(3-hydroxy-butyl)-[1,3,5]triazinan-1-yl]-butan-1-ol
(48) and p-Tolylisocyanate

4-[3,5-Bis-(3-hydroxy-butyl)-[1,3,5]triazinan-1-yl]-butan-1-ol (48) (2.00 g, 6.60
mmol) and tetrahydrofuran (100 mL) were added to the calorimetry reactor, which was
sealed, placed into a temperature constant bath, and connected to the electronic sensors.
The temperature was equilibrated to 25°C. p-Tolylisocyanate (2.50 mL, 19.8 mmol) was
injected by pump at a rate of 5 mL/min and the reaction was monitored for total power,
total heat transferred, reactor temperature and reference temperature by the calorimetry
software. When the reaction was completed (no further change in total power) the data
was collected and the integrated rate law was plotted to determine reaction order and rate
constant.

Reaction Calorimetry with 5-[3,5-Bis-(3-hydroxy-pentyl)-[1,3,5]triazinan-1-yl]-pentan-1-
ol (49) and p-Tolylisocyanate

5-[3,5-Bis-(3-hydroxy-pentyl)-[1,3,5]triazinan-1-yl]-pentan-1-ol (49) (2.28 g, 6.61
mmol) and tetrahydrofuran (100 mL) were added to the calorimetry reactor, which
was sealed, placed into a temperature constant bath, and connected to the electronic
sensors. The temperature was equilibrated to 25°C. p-Tolylisocyanate (2.50 mL, 19.8
mmol) was injected by pump at a rate of 5 mL/min and the reaction was monitored for
total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. When the reaction was completed (no further change in total power) the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 6-[3,5-Bis-(3-hydroxy-hexyl)]-1,3,5-triazinan-1-yl]-hexan-1-ol (50) and p-Tolylisocyanate**

6-[3,5-Bis-(3-hydroxy-hexyl)]-1,3,5-triazinan-1-yl]-hexan-1-ol (50) (2.56 g, 6.60 mmol) and tetrahydrofuran (100 mL) were added to the calorimetry reactor, which was sealed, placed into a temperature constant bath, and connected to the electronic sensors. The temperature was equilibrated to 25°C. p-Tolylisocyanate (2.50 mL, 19.8 mmol) was injected by pump at a rate of 5 mL/min and the reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. When the reaction was completed (no further change in total power) the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-1,3,5-triazinan-1-yl]-ethoxy)-ethanol (54) and p-Tolylisocyanate**

2-(2-(3,5-Bis-[2-(2-hydroxy-ethoxy)-ethyl]-1,3,5-triazinan-1-yl]-ethoxy)-ethanol (54) (4.70 g, 13.0 mmol) and tetrahydrofuran (100 mL) were added to the calorimetry reactor, which was sealed, placed into a temperature constant bath, and connected to the electronic sensors. The temperature was equilibrated to 25°C. p-Tolylisocyanate (5.0 mL, 40 mmol) was injected by pump at a rate of 5 mL/min and the reaction was monitored for total power, total heat transferred, reactor temperature and
reference temperature by the calorimetry software. After 1 h, the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 1-Hexanol, p-Tolylisocyanate and DABCO (1:1:1 ratio)**

Bicyclo(2,2,2)-1,4-diazaoctane (DABCO) (0.892 g, 7.95 mmol) and tetrahydrofuran (100 mL) were placed into the reactor and equipped with a mechanical stirrer and detection probes. The temperature was equilibrated to 25°C and 1-hexanol (1.00 mL, 7.97 mmol) and p-tolylisocyanate (1.00 mL, 7.93 mmol) were injected by syringe. The reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. After 1 h, the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 1-Hexanol, p-Tolylisocyanate and DABCO (3:1:1 ratio)**

Bicyclo(2,2,2)-1,4-diazaoctane (DABCO) (0.892 g, 7.95 mmol) and tetrahydrofuran (100 mL) were placed into the reactor and equipped with a mechanical stirrer and detection probes. The temperature was equilibrated to 25°C and 1-hexanol (3.00 mL, 23.9 mmol) and p-tolylisocyanate (1.00 mL, 7.93 mmol) were injected by syringe. The reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. After 1 h, the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 1-Hexanol, p-Tolylisocyanate and DABCO (1:3:1 ratio)**

Bicyclo(2,2,2)-1,4-diazaoctane (DABCO) (0.892 g, 7.96 mmol) and tetrahydrofuran (100 mL) were placed into the reactor and equipped with a mechanical...
stirrer and detection probes. The temperature was equilibrated to 25°C and 1-hexanol (1.00 mL, 7.97 mmol) and \( p \)-tolylisocyanate (3.00 mL, 23.8 mmol) were injected by syringe. The reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. After 1 h, the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 1-Hexanol, \( p \)-Tolylisocyanate and DABCO (1:1:0.5 ratio)**

Bicyclo(2,2,2)-1,4-diazaoctane (DABCO) (0.447 g, 3.98 mmol) and tetrahydrofuran (100 mL) were placed into the reactor and equipped with a mechanical stirrer and detection probes. The temperature was equilibrated to 25°C and 1-hexanol (1.00 mL, 7.97 mmol) and \( p \)-tolylisocyanate (1.00 mL, 7.93 mmol) were injected by syringe. The reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. After 1 h, the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.

**Reaction Calorimetry with 1-Hexanol, \( p \)-Tolylisocyanate and DABCO (3:1:0.5 ratio)**

Bicyclo(2,2,2)-1,4-diazaoctane (DABCO) (0.447 g, 3.98 mmol) and tetrahydrofuran (100 mL) were placed into the reactor and equipped with a mechanical stirrer and detection probes. The temperature was equilibrated to 25°C and 1-hexanol (3.00 mL, 23.9 mmol) and \( p \)-tolylisocyanate (1.00 mL, 7.93 mmol) were injected by syringe. The reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. After 1 h, the data
was collected and the integrated rate law was plotted to determine reaction order and rate constant.

Reaction Calorimetry with 1-Hexanol, $p$-Tolylisocyanate and DABCO (1:3:0.5 ratio)

Bicyclo(2,2,2)-1,4-diazaoctane (DABCO) (0.447 g, 3.98 mmol) and tetrahydrofuran (100 mL) were placed into the reactor and equipped with a mechanical stirrer and detection probes. The temperature was equilibrated to 25°C and 1-hexanol (1.00 mL, 7.97 mmol) and $p$-tolylisocyanate (3.00 mL, 23.8 mmol) were injected by syringe. The reaction was monitored for total power, total heat transferred, reactor temperature and reference temperature by the calorimetry software. After 1 h, the data was collected and the integrated rate law was plotted to determine reaction order and rate constant.
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139
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APPENDIX 1

SPECTRAL DATA