# Investigations of Polymorphic Germylene Structures, Experimental Calculations of a New Boron-Sulfur Heterocycle and Assessment of a Safety Curriculum in an Undergraduate Laboratory

**by**

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Chemistry)
in The University of Michigan
2011

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# Dedication

This thesis is dedicated to my mom and dad. Thanks to their love and constant support I have achieved this.

# Acknowledgments

First and foremost I would like to thank my advisors, Dr. John P. Wolfe and Dr. Mark M. Banaszak Holl. I would be lying if I said having two advisors was easy, let alone confusing. I want to thank Dr. Wolfe most of all for the constant support; academically, professionally, and personally that I received. Without it, I would not be at this point today. I want to thank Dr. Banaszak Holl for allowing the extreme flexibility in projects and experience I have received- I don't think there is a lab in this building I have not worked in, or an advisor I have not worked for. The wide scope of experiences I have gained could not have been achieved in any other lab.

I would like to thank my committee members, Dr. John Montgomery, Dr. Jerome Nriagu, and Dr. Vilma Mesa for agreeing to be on my committee and for various support and interactions over the years.

I thank Dr. John Montgomery for being my professor in mechanisms and spectroscopy, two of the most important courses for "organic" students like myself. I also want to thank Dr. Montgomery for the added assistance on my original research proposal.

I thank Dr. Jerome Nriagu for teaching Environmental Chemistry and expanding my love for environmental awareness.

I thank Dr. Vilma Mesa for agreeing to join my committee when my graduate career took a drastic change in direction. The additional meetings were a great asset to my finishing this thesis.

I want to thank my husband. Without his constant love and support I would not have reached this point. He insisted that making the decision to come to the University of Michigan was to be my own and then drove up every weekend for two years before making the move to Ann Arbor. With the support of my husband I am finishing the degree I started many years ago. The sad days, the manic days the long days in the lab, my husband has stood by my side, supporting me in every decision. I am truly grateful to have such a caring and understanding partner in my life, for the rest of our lives.

I thank my family, for either supporting my decisions, or pushing me to complete what I started, whether I liked it or not.

I thank my husband’s parents, for putting a roof over his head when we lived in separate states, for giving us a place to stay for our many trips home and for being a loving addition to my family.

Credit has to be given to my high school chemistry teacher, Dr. Marvin McCollum, for my love for chemistry. Having taken two years of chemistry in high school, he showed us the love and the respect that chemistry deserves. From my undergraduate program, at the University of Cincinnati, I thank my advisor, Dr. Anna D. Gudmundsdottir and the great group of researchers she had. Personally, I thank Dr Pradeep Singh, a Post-Doc in the Gudmundsdottir lab who had the patience to teach me laboratory basics, as well as Dr. Sridhar Rajam, a first year graduate student at the time, I had the distinct pleasure working for. Other memorable labmates I would like to thank would include Dr. Rajesh Murthy, Dr. Jagadis Sankaranarayanan, Dr. Siva Muthukrishnan, and Dr. Dr. Abhijit Jadhav.

Many thanks go to my good friends from Cincinnati who made everyday bearable, my best friend Tiffany McConnell, may she rest in peace, Susan Zaghlool, Pharm. D., Hetal Desai Pharm. D., Bhavika Patel Pharm. D., Christine Lemon, Amos Doepke, and Aryeh Pridnoff.

I also thank all of the wonderful people who have helped me along the way while I have been here at the University of Michigan. This could take pages, especially since I have been a full member of two very different labs. To start; I thank Dr. Josie Nakhla and Dr. Myra Beudeau-Bertrand, Dr. Jon Fritz and Dr. Natalie Giampietro, graduates of the Wolfe Lab. I want to thank Natalie personally for all of the help she has given me over the years. Natalie has always been a good shoulder to lean on, a good friend to have, and a very intelligent, hard working member of the Wolfe Lab. She was always an inspiration to me, someone I strive to be, and a colleague that I will continue to contact.

Dr. Pascale Leroueil, Dr. Kevin Landmark, Dr. Chris Kelly, Dr. Randon H Walker, Dr. Alan Kiste, Dr. Doug Mullen and Dr. Dan McNerny of the Banaszak Holl lab have also been wonderful companions to have along the way.

Thanks go to those who have been on this journey along with me Dr. Georgia Lemen, Dr. Duy (Peter) Mai and Dr. Joshua Neukom, fellow 2006 cohorts of the Wolfe Lab. I would not change lab mates for anything; they have been an interesting group to be involved with, in which every day was an adventure.

I would also like to acknowledge the newer labmates and wish them the best in their time at the University of Michigan. Those include Wolfe lab members: Amanda

Ward, Dani Schultz, Nick Babij and Justin Tham. Banaszak Holl lab members include Juimei Chen, Becky Matz, Rahul Rattan, Ming (Flora) Fang, Mallory van Dongen, and Casey Dougherty.

Over the many years, many people have been a wonderful part of my life and I want to thank my good friends Dr. Katrina Lexa and Dr. Amy Payeur, two wonderful ladies of two very different labs, that I had the privilege of knowing and having by my side, even on my wedding day. Other special people I want to thank, in no particular order, include; Devon Triplett, Christina Nieh, Zack Bryan, Amit Pithadia, Dr. William Porter, Ted Boron, Dr. Bob Rarig, Dr. Caleb Bates, Tanya Breault, Annie Labut, Anna Merkle, Brannon Gary, Dr. Andrew Higgs, Linda Baruch, Jody Schweickart, Angie Butterweig, Dr. Lisa Prevette, and Dr. Joseph Wallace,

I have to thank The University of Michigan, the Camille and Henry Dreyfus Foundation, and the National Science Foundation (CHE 0453849) for supporting my work.

The support of many members of the Chemistry Department also needs to be recognized. Personal thanks go to Dr. Kathleen Nolta for allowing me to be her Administrative Assistant for many terms and evolve the Chem 211 curriculum as well as for helping me evolve as a person. She never let me give up, and has believed in me every step of the way. Thanks go to Bev Lange, Laura Labut and Debra Buck for administrative help; Tracy Stevenson for fixing the many laboratory issues; Rich Giszczak for keeping this department safe, and giving me the necessary data to complete chapter 4; Roy Wentz for the many broken flasks you have fixed for us over the years; Eugenio Alvarado and Chris Kojiro for NMR assistance; Jeff Kampf for the beautiful crystal structures that facilitated chapter 2, and assisted in chapter 3. I am sure many more people in the department need to be thanked for everything they do on a daily basis; your efforts have not gone unrecognized.

# Preface

Admittedly, the following thesis is a collage of interesting works that artfully depict the road I have taken to complete my dissertation. Initially, I was a bright-eyed chemist who wanted to blur the lines of environmental and organic chemistry. During my first year rotations, I wanted to explore the intersection of physical and organic chemistry. Following my first year, I decided to investigate the boundary of inorganic and organic chemistry: organometallic chemistry. As time went on, that border became increasingly convoluted. I am technically an organic chemist, but as you can see from the following body of work, the label “organic chemistry” only accurately encompasses a small fraction of my work.

After completing my graduate career in chemistry, I will continue to follow my heart to Public Health. I intend to earn a Master’s Degree in Industrial Hygiene with a concentration in Hazardous Substances. I love to think of graduate school as a journey of discovery, and I am certain that it has helped me to discover more about who I am. Because of the opportunities I received here at the University of Michigan, I have rediscovered my desire to understand chemistry, but I have also discovered that I love to help facilitate others’ understanding of chemical hygiene.

This thesis encompasses a variety of topics tangential to the centralized theme of organic chemistry. I have found that being an organic chemist does not limit me to the synthesis of carbon-based molecules. Rather, using organic chemistry as my base of knowledge has facilitated a very interesting and diverse graduate career.

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# List of Abbreviations

| | |
|---|---|
| Bu | butyl |
| CHEM | Chemistry |
| Cp | cyclopentadiene |
| Cp* | pentamethylcyclopentadiene |
| DFT | density functional theory |
| DSC | differential scanning calorimetry |
| equiv | equivalents |
| GIAO | gauge invariant (including) atomic orbitals |
| GSI | graduate student instructor |
| h | hour(s) |
| hlm | Hierarchal Linear Model |
| HOMO | Highest Occupied Molecular Orbital |
| *i*-Pr | isopropyl |
| LUMO | Lowest Unoccupied Molecular Orbital |
| M | molarity |
| Me | methyl |
| NMR | nuclear magnetic resonance |
| NICS | nucleus independent chemical shifts |

| | |
|---|---|
| NSAID | non-steroidal anti inflammatory drug |
| OSHA | Occupational Safety and Health Administration |
| Ph | phenyl |
| PPE | personal protection equipment |
| R | alkyl group |
| RSE | resonance stabilization energy |
| rt | room temperature |
| THF | tetrahydrofuran |
| TMS | trimethylsilyl |
| VT | variable temperature |
| TZVP | triple zeta valence polarized |

# Abstract

The dynamic interaction between chemistry and humankind is explored via investigations with benign substrates and the incorporation of proper laboratory technique instruction to a general audience. This intersection will be discussed in further detail in the introductory chapter of this thesis.

The second chapter of this thesis describes the determination of two polymorphic structures from relatively non-toxic Cp*GeCl. The investigation of the polymorphic stability led to discovery of a solution equilibrium between monomeric and dimeric or higher oligomeric species. These experiments revealed the conversion of polymorphic structures in solid state and solution, allowing a thorough exploration of the thermodynamic and kinetic stability of each of the polymorphic structures.

The third chapter of this dissertation describes computational analysis of the aromaticity of the recently prepared boron heterocycle, 2-diiosopropylamino-2*H*-1,2-thiaborin. The importance and potential utility of aromatic boron-containing heterocycles in electronic devices and hydrogen storage is discussed. The theory behind computational chemistry and the analysis of the aromaticity, HOMO/LUMO, and nuclear magnetic resonance shifts of 2-diiosopropylamino-2*H*-1,2-thiaborin are also reported. NICS (1) calculations determined that external $\pi$-interactions of the external amino substituent greatly decrease the aromaticity of the parent ring.

The fourth chapter describes the development and analysis of the effectiveness of a chemical hygiene-based laboratory curriculum incorporated in the University of Michigan undergraduate organic chemistry laboratory course, Chemistry 211. There is a great need to educate the general population of undergraduates enrolled in lower-division organic chemistry courses at the University of Michigan and in other universities in chemical hygiene. Previous laboratory curricula lacked in-depth discussions on proper laboratory practices. Through weekly reading assignments, quizzes, colorful posters and other educational materials, the students were exposed to information about chemical safety. Surveys and in-class observations were used to analyze the effectiveness of the newly instituted curriculum. The results from this study indicate that teaching the students and the graduate student instructors chemical hygiene can decrease the overall number of laboratory accidents and increase awareness of chemical safety.

# Chapter 1

# Introduction

## 1.1 Introduction

Despite numerous and diverse efforts to improve the public image of chemistry, the subject has always been looked upon suspiciously by the general population.[1] Nevertheless, qualifying terms like "green" or "environmental" are becoming more common among scientists and the public. While it is well-known that discoveries within the field of chemistry have enhanced the quality of modern life with regards to energy, health, transportation, and communications, these innovations have come with a cost.[2] From local environments to global communities, ecosystems have been contaminated and people have been endangered. There is still a great need to improve the social response to chemistry-related subjects. Better education about the value of chemical investigation is still of paramount importance, and the chemistry itself needs to be better understood. The fear of chemistry that prevails in many social and academic areas is centered on an overwhelming lack of understanding.

For years, chemists like Dr. Paul Anastas have been trying to change the world's view of the field by showing how chemistry can be conducted in a cleaner and safer manner. Known as the "father of green chemistry" for having coined the term in 1991, Anastas has made his life's work about "the design of new products and processes that reduce or eliminate the use and generation of hazardous substances".[3] Social trends leaning toward environmental or green chemistry create an opening for the general public to understand chemistry. However, relaying the knowledge of chemistry discoveries from the chemist to the general public is a multi-step process. It is an essential process that will continue to be important to our society as a whole.

Society is not the only group concerned with creating green chemistry.[4] Businesses, like pharmaceutical companies, have become increasingly interested in implementing a cost-effective way to become more socially responsible.[5] This is all explicitly described in the "Triple Bottom Line", a notion first defined by John Elkington.[6] Economic, social, and environmental reasons are fundamental factors required for transforming commercial processes into sustainable ventures. Merging the profit-conscious business view with the ideal of academic research and discovery will require a lot of analysis. The use of more environmentally-friendly solvents and reaction conditions must become the goal of academia, industry, and government. Bridging this gap between the consumer world and the work of pure research is becoming a more common goal among todays' chemists, and also a goal of this thesis.

Main group elements such as germanium or boron are generally considered to be comparatively less-toxic and multi-functional in the field of chemistry. To date, germanium is widely considered to lack the toxicity of its tin counterparts.[7-9] Similarly, boron is regularly used in chemical applications, is naturally abundant in the environment, and commonly found in a healthy diet of fruits and vegetables.[10] Choosing elements like these provides a responsible option for chemical investigations. Also, expanding the public's knowledge, of and respect for, chemistry is an important first step in gaining support for future green efforts. Even with better choices, the ability to safely handle chemicals is a challenge. Understanding chemical hygiene would not only help to minimize the fears surrounding chemistry, but it could facilitate a more generalized appreciation of the field and efforts to improve the field.

## 1.2 Organometallic Chemistry

### *1.2.1 What is a Germylene?*

Simply stated, germylenes are divalent germanium compounds in which the central atom has two covalent bonds, an open p-orbital and a pair of electrons (Figure 1.1). They are considered to be carbene analogs. Other group IV metals; Si, Ge, Sn and Pb, can also exist as neutral divalent species, or carbene analogs. The importance behind the reactivity of germylenes lies in the ability for them to act as both Lewis acids and Lewis bases. Germylenes that exist as a stable monomer under standard conditions in the solid state, such that of bis[bis(trimethylsilyl)methyl]germylene **1** and 2,2,5,5-tetrakis(trimethylsilyl)-1-stannacyclopentane-1,1-diyl **2 (**Figure 1.2**)** have been utilized in our work.[11, 12]

**Figure 1.1: General Structure of a Germylene**

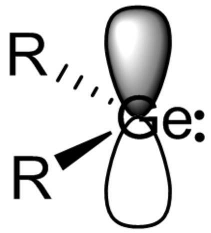
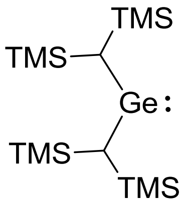
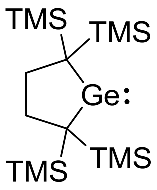


**Figure 1.2: Stable Monomeric Germylenes**



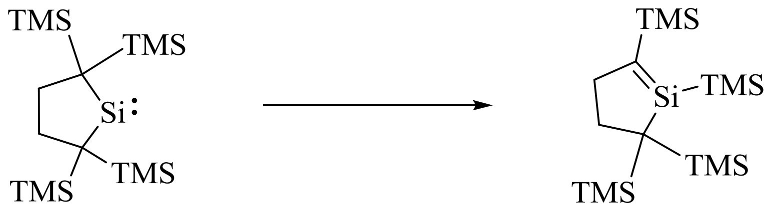
**1**



**2**

### *1.2.2 Advantages of Germanium*

Previous work has involved utilizing germylenes and other group IV metals to undergo C-H activation reactions.[13-16] This work has focused on using germylenes rather than the more reactive stannylene substrates for three main reasons. The first and most important reason is the lower toxicity of organogermanium reagents as compared to organotin complexes.[7-9] Even though silylene complexes are cheaper to synthesize and are much less toxic, the high reactivity and instability of these complexes is a problem. In particular, the cyclic silylene Kira complex **3** is extremely reactive; however at room temperatures, it isomerizes into a silaethene derivative **4** (Scheme 1.1).[17, 18] In contrast and as previously stated, germylenes are comparably stable complexes. Finally, germylenes were used in this research to widen the possible reaction scope. Germylenes can exhibit substantial functional group tolerance. The cyclic germylene can react in the presence of alkenes and carbonyls, which is not possible with the silylene analog. Neither the germylene nor the stannylene were shown to react with alkenes, suggesting that allylic C-H activation products could be feasible.[18]

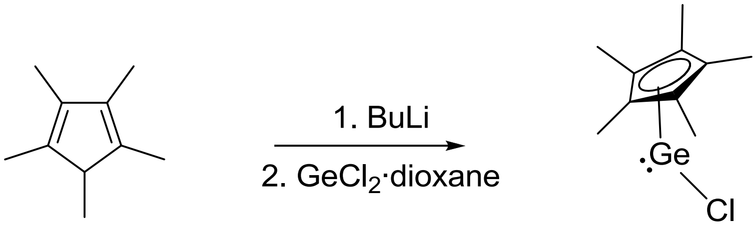


**3**

**4**

**Scheme 1.1: Isomerization into 1-Silylsilaethene**

The search for an alternative germylene that could be easily synthesized and is monomeric in solid state led to germylene **5**, Cp*GeCl, synthesized by Jutzi *et al* (Scheme 1.2).[19] Initial studies explored the reactivity of Jutzi's germylene, and revealed a lack of reactivity. This complex failed to participate in C-H activation reactions, and surprisingly oxidative addition into the C-I bond of phenyliodide was also not observed. This lack of reactivity incited a further examination into the molecular structure of **5**. X-ray crystallographic studies determined the presence of polymorphic structures in solid state, a phenomenon further explained in chapter 2.



**5**

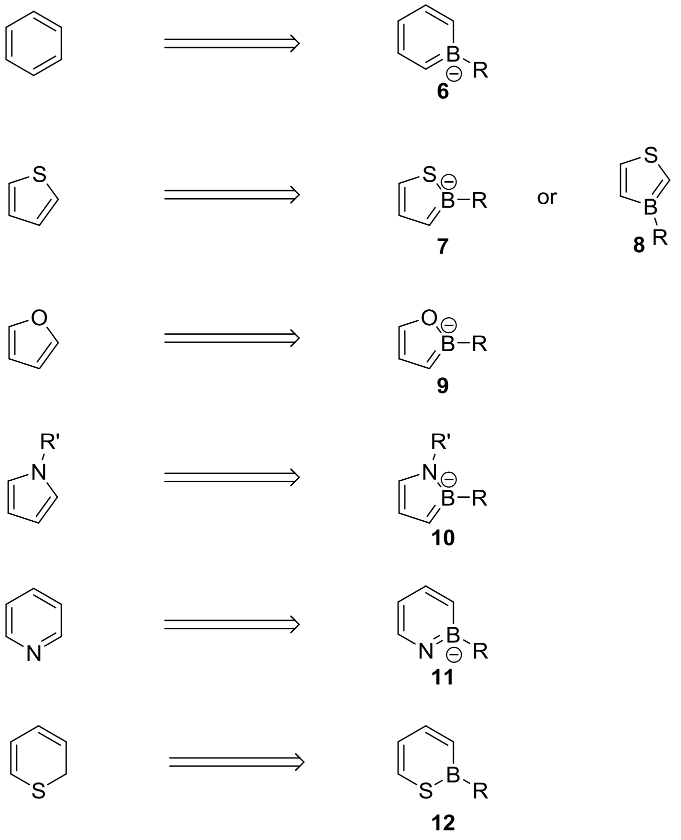
**Scheme 1.2: Synthesis of Jutzi's Germylene**

## 1.3 Computational Organic Chemistry

### *1.3.1 Boron Heterocycles*

Over the last couple decades research involving various boron heterocycles has been of significant importance.[20-30] Boron heterocycles are classically synthesized by replacing a CH in an aromatic ring by an isoelectronic $BH^-$ group. Various examples of previously synthesized compounds are shown in Figure 1.3, including boratabenzene **6**, anionic 1,2-thiaborolyl **7**, 1,3-thiaborolyl **8**, 1,2-oxaborolyl **9**, 1,2-azaborolyl **10**, and 1,2-azaboratabenzene **11**. The third chapter in this thesis will describe the synthesis and computational analysis of 2-Diiosopropylamino-2*H*-1,2-thiaborin **12**.

**Figure 1.3: Select Boron Heterocycles**



### *1.3.2 Why Boron Heterocycles?*

Due to the similar aromaticity of the parent compound, boron heterocycles have potential to be better π-donors for coordination to metals. The increased donation of the boron electrons, allows for hydrogen storage applications,[31, 32] and use in electronic materials.[33-35] The possibility for electron storage makes the synthesis of **12** to be of increasing interest. Detailed computational analysis was completed for 2-Diiosopropylamino-2*H*-1,2-thiaborin **12** and compared to that of 1,2-azaboratabenzene **11**. The aromaticity was determined through NICS(1) calculations which will be further discussed in Chapter 3.

## 1.4 Safety in the Organic Chemistry Laboratories

### *1.4.1 Undergraduate Organic Chemistry Chemical Hygiene Curriculum*

Initiated fall 2010, revisions of the Organic Chemistry Laboratory class, Chemistry 211, included incorporation of chemical hygiene topics including proper waste disposal, proper laboratory attire and general laboratory safety. Weekly readings, quizzes, and a variety of illustrative materials used inside and outside of the laboratory were utilized in order to introduce the new curriculum. This thesis will cover the implementation of the curricular additions and the assessment of the effectiveness of the curriculum as written.

### *1.4.2 Curriculum Effectiveness Assessment*

Assessment of the effectiveness was conducted in a variety of ways. First, pre- and post- lab surveys were given during the introductory course of the two-term sequence, Chemistry 211. Next, post- lab surveys were conducted after Chemistry 216, the next laboratory course in the sequence. Finally, in-class observations were conducted throughout the winter 2011 Chem 211 and 216 courses. A comparison was done in order to correlate survey results to reported accident data each term. Overall, reported accidents in the 2010-11 school year dropped 21% since the previous year, and 19% compared to the running five year average. Students showed an understanding of laboratory safety concepts according to in-class observations in Chem 211 compared to a control group. Also, there seemed to be a significant improvement in technical skill and a consistent level of conceptual understanding based on results taken following the next laboratory course in the series, Chem 216.

### 1.5 Summary

This thesis will initially discuss scientific discovery with the relatively benign main group metals, germanium and boron. The discovery of a new group IV polymorphic crystal structure and the investigation into the solution equilibria has increased the potential utility of germanium. The computational analysis of the aromaticity of a new boron-sulfur heterocycle has increased the desire for synthesis of the parent compound. Then expansion of modern chemical hygiene practices to the general undergraduate population via the creation and assessment of chemical hygiene taught to a large public university is assessed.

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# Chapter 2

# Parallelograms and Ladders: Polymorphic Solid State Structures and Solution Equilibria of Cp*GeCl

## 2.1 Introduction

### *2.1.1 Crystal Polymorphism*

Polymorphism (Greek) is literally defined as ”many forms”.[1] From the same idea, “crystal polymorphism” defines a group of materials sharing the same chemical composition while differing in either lattice structure or crystalline composition.[2] There is a lot of scientific and practical interest in polymorphic structures because compositionally identical substances may be vastly different in their bulk physical properties. These properties include color, density, melting point, solubility, and dissolution rate.[3] These differences in bulk physical properties are of utmost importance in pharmaceutical and optical applications, a fact that has led to many detailed studies over the years designed to better understand and, in some cases, to better control crystal polymorphism.

Polymorphic structures are a well-documented problem and an enormous concern in the pharmaceutical industry. Due to the possible differences in bioavailability, manufacturability and stability of the molecules, research has been ongoing to further understand the formation of polymorphic structures.[2, 4, 5] Tawashi was the first to document polymorphs of a pharmaceutical by observing that aspirin (*ortho*-acetylsalicylic acid) had two polymorphic forms[6] both structures have now been well-studied.[7-10] Other common polymorphic pharmaceuticals and their uses are listed in Table 2.1.[2]

**Table 2.1: Pharmaceuticals and Number of Known Polymorphs**

| | **Polymorphs** | **Application** |
|---|---|---|
| Chloramphenicol Palmitate | 2 | antibiotic |
| Carbmazepine | 4 | anticonvulsant |
| Sulfapyridine | 7 | antibiotic |
| Nabumetone | 2 | NSAID |
| Spiranolactone | 6 | diuretic |
| Enalapril maleate | 2 | ACE inhibitors |
| Ranitidine HCL | 2 | histamine $H_2$-receptor antagonist |
| Warfarin VA | 2 | anticoagulant |
| Prednisolone tetrabutylacetate | 2 | steroid |
| Ampicillin | 3 | antibiotic |

While organic polymorphs are well known, organometallic molecules can also exhibit crystal polymorphism. An organometallic pharmaceutical that provides an example of this phenomenon is titanocene dichloride, used in chemotherapies. Titanocene dichloride and its derivative, Di-μ-chloro-bis[bis($\eta^5$-cyclopentadienyl)titanium(III)], each have two known polymorphic structures.[11-13] A survey of the literature in the Cambridge database indicates that 3.2% of all published crystal structures are polymorphs (17,232/541,748).[14] Additionally, 4.4% of all organic crystal structures (10,159/231,963) are polymorphs and, when coordination complexes are included in the group, the percent of organometallic compounds in the group of polymorphs drops to 2.3% (7.401/321,916) of reported crystal structures.

### *2.1.2 Group 14 Polymorphs*

$ER_2$ (E = C, Si, Ge, Sn, Pb) species have a rich donor/acceptor chemistry because of the presence of an $sp^2$-like lone pair on E as well as an empty p-like orbital. Four examples of $ER_2$ compounds have been previously characterized with polymorphic structures.[15-19] $Sn[2,4,6\text{-}(CF_3)_3C_6H_5]_2$ crystallizes in a $P\bar{1}$ phase containing Sn···Sn interactions of 3.639(1) Å and a density of 2.104 g/cc, whereas the $P2_1/a$ phase contains no close Sn···Sn interactions and has a density of 2.126 g/cc.[16, 19] Based on the principle of closest packing,[20, 21] the phase containing Sn···Sn interactions is expected to have a higher free energy and less stability because of its lower density. The two polymorphs identified for $Ge[N(2,4,6\text{-}(CF_3)_3C_6H_5)_2]_2$ also follow the principle of closest packing. The more stable polymorph Pccn has intramolecular Ge···Ge distances of 2.840 Å and density of 2.126 g/cc whereas the $P2_1/n$ polymorph has intramolecular Ge···Ge distances of 2.857 Å and a density of 2.111 g/cc.[18]

This chapter discusses an X-ray crystallographic analysis of Cp*GeCl and the comparison between the dimeric $P2_1/n$ and the C2/c ladder polymorph structures. This case is interesting because both Ge···Ge and Ge-Cl interactions have the potential to play a role in intermolecular interactions.[22] The dimeric $P2_1/n$ polymorph with the shorter E···E interaction has the greatest density and is the more stable polymorph as indicated by neat melting/recrystallization experiments; however, the $P2_1/n$ structure is also substantially more soluble than the polymorphic ladder, C2/c. The $^1H$ NMR spectrum of Cp*GeCl is highly temperature and concentration dependent. Data for these equilibria are presented and interpreted in terms of an equilibrium between the Cp*GeCl monomer and either a dimer or a higher oligomer species.

## 2.2 Results and Discussion

Cp*GeCl was synthesized according to the method published by Kohl and Jutzi.[23] Crystals were obtained via two different methods. Sublimation *in vacuo* at 0.2 torr and 65 °C resulted in yellow blocks, Form I. Crystallization from THF, benzene, or hexanes at room temperature resulted in colorless blocks, Form II. X-ray crystallographic analysis revealed that two polymorphs of Cp*GeCl had been obtained. Crystallographic information for Form I grown via sublimation and Form II grown from THF solution is summarized in Figure 2.1and Table 2.2.

**Figure 2.1: ORTEP of the molecular structure of Cp*GeCl.** Selected bond lengths (Å) and angles (°) for Form I ($P2_1/n$): Ge-Cl, 2.3872(7); Ge-C1, 2.2128(14); Ge-C2, 2.2241(13); Ge-C3, 2.4294(14); Ge-C4, 2.4889(14), Ge-C5, 2.596(1); C1-Ge-Cl, 96.13(4); C2-Ge-Cl, 100.10(4). Selected bond lengths (Å) and angles (°) for Form II (C2/c): Ge-Cl, 2.4295(3); Ge-C1, 2.300(11); Ge-C2, 2.2402(12); Ge-C3, 2.495(1); Ge-C4, 2.4534(12); Ge-C5, 2.604(1); Cl-Ge-C1, 98.45(3); Cl-Ge-C2, 92.75(3). Selected bond lengths (Å) and angles (°) for Cp*GeCl computed using density functional theory (B3LYP/6-31G*): Ge-Cl, 2.414; Ge-C1, 2.258; Ge-C2, 2.297; Ge-C3, 2.566; Ge-C4, 2.568; Ge-C5, 2.734.

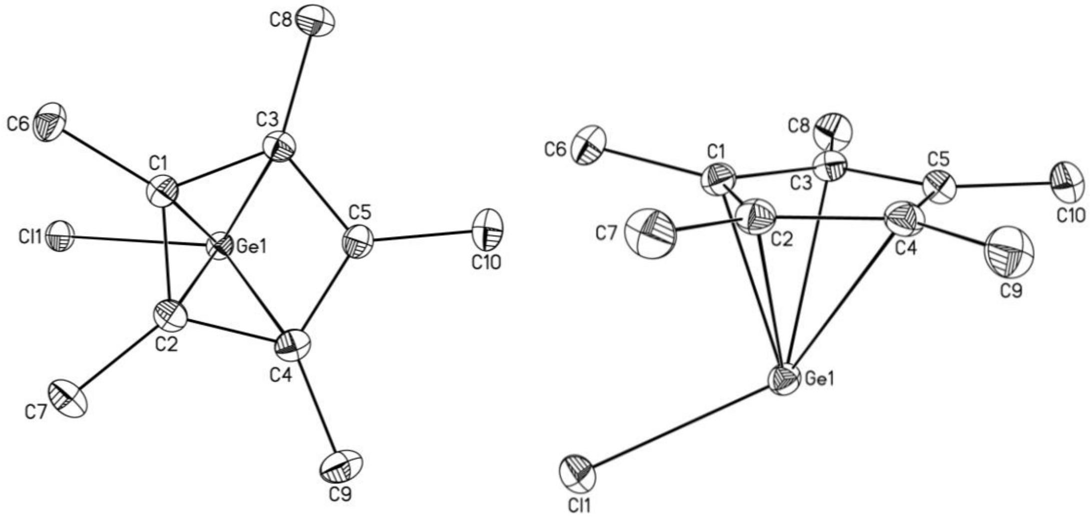
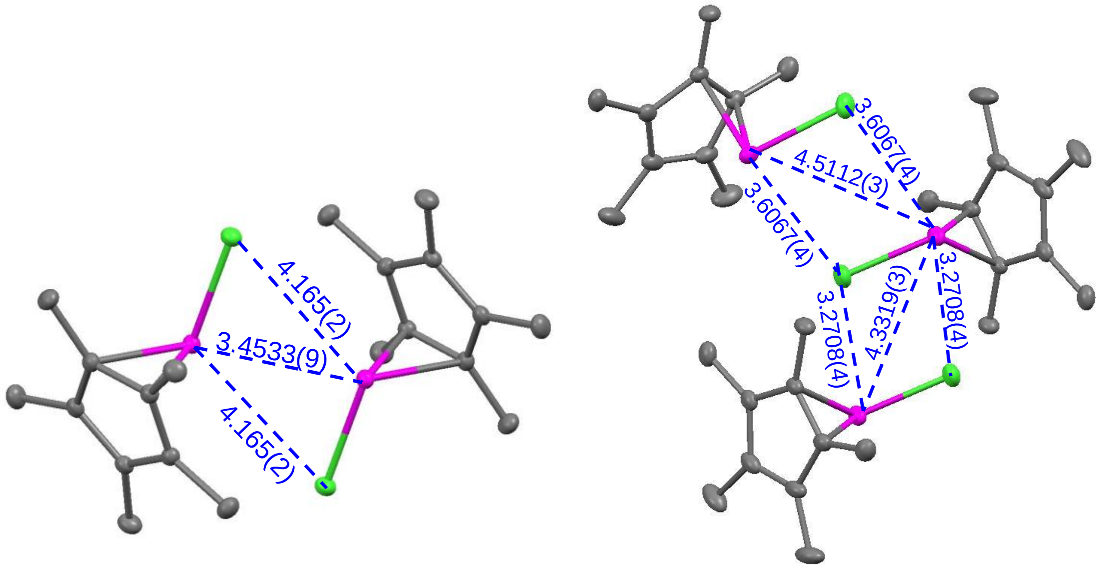


**Table 2.2: Crystallographic Information for Forms I and II of Cp*GeCl**

| | **Form I** | **Form II** |
|---|---|---|
| color | yellow | colorless |
| crystal system | monoclinic | monoclinic |
| space group | $P2_1/n$ | C2/c |
| Temperature | 85 (2) K | 85(2) K |
| $a$ (Å) | 9.0939(18) | 16.3143(7) |
| $b$ (Å) | 6.8790(14) | 12.0713(6) |
| $c$ (Å) | 17.395(4) | 11.8225(5) |
| $\alpha$ (deg) | 90 | 90 |
| $\beta$ (deg) | 102.54(3) | 109.368(1) |
| $\gamma$ (deg) | 90 | 90 |
| $Z$ | 4 | 8 |
| V (Å$^3$) | 1062.2(4) | 2196.50(17) |
| $\rho$ (g/cm$^3$) | 1.521 | 1.471 |
| data/parameters/restraints | 2999/0/114 | 39241/0/114 |
| GOF | 1.114 | 1.098 |
| $R_1$ ($I > 2\sigma$, all data) | 0.0195, 0.0201 | 0.0197, 0.0213 |
| $wR^2$ ($I > 2\sigma$, all data) | 0.0493, 0.0495 | 0.0517, 0.0526 |

**Figure 2.2: Isolated $Ge_2Cl_2$ parallelograms are present in Form I.** Two unique $Ge_2Cl_2$ parallelograms forming an extended ladder structure are present in Form II. Selected bond lengths (Å) and angles (°) for Form I ($P2_1/n$): Ge-Ge, 3.4533(9); Cl-Cl, 5.845(2); Ge-Cl, 2.3872(7); Ge-Cl, 4.165(2); Cl-Ge-Cl 123.99(2); Ge-Cl-Ge, 56.01(2). A perfect parallelogram is enforced by crystal symmetry. Selected bond lengths (Å) and angles (°) for Form II (C2/c): Parallelogram (a) Ge-Ge 4.3319(3); Cl-Cl, 3.7994(7); Ge-Cl, 2.4295(3); Ge-Cl, 3.2708(4); Cl-Ge-Cl, 82.17(1); Ge-Cl-Ge 97.83(1). A perfect parallelogram is enforced by crystal symmetry. Parallelogram (b) Ge-Ge, 4.5112(3); Cl-Cl, 4.1544(7); Ge-Cl, 2.4295(3); Ge-Cl, 3.6067(4); Cl-Ge-Cl, 84.59(1); Ge-Cl-Ge, 94.71(3); this is a distorted parallelogram with a Ge-Cl-Ge-Cl torsion of 10.89(2). Selected bond lengths (Å) and angles (°) for Cp*GeCl computed using density functional theory (B3LYP/6-31G*): Ge-Cl, 2.414; Ge-Cl, 3.463; Ge-Ge, 4.434; Cl-Cl, 3.997; Cl-Ge-Cl, 83.67; Ge-Cl-Ge, 96.33.

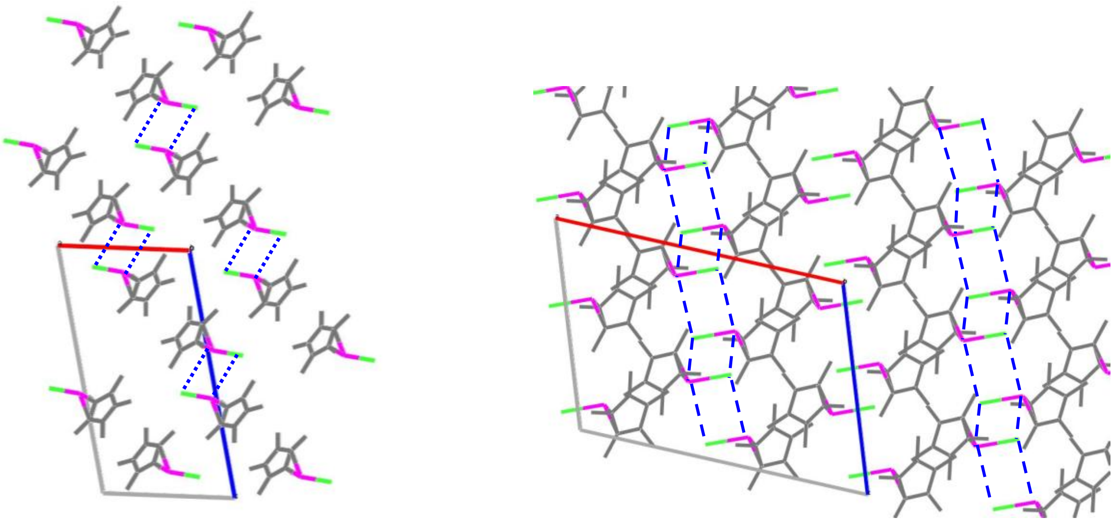


**Form I** **Form II**

Form I ($P2_1/n$), a dimer in the geometry of a parallelogram is formed by two Cp*GeCl units (Figure 2.2, Form I). The Ge-Cl bond length is 2.3872(7) Å, which is larger than the sum of the covalent radii of 2.21 Å. The Ge···Cl intermolecular distance of 4.165(2) Å is larger than the sum of the Van der Waals radii of 3.9 Å.[24] The intermolecular Ge···Ge distance of 3.4533(9) Å is substantially shorter than the sum of the Van der Waals radii of 4.2 Å. The intermolecular Cl···Cl distance of 5.845(2) Å is far greater than the sum of the van der Waals radii. The $P2_1/n$ form has a density of 1.521 g/cm$^3$.

Colorless Polymorph Form II (C2/c) consists of alternating parallelograms that generate an infinite ladder (Figure 2.2, Form II). The Ge-Cl bond length of 2.4295(3) Å is slightly longer than that of the $P2_1/n$ structure; however, the intermolecular Ge···Cl distances are 3.607(4) Å and 3.271(4) Å, which are substantially shorter than both the Ge···Cl contact in Form I and the sum of the Ge and Cl Van der Waals radii. The Ge···Ge distances are 4.5112(3) Å and 4.3319(3) Å larger than the sum of Ge Van der Waals radii and substantially greater than the Ge···Ge contact observed for Form I. The Cl···Cl distances are 4.1544(7) Å and 3.7994(7) Å, both shorter than observed for Form I. The C2/c form has a density of 1.471 g/cm$^3$. Packing diagrams for both forms are illustrated in Figure 2.3.

**Figure 2.3: Packing diagrams with the Ge···Ge interactions and $Ge_2Cl_2$ parallelograms highlighted (along axis b).**



**Form I** **Form II**

A similar ladder has been seen previously with a tin analog, CpSnCl.[25] In this case, a single type of parallelogram formed an infinite ladder. The Sn···Sn distances were 4.702(3) Å, which are greater than the sum of the Van der Waals radii of 4.34 Å. The intermolecular Sn···Cl distances are 3.240 Å which is substantially less than the sum of the Van der Waals radii of 3.92 Å.[26] The overall area of the parallelogram for CpSnCl is 2.4 % bigger than that observed for Form I of Cp*GeCl and 6.7 % bigger than that observed for Form II parallelogram (a), and 3.3 % smaller than Form II parallelogram (b) when torsion is taken into consideration.

Density functional theory (DFT) calculations were conducted to explore the structure of an isolated Cp*GeCl dimer. The Ge-Cl bond distance and Ge···Cl contact were calculated to be 2.414 and 3.462 Å, respectively. The Ge···Ge and Cl···Cl distances were calculated to be 4.434 and 3.997 Å, respectively. The experimentally determined dimeric form gives rise to a substantially shorter Ge···Ge distance and a parallelogram with a Cl-Ge-Cl angle of 123.99° versus 83.67° for the computed structure, which more closely matches the C2/c parallelogram (a) (82.16°). The computation of the experimental structure containing the shorter 3.4533(9) Å Ge···Ge contact indicates the presence of a weak Ge-Ge bond composed of sp-hybrid orbitals. This interaction is not present in the computed structure minimized in vacuum with the longer 4.434 Å Ge···Ge contact. Despite the presence of weak Ge-Ge bonding, the DFT minimized structure was 7 kcal/mol more stable than the dimer structure using the X-ray coordinates. This suggests that crystal packing forces play a substantial role in the metrical parameters observed for the experimental dimer structure.

In order to explore which polymorph was more thermodynamically stable, single crystals were placed into X-ray capillary tubes, and after four melting and cooling cycles, the space group of the resulting crystals was ascertained by X-ray diffraction. Form I retained the $P2_1/n$ space group; however, Form II was found to have interconverted from C2/c to $P2_1/n$, indicating that Form I is the more stable polymorph. This conclusion is consistent with the principle of closest packing,[20, 21] which states that the denser $P2_1/n$ form (1.521 g/cm$^3$) should be more thermodynamically stable than the less dense C2/c form (1.471 g/cm$^3$). Interestingly, Form I, despite being the more stable crystalline form, dissolves in toluene, benzene, and acetonitrile to a far greater degree than Form II. Based on the amounts required to form saturated solutions, Form I is ~5x more soluble than Form II. It is possible that this apparent solubility differential is a kinetic effect and that the dimers dissolve more quickly than the infinite ladders, since the more stable crystal should coincide with the less soluble form.[3] DSC studies were conducted, but due to the atmospheric instability of the polymorphs, results were not reproducible.

The $^1$H NMR chemical shift of Cp*GeCl was found to be concentration dependent in all solvents tested including toluene-$d_8$, benzene-$d_6$, and acetonitrile-$d_3$. For instance, in toluene-$d_8$, a concentration range of 0.65 to 0.016 M was explored, giving a variation in chemical shift of 1.783 to 1.681 ppm as illustrated in Figure 2.4. Four different concentrations of Cp*GeCl derived from Form I crystals were made up (0.1, 0.2, 0.4 and 0.5 M) in toluene-$d_8$ and the temperature was varied from room temperature 25 °C to -80 °C. The same process was repeated using Form II crystals, although only 0.016 and 0.008 M solutions were employed due to solubility constraints. The spectra are shown for the 0.2 M case with the observed range of chemical shifts varying from 1.197 to 1.744 ppm, respectively (Figure 2.5). A summary of the temperature and concentration dependent $^1$H chemical shift data is provided in Figure 2.6. Previous cryoscopic molecular weight studies by Kohl and Jutzi indicate that Cp*GeCl is a monomer in the 0.02 – 0.04 M concentration range.[23]

**Figure 2.4: Concentration dependent $^1$H NMR spectra of Cp*GeCl.** Concentrations shown include 0.65 M, 0.6 M, 0.32 M, 0.16 M and 0.05 M at 25 °C.

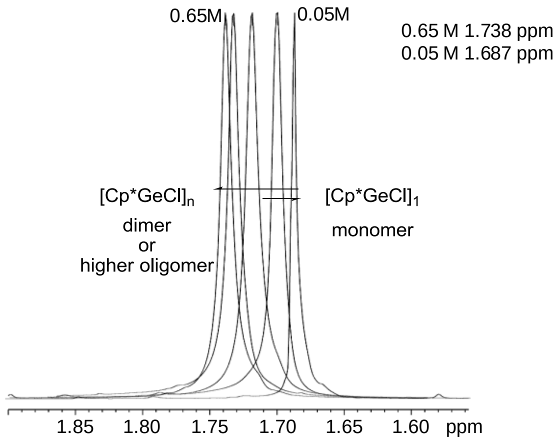


**Figure 2.5: Variable Temperature $^1$H NMR of Cp*GeCl in toluene-$d_8$.** Temperatures shown include -80 °C, -75 °C, -65 °C, -55 °C, -45 °C and -20 °C for a 0.2 M solution.

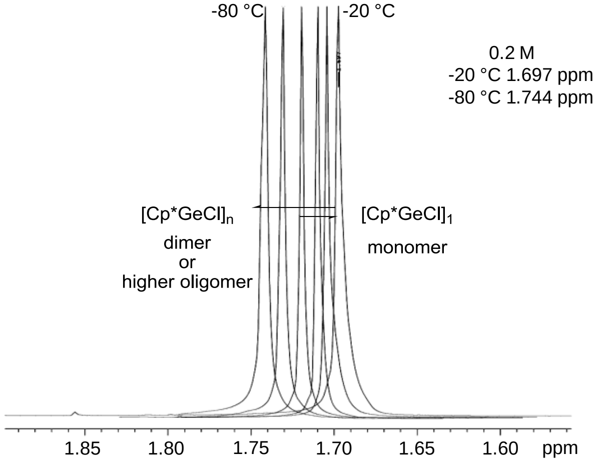
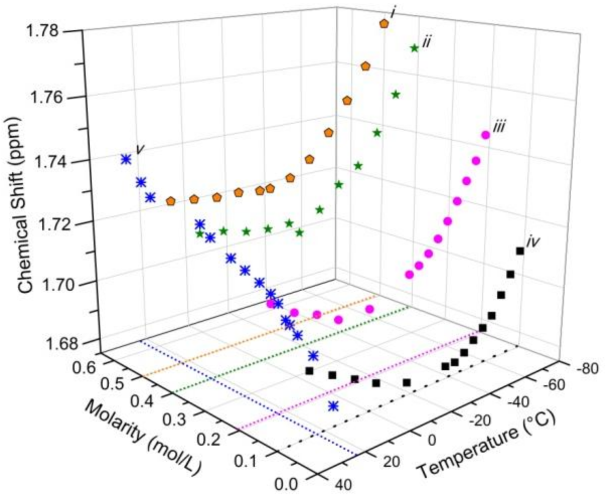
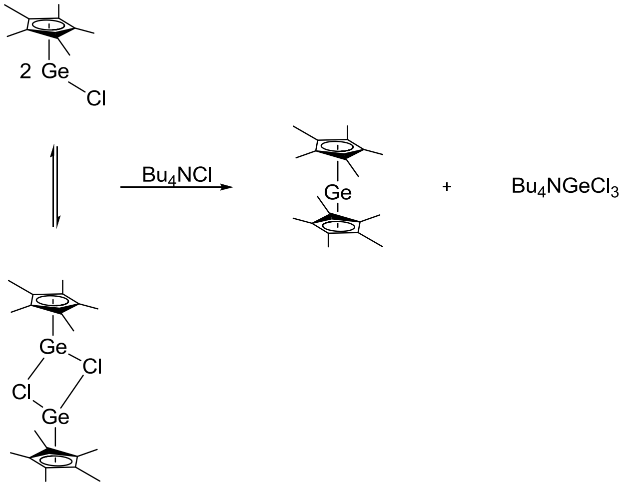


**Figure 2.6: A summary of $^1$H NMR chemical shift as a function of temperature and concentration for Cp*GeCl in toluene-$d_8$.** *i*. 0.5 M VT $^1$H NMR, *ii*. 0.4 M VT $^1$H NMR, *iii*. 0.2 M VT $^1$H NMR, *iv*. 0.1 M VT $^1$H NMR, *v*. Dilution Experiments rt $^1$H NMR.



Alternative hypotheses for the observed equilibria in the NMR spectrum include an equilibrium involving dissociation of $Cl^-$ and an equilibrium of Cp*GeCl with $Cp^*_2Ge$. If the disassociation of a chloride ion was occurring, as previously proposed,[23] then the equilibrium could be shifted in the opposite direction by adding additional $Cl^-$.

To test this, $Bu_4NCl$ was added to three different concentrations of Cp*GeCl (0.05 M, 0.2 M and 0.52 M). In each case, a new peak immediately appeared at 1.922 ppm in the $^1H$ NMR spectrum and the remaining Cp*GeCl-derived peak shifted upfield consistent with a *decreased* concentration of Cp*GeCl. The addition of ½ equiv of $Bu_4NCl$ for Cp*GeCl present was sufficient to consume all of the Cp*GeCl. The $^1H$ NMR spectrum was consistent with the irreversible formation of $Cp^*_2Ge$ (Scheme 2.1), and this was confirmed by single crystal X-ray diffraction. This product had been previously reported by Jutzi et al. where they described the disproportionation of Cp*GeCl to form $Cp^*_2Ge$.[23]



**Scheme 2.1: Effect of Cl⁻ on the equilibrium of Cp*GeCl with $[Cp^*GeCl]_2$.**

We further tested to see if $Cl^-$ was present by adding methyl mesylate. A control reaction was conducted by adding methyl mesylate to a solution of $Bu_4NCl$ in toluene. Methyl chloride was instantaneously formed, visible via $^1H$ NMR; however, the addition of methyl mesylate to various concentrations of Cp*GeCl (0.18, 0.09 and 0.06 M) in toluene-$d_8$ gave no reaction and no methyl chloride was observed. This is strong evidence against an equilibrium involving $Cl^-$ ion.

If a disproportionation reaction of Cp*GeCl formed some $Cp^*_2Ge$ in solution, it is possible that the equilibria observed could result from an exchange involving these two species. In order to test this, an authentic sample of $Cp^*_2Ge$ was synthesized. A 0.03 M solution was prepared in toluene-$d_8$ and $^1H$ NMR spectra were taken with 0, 0.5, 1, 2, 4 and 6 molar equiv of Cp*GeCl. The two expected singlets were observed. The $Cp^*_2Ge$ peak did not change in any fashion as a function of the added Cp*GeCl. The Cp*GeCl peak increased in intensity and shifted downfield with increased concentration as expected.

## 2.3 Conclusions

In conclusion, X-ray crystallographic studies of Cp*GeCl revealed two polymorphic structures. Yellow Form I is a dimer in the solid state that dissolves readily in organic solvents and is the more stable form. Colorless Form II is an infinite ladder structure that is sparingly soluble in organic solvents. No evidence for the interconversion of Cp*GeCl to $Cp^*_2Ge$ was observed in benzene-$d_6$, toluene-$d_8$, or acetonitrile-$d_3$ solvents at 23 °C. In addition, no evidence was found for an equilibrium involving the disassociation of $Cl^-$. Based upon $^1H$ NMR and cryscopic studies, a fast monomer-dimer or monomer-higher oligomer equilibrium is proposed. Further studies would include further analysis of the solution equilibria, and investigations into other germanium polymorphic structures.

## 2.4 Experimental Section

All manipulations were performed using air free techniques in an inert atmosphere box using dry, deoxygenated solvents. All solvents were degassed and dried over sodium benzophenone ketyl. Acetonitrile-$d_3$ was dried over $P_2O_5$ and stored over 4 Å sieves. Cp*GeCl was prepared using literature methods.[23] $^1$H NMR spectra were recorded on a Varian Inova 400 spectrometer at 399.367 MHz. The spectra were referenced to the residual protons in toluene-$d_8$ at 2.09 ppm, acetonitrile-$d_3$ at 2.19 ppm, benzene-$d_6$ at 7.16 ppm or an internal standard, and tetramethylsilane at 0.00 ppm. The $P2_1/n$ form of Cp*GeCl was employed for the majority of concentration and temperature dependent $^1$H NMR spectra and for all of the cryoscopic molecular weight determinations due to ease of synthesis. Limited temperature dependent $^1$H NMR experiments were carried out with the C2/c material to verify that the results were polymorph independent.

**Structural Determination of Cp*GeCl ($P2_1/n$) (Form I):** Yellow blocks of **Form I** were grown by sublimation under vacuum at 65 °C. A crystal of dimensions 0.43 x 0.33 x 0.29 mm was mounted on a Bruker SMART APEX CCD-based X-ray diffractometer equipped with a low temperature device and fine focus Mo-target X-ray tube ($\lambda$ = 0.71073 A) operated at 1500 W power (50 kV, 30 mA). The X-ray intensities were measured at 85(1) K; the detector was placed at a distance 5.055 cm from the crystal. A total of 4095 frames were collected with a scan width of 0.5° in $\omega$ and 0.45° in phi with an exposure time of 10 s/frame. The integration of the data yielded a total of 50909 reflections to a maximum $2\theta$ value of 60.30° of which 2999 were independent and 2935 were greater than $2\sigma(I)$. The final cell constants (Table 2.2) were based on the xyz centroids of 9994 reflections above 10$\sigma$(I). Based on indexing using the program CELL_NOW, the crystal was determined to be a two-component, non-merohedral twin with the domains related by a rotation of 179.3 degrees about the direct and reciprocal [0 1 0] axis. Analysis of the data showed negligible decay during data collection; the data were processed and merged with TWINABS and corrected for absorption. The structure was solved and refined with the Bruker SHELXTL (version 2008/3) software package, using the space group $P2_1/n$ with Z = 4 for the formula $C_{10}H_{15}GeCl$. All non-hydrogen atoms were refined anisotropically with the hydrogen atoms placed in idealized positions. Single reflections and composite reflections involving the primary domain were used in preparing a HKLF 4 format reflection file for this refinement. Full matrix least-squares refinement based on $F^2$ converged at R1 = 0.0195 and wR2 = 0.0493 [based on I > 2sigma(I)], R1 = 0.0201 and wR2 = 0.0495 for all data. Additional details are presented in Table 2.2.

**Structural Determination of Cp*GeCl (C2/c) (Form II):** Colorless blocks of **Form II** were grown from a tetrahydrofuran solution at 25 °C. A crystal of dimensions 0.22 x 0.15 x 0.13 mm was mounted on a Bruker SMART APEX CCD-based X-ray diffractometer equipped with a low temperature device and fine focus Mo-target X-ray tube ($\lambda$ = 0.71073 A) operated at 1500 W power (50 kV, 30 mA). The X-ray intensities were measured at 85(1) K; the detector was placed at a distance 5.055 cm from the crystal. A total of 3850 frames were collected with a scan width of 0.5° in $\omega$ and 0.45° in phi with an exposure time of 15 s/frame. The integration of the data yielded a total of

39241 reflections to a maximum 2θ value of 60.16° of which 3085 were independent and 2896 were greater than 2σ(I). The final cell constants (Table 2.2) were based on the xyz centroids of 9921 reflections above 10σ(I). Analysis of the data showed negligible decay during data collection; the data were processed with SADABS and corrected for absorption. The structure was solved and refined with the Bruker SHELXTL (version 2008/3) software package using the space group C2/c with Z = 8 for the formula $C_{10}H_{15}GeCl$. All non-hydrogen atoms were refined anisotropically with the hydrogen atoms placed in idealized positions. Full matrix least-squares refinement based on $F^2$ converged at R1 = 0.0197 and wR2 = 0.0517 [based on I > 2sigma(I)], R1 = 0.0213 and wR2 = 0.0526 for all data. Additional details are presented in Table 2.2.

**Concentration Dependent $^1$H NMR Spectroscopy Experiments:** The samples were prepared by dissolving 84 mg of Cp*GeCl ($P2_1/n$) in 0.5 ml of toluene-$d_8$. Serial dilution was used to generate 0.65 to 0.05 M solutions. Due to the slow dissolution rate of Cp*GeCl (C2/c), these experiments could not be conducted on both polymorphs.

**Variable-Temperature $^1$H NMR Spectroscopy Experiments:** The samples were prepared by dissolving 13-61 mg of Cp*GeCl ($P2_1/n$) or Cp*GeCl (C2/c) in 0.5 ml of toluene-$d_8$ or acetonitrile-$d_3$. Variable-temperature measurements were performed by decreasing the temperature from 25 °C in 5-10 °C increments. At each temperature, the solution was allowed to equilibrate for 15 minute before spectra were taken. The temperature was lowered to -25 °C in acetonitrile, and -80 °C in toluene. Once the lower limit was reached, the temperature was allowed to rise in 10 °C increments and spectra were obtained every 40 °C until room temperature was reached. The samples were reshimmed as needed during the experiment.

**Chloride Ion addition $^1$H NMR Spectroscopy Experiments:** The samples were prepared by dissolving 7-63 mg of Cp*GeCl ($P2_1/n$) in 0.5 ml of toluene-*d₈*. All measurements were taken at 25 °C. After the initial spectrum was taken, 0.1, 0.3, 0.5 and 1.0 equiv of tetrabutylammonium chloride were added and $^1$H NMR spectra were taken for each addition. The spectra were referenced to the internal standard peak at 0.00 ppm due to the overlapping peaks of the butyl groups at 2.09 ppm.

**Electrophilic Induced $S_N2$ Reaction Experiments:** A control reaction of the addition of tetrabutylammonium chloride (1 equivalent) to methyl mesylate (1 equivalent) in toluene-$d_8$ (0.5 mL) was used to verify reactivity of chloride ion in solution. To a solution of Cp*GeCl ($P2_1/n$) (22 mg) in toluene-$d_8$ (0.5 mL), 1 equivalent of methyl mesylate (10 mg) was added and the reaction was monitored by $^1$H NMR spectroscopy. At all concentrations (0.18, 0.09 and 0.06 M) studied, no reaction occurred, and no formation of methyl chloride was observed.

**Cp*GeCl to $Cp*_2Ge$ Interconversion Experiments:** 5 mg of $Cp*_2Ge$ was dissolved in toluene-$d_8$ (0.5 mL) and all measurements were made at 25 °C. After the initial spectrum was taken, 0.5, 1.0, 2.0 and 4.0 equiv of Cp*GeCl ($P2_1/n$) were added and spectra were taken at each ratio. As concentration increased, a downfield shift of the Cp* moiety was observed, ascribed to the monomer and either a dimer or a higher oligomer exchange, along with increase in peak intensity relative to both the internal standard and $Cp^*_2Ge$. No evidence for exchange between Cp*GeCl and $Cp^*_2Ge$ was observed.

**Density Functional Calculations:** All computations were carried out using the B3LYP functional and the 6-31G* basis set using Spartan '08 (Wavefunction, Inc.).[27]

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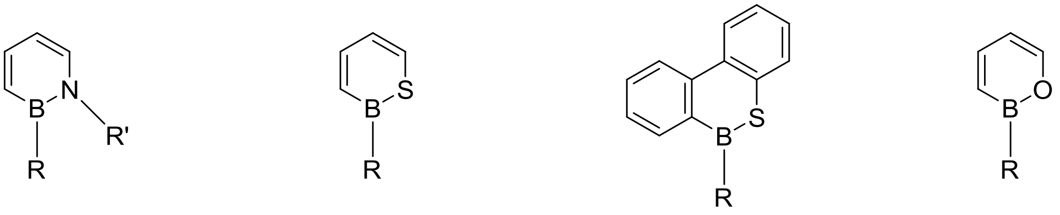
# Chapter 3

## 2*H*-1,2 Thiaborin: A New Boron-Sulfur Heterocycle

### 3.1 Introduction

Recently, the six-π-electron boron-nitrogen heterocycle, 1,2-dihydro-1,2-azaborine **1**,[1, 2] has attracted considerable attention due to its aromaticity[3-12] and its potential uses in electronic devices[13-15] and in hydrogen storage.[16] The analogous boron-sulfur heterocycle, 2*H*-1,2-thiaborin **2**, should also be interesting. Prior work on 2*H*-1,2-thiaborins is confined to the ring-fused derivatives **3** published in the 1960s.[17, 18] Although **3b** was reported to display an aromatic UV spectrum, little other information is available. Clearly, the synthesis of a minimally-substituted derivative of this parent ring system would be highly desirable. The synthesis, spectroscopic and structural characterization, and DFT calculations of 2-(diisopropylamino)-2*H*-1,2-thiaborin **2c** will be discussed.

**Figure 3.1: Analogous Boron Heterocycles**



**1a,** R=R'=H
**1b,** R=Ph, R'=H

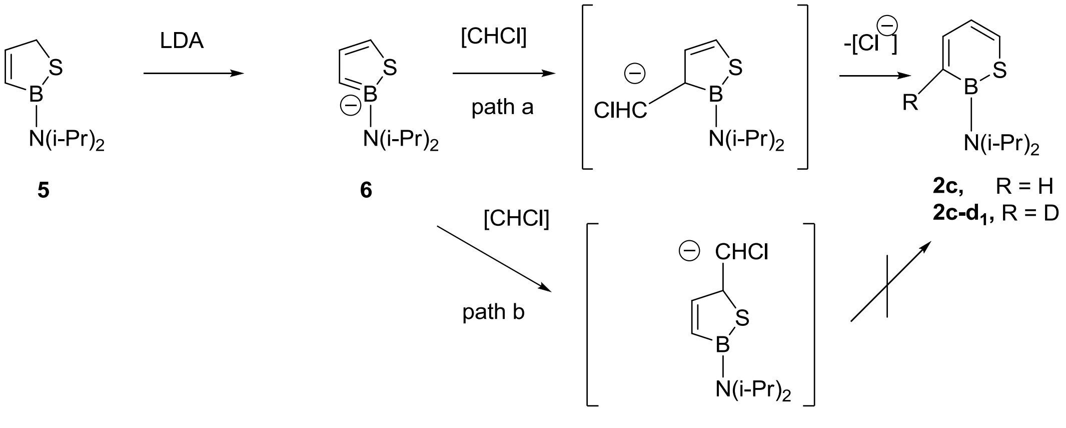
**2a,** R=H
**2c**, R=N(i-Pr)$_2$

**3b**, R=Ph

**4b**, R=Ph

## 3.2 Results and Discussion

The synthesis of **2c** was performed by Dr. Arthur J. Ashe, III. This synthesis involved an extension of the carbenoid ring-expansion route previously used to prepare both **1b**[5, 19] and the analogous boron-oxygen heterocycle **4b**.[20] Treatment of the readily available 2,5-dihydro-2-(diisopropylamino)-1,2-thiaborole **5**[21] with two equivalents of LDA in THF followed by a reaction with excess methylene chloride afforded a 15% yield of **2c**. The 2*H*-1,2-thiaborin **2c** was distilled from the reaction mixture and isolated as a pale yellow oil which solidified to well-formed block-like crystals, mp = 21 $^{o}$C. When the reaction was performed using $d_2$-methylene chloride, the deuterium was found exclusively at the 3-position. The reaction is consistent with the *in situ* formation of chlorocarbene which adds to C(3) of 1,2-thiaborolide **6** (path a) Scheme 3.1. Subsequent ring expansion followed by loss of chloride affords **2c** as illustrated. It had been previously found that the C(5) position of **6** is more nucleophilic than C(3).[21] We speculate that any chlorocarbene attack at C(5) (path b) does not lead to low molecular weight products but is responsible for the relatively modest yield of **2c**.



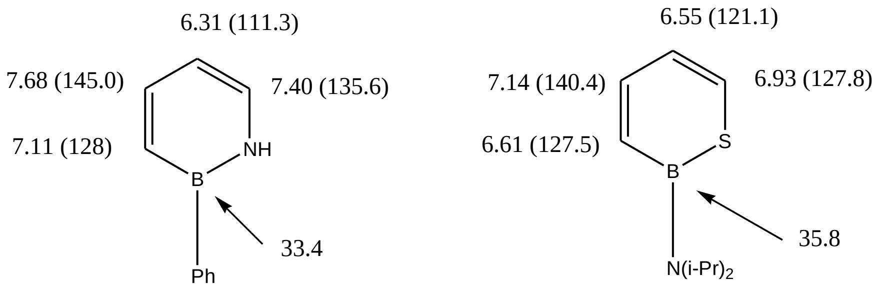
**Scheme 3.1: Ring Expansion to Afford 2-(Diisopropylamino)-2*H*-1,2-Thiaborin**

2-(Diiosopropylamino)-2*H*-1,2-thiaborin has been characterized by $^{1}$H, $^{11}$B, and $^{13}$C NMR spectroscopy, high resolution mass spectroscopy, UV absorption spectroscopy and X-ray diffraction. All spectroscopies are consistent with the assigned structure.

Slow recrystallization from the melt gave crystals of **2c** suitable for X-ray diffraction. The molecular structure, illustrated in Figure 3.3, shows a planar (±0.015(2)Å) 2*H*-1,2-thiaborine ring. Although partial disorder between S(1) and C(1) limits the accuracy of the bond distances, the structure is consistent with diene π-bonding in the ring, in which the C-C double bonds are shorter than the C-C single bond. The short distance (1.401(7)Å) between boron and the sp$^{2}$-hybridized nitrogen indicates exocyclic B-N π-bonding, which is independently shown by the rotational barrier about the B-N bond. Slow rotation about the B-N bond makes the $^{i}$Pr groups non-equivalent in both the both the $^{1}$H and $^{13}$C NMR spectra recorded at 0 °C. On heating **2c** in $CDCl_3$ to 50 °C the methine signals in the $^{13}$C NMR spectrum (δ 49.26, 45.76) coalesce, indicating a barrier to rotation about the B-N bond of $\Delta G^{*} = 14.2 \pm 0.5$ kcal/mol. To some extent this exocyclic π-bonding is likely to diminish the endocyclic π-bonding in the ring.[22-27]

The $^{1}$H, $^{11}$B, and $^{13}$C NMR chemical shift values of **1b** and **2c** are compared in Figure 3.2. The $^{1}$H NMR spectrum of **2c** in $CDCl_3$ shows a characteristic first order pattern which strongly resembles those shown by 1,2-dihydro-1,2-azaborines **1**. The chemical shift values of **2c** are at higher field than those of **1b**. However both sets of compounds show signals in the aromatic region (6.6 – 7.1ppm) which is consistent with a diamagnetic ring current for both. The $^{11}$B and $^{13}$C NMR chemical shifts of the two compounds are also quite similar which is consistent with similar electronic structures for the two families of heterocycles.

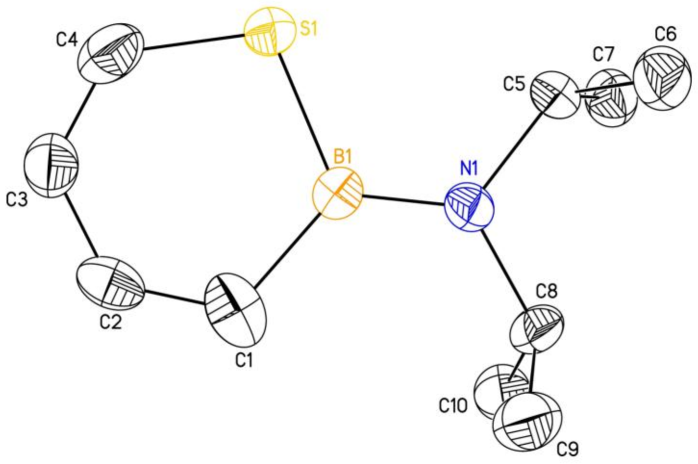
**Figure 3.2: Comparison of the $^1$H NMR, $^{13}$C NMR (in parentheses) and $^{11}$B NMR (arrows) chemical shift values of 1b and 2c in THF-$d_8$.** [Note that the $^1$H NMR signals of 1b in chloroform overlap.]



**1b** **2c**

The UV absorption spectrum of **2c** in hexane displays a low energy band at 326 nm, which shows marked vibronic fine structure. For comparison the lowest energy maximum of **1a** is at 269 nm,[8] while that of **1b** is at 287 nm.[5] Since these bands are clearly sensitive to the substituent at boron, precise comparison with **2c** is tenuous. However the significant red shift of **2c** relative to derivatives of **1** is consistent with a smaller HOMO/LUMO gap.

**Figure 3.3: Solid-state structure of 2c (ORTEP).**



Thermal ellipsoids are set at the 50% probability level. Hydrogen atoms have been omitted for clarity. Selected mean distances from the four nonequivalent molecules in the unit cell (Å): B(1)-S(1), 1.844(2); B(1)-C(1), 1.601(34); C(1)-C(2), 1.350(9); C(2)-C(3), 1.411(3); C(3)-C(4), 1.335(5); C(4)-S(1), 1.707(6); B(1)-N(1), 1.401(7). For comparison, selected bond distances (Å) computed using DFT (B3LYP/TZVP): B(1)-S(1), 1.859; B(1)-C(1), 1.541; C(1)-C(2), 1.358; C(2)-C(3), 1.432; C(3)-C(4), 1.348; C(4)-S(1), 1.728; 1.541; B(1)-N(1), 1.423.

The experimental data on **2** are supported by calculations.[28] The bond distances of **2c** have been calculated at the density function theory (DFT) B3LYP/TZVP level (Figure 3.3). The calculated bond distances for corresponding atoms agree with the mean crystallographic values from the four independent molecules of **2c** in the unit cell within an average value of ±0.03Å. Considering the partial disorder in the crystal, this is a good level of agreement. The $^{1}$H, $^{11}$B, and $^{13}$C NMR chemical shifts of **2c** have been calculated at B3LYP/TZVP level. Again agreement with the experimental values is satisfactory. The HOMO/LUMO gap for **1a** has been calculated by Dixon, Liu and co-workers to be 5.32 eV.[8] The calculated HOMO/LUMO gap was 4.98 eV for **2a** and 4.30 eV for **2c**. The smaller gap is consistent with the observed red shift in the UV spectrum of **2c** vs. **1a**.

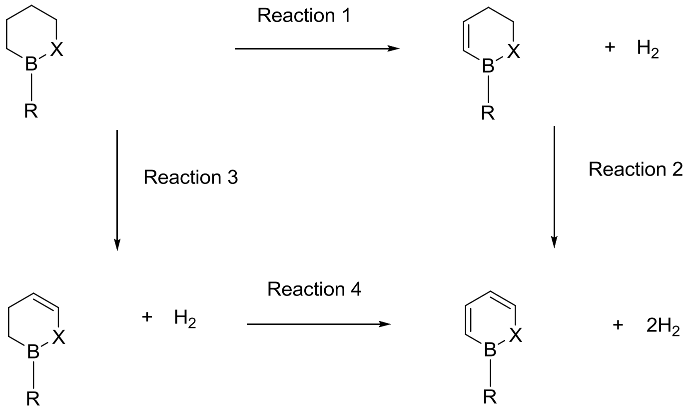
The calculations allow evaluation of the aromatic character of **2** for which there is no direct experimental evidence.[29] Table 3.1 shows calculated magnetic and energy data for benzene, **1a**, **2a**, and **2c**. The Nucleus Independent Chemical Shift [NICS(1)] values have become an important magnetic criterion of aromaticity.[30] The NICS(1) values of **1a** and **2a** are similar suggesting a comparable level of aromaticity which is about 30% less than that shown by benzene. On the other hand the NICS(1) value of **2c** is significantly smaller indicating that the B-N($^i$Pr)$_2$ substituent diminishes the aromaticity of the thiaborin ring system. The resonance stabilization energy (RSE) of **1a** has been calculated by Dixon, Liu and co-workers as 21 kcal/mol which is approximately 13 kcal/mol less than benzene.[8] In a similar manner using dehydrogenation reactions 1-4 in Figure 3.4, the RSE of **2a** is found to be 16 kcal/mol and **2c** is found to be only 8 kcal/mol. Thus the calculated energies suggest that aromaticity declines in the series: benzene >> **1a** > **2a** >> **2c**.

**Table 3.1: NICS(1) Values and Stabilization Energy Data (kcal/mol) for Benzene, 1a, 2a and 2c.**

| **Entry** | **Benzene**[a] | **1a**[a] | **2a** | **2c** |
|---|---|---|---|---|
| NICS(1) | -10.4 | -7.3 | -6.8 | -3.6 |
| $\Delta H_{298}$ (Reaction 1) | | 25.7 | 23.9 | 23.3 |
| $\Delta H_{298}$ (Reaction 2) | | 4.7 | 10.9 | 15.6 |
| $\Delta H_{298}$ (Reaction 3) | | 24.4 | 26.4 | 23.5 |
| $\Delta H_{298}$ (Reaction 4) | | 6.1 | 8.4 | 15.5 |
| RSE | 34.1 | 20±2 | 16±3 | 8±0.2 |

[a] Ref. (8). All other data from this work.

**Figure 3.4: Dehydrogenation Reactions of 1a, 2a, and 2c.**



For **1a**, R = H; X = NH
For **2a**, R = H; X = S
For **2c,** R = N(i-Pr)$_2$; X = S

## 3.3 Theory

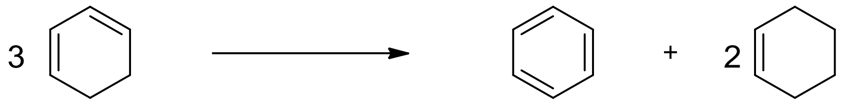
Choice of basis set for *ab initio* calculations is extremely important, as it needs to be large enough to handle to the applied electron effects but accurate enough to detect differences between specific molecules. Ahlrichs-TVZP, triple valence zeta polarized basis set is good for larger molecules and gives accurate results in a short time period.[31] This basis set is comprised of ten s-type, five p, two d, and one f functional that are contracted into four s, three p, two d and one f functional which are formulated to give the lowest possible grounds state energy.[32]

Nucleus-Independent Chemical Shifts or NICS was first introduced in 1996 by Schleyer, Maerker, Dransfeld, Jiao, and Hommes to avoid perturbation of the wave function by neighboring hydrogens.[33] NICS is typically computed using a virtual nucleus at or above the ring center. A negative isotropic value indicates the presence of aromaticity, the more negative the value, the more aromatic.[34] GIAO or gauge-invariant atomic orbitals are used to explore the $\pi$-electron ring currents based on Hückel theory.[31] Hückel theory was developed in the 1930's as the first semi-emperical molecular orbital method, applied to only planer molecules with delocalized $\pi$-bonding.[35, 36] The Hamiltonian for the $\pi$-electrons is assumed to be separate from the $\sigma$ framework. Thus, the variational method illustrated in equation 3.1 expresses the minimized energy of the $\pi$-electrons calculated via the Hückel theory assumptions.[37]

$$W_i = \frac{\int \varphi_i^* \hat{H}_1^{eff} \varphi_i d^3 r}{\int \varphi_i^* \varphi_i d^3 r} \qquad \textbf{(3.1)}$$

Where the variation of the *i*th delocalized orbital is defined by $\hat{H}_1^{eff}$, the effective Hamiltonian operator, $d^3r$ is the electrons volume element.

The process of calculating *isodesmic* reactions, or dehydrogenation reactions, was first developed by Hehre, Ditchfield, Radom, and Pople.[38] The assumptions made are that there is no net loss of formalized bonding, the number of formalized bond types; single, double or triple bonds, stays consistent on either side of the reaction.[38, 39] The conjugation or resonance stabilization energy in molecules can be assessed in comparison to an *isodesmic* reaction involving cyclohexa-1,3-diene in the formation of benzene (Scheme 3.2).



**Scheme 3.2: Resonance Stabilization Energy of Benzene**

## 3.4 Experimental Section

**Synthesis of 2-(Diiosopropylamino)-2*H*-1,2-Thiaborin.** Throughout the elegant synthesis of the title compound all manipulations were performed by the skillful hands of Dr. Arthur J. Ashe, III.

A solution of **5** (1.0g, 5.5mmol) in THF (3.0mL) was added dropwise with stirring to a solution of LDA (11.0 mmol) in THF (20 mL) at -78 $^{o}$C. The mixture was allowed to warm slowly to 25 $^{o}$C for 3 h during which time the color darkened to red-brown. The mixture was then cooled to -78 $^{o}$C and methylene chloride (6 mL) was added dropwise. After 45 min the mixture was allowed to warm to -25 $^{o}$C for 12h. Volatiles were removed in vacuum and the residue was extracted with pentane (20 mL). After decanting from the insoluble material the solvent was removed under vacuum leaving a red-brown tar which was distilled pot-to-pot at 50-60 $^{o}$C ( 0.05 torr) to give 168 mg (16%) of product as an oil which solidified to pale yellow block-like crystals, mp= 21 $^{o}$C. $^{1}$H NMR (500 MHz, THF-$d_8$, T = 25 $^{o}$C): δ 1.25 br d (12H), 3.75 br m (2H), 6.55 dd, J = 8.6, 6.6 Hz (1H), 6.60 d, J = 13.2 Hz (1H), 6.93 d, J = 9.4 Hz (1H), 7.14 dd, J = 13.0, 7.0 Hz (1H). $^{1}$H NMR (500 MHz, $CDCl_3$, T = 0 $^{o}$C): δ 1.25 br d (12H); 3.75 br d (2H); 6.61 dd, J = 8.9, 6.9 Hz (1H); 6.66 d, J = 13.2 Hz (1H); 6.96 d J = 8.9 Hz (1H); 7.21 dd J = 13.2, 6.9 Hz (1H). $^{11}$B NMR (160.4 MHz, $CDCl_3$ ): δ 35.8. $^{13}$C NMR (160.4 MHz, $CDCl_3$) (T = 0 $^{o}$C): δ 140.4, 127.8, 126 br, 121.5, 49.26 br, 45.76 br, 23.56 br 21.52 br, (T = 50 $^{o}$C) δ: peaks >50 are the same, 47.5 br, 22.3 br. HRMS (EI,m/z): calcd for $C_{10}H_{18}{}^{11}BNS$ ($M^+$), 195.1253; found, 195.1251. UV (hexane; $\lambda_{max}$, nm 322. Anal. Calcd for $C_{10}H_{18}BNS$; C, 61.55; H, 9.30; N, 7.18. Found: C, 61.05; H, 9.81; N, 6.66. **2c**-$d_1$: When the above reaction was performed using methylene chloride-$d_{2}$, the isolated product had a deuterium at C(3) as shown by $^1$H NMR: no signal at δ 6.60, δ 7.14 signal now br d ( J = 6.6 Hz). HRMS(EI,m/z): calcd for $C_{10}H_{17}{}^2H^{11}BNS$ ($M^+$): 196.1316. Found 196.1317.

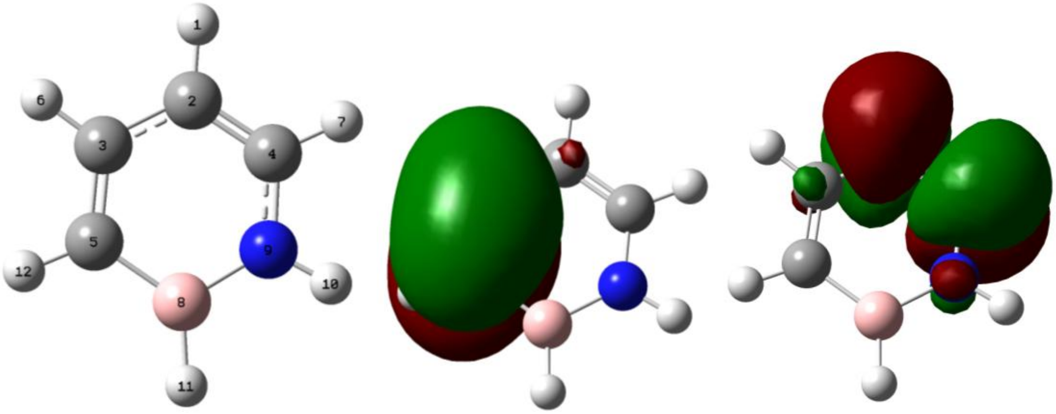
**Structural Determination of 2c.** $C_{10}H_{18}BNS$, orthorhombic, *Pca2(1)*, *a* = 26.1590(18) Å, *b* = 8.5982(2) Å, *c* = 20.5101(4) Å, *V* = 4613.1(3) Å$^3$, *Z* = 16, $D_c$ = 1.124 g cm$^{-3}$, *T* = 85(2) K, λ( Cu Kα) = 1.54187 Å. Final R indices (I > 2σ(I)): R1 = 0.0502, wR2 = 0.1194. R indices (all data): R1 = 0.0608, wR2 = 0.1278. GOF on $F^2$ = 1.076. Colorless plates of **2c** were grown from a neat solution of the compound at 21 °C. A crystal of dimensions 0.18 x 0.11 x 0.05 mm was mounted on a Rigaku AFC10K Saturn 944+ CCD-based X-ray diffractometer equipped with a low temperature device and Micromax-007HF Cu-target micro-focus rotating anode (λ = 1.54187 A) operated at 0.2 kW power (20 kV, 10 mA). The X-ray intensities were measured at 85(1) K with the detector placed at a distance 42.00 mm from the crystal. A total of 1760 images were collected with an oscillation width of 1.0° in ω. The exposure time was 10 sec. The integration of the data yielded a total of 55448 reflections to a maximum 2θ value of 136.42° of which 8412 were independent and 7168 were greater than 2σ(I). The final cell constants (Table 1) were based on the xyz centroids of 23413 reflections above 10σ(I). Analysis of the data showed negligible decay during data collection; the data were processed with CrystalClear 2.0 and corrected for absorption. The structure was solved and refined with the Bruker SHELXTL (version 2008/4) software package, using the space group Pca2(1) with Z = 16 for the formula $C_{10}H_{18}BNS$. There four independent molecules in the asymmetric unit. Full matrix least-squares refinement based on $F^2$ converged at R1 = 0.0502 and wR2 = 0.1194 [based on I > 2sigma(I)], R1 = 0.0608 and wR2 = 0.1278 for all data. The six-member aromatic ring is disordered by 180 deg. rotation about the boron-nitrogen bond for all four molecules with mixed occupancy S/C sites.

**Density Functional Calculation.** All structures were optimized using the B3LYP functional and the Ahlrichs-TZVP basis set.[40, 41] Geometry optimizations were performed with the program package Gaussian 09.[28] The NMR chemical shift calculations were obtained at the DFT B3LYP level with the Ahlrichs-TZVP basis set using the GIAO formalism to treat the gauge invariance problem. The nucleus-independent chemical shifts (NICS) were calculated at the approximate center of the rings and at 1 Å and 2 Å above the ring on the axis perpendicular to the ring and passing through the approximate center of the ring. Heats of formation were calculated at the G4MP2 level for use in the resonance energy calculations and isodesmic reactions based on the work by Dixon, Liu and co-workers.[8] Reproduction of the calculations for **1a** were completed, and found to be in agreement. The resonance stabilization energy (RSE) represents energy stabilization with respect to a model system.[42, 43] The choice of the model system is crucial. The most commonly used model for benzene is based on the heats of hydrogenation of cyclohexene, cyclohexadiene, and benzene as originally explored experimentally by Kistiakowsky and co-workers.[44] The lower symmetry of **2** makes application of this method more complex. We have chosen to define the RSE of **2a** as the mean of the difference of the calculated enthalpies between reactions (1) and (2) and (3) and (4)

(**Table 3.3**). The RSE of **2c** is the corresponding differences between reactions (5) and (6) and (7) and (8) (**Table 3.3**).

In the following, a brief explanation of the different models in Tables and Figures is provided along with Cartesian coordinates.

**Figure 3.5: Structure 1a (B3LYP/TZVP)**



| | |
|---|---|
| **HOMO** | -6.3368eV |
| **LUMO** | -0.9398eV |
| **GAP** | 5.40eV |

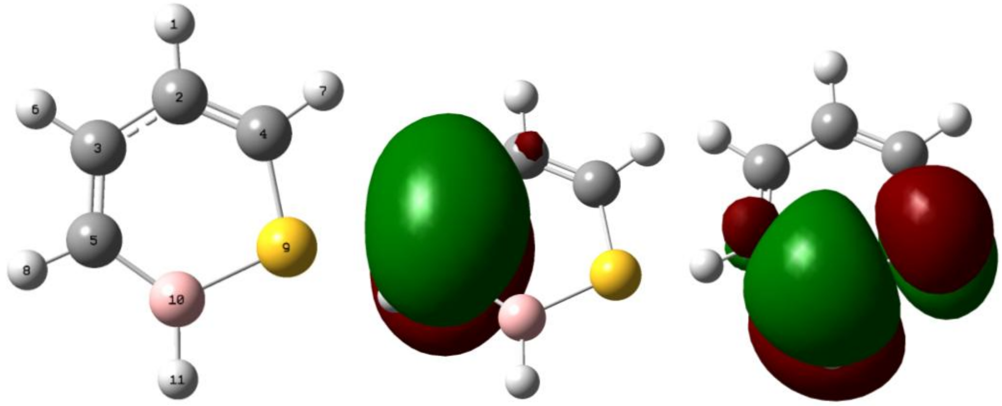
**Bond Distances (Å)**

| | |
|---|---|
| C5=C3 | 1.3726 |
| C3-C2 | 1.4207 |
| C2=C4 | 1.3637 |
| C5-B | 1.5115 |
| C4-N | 1.3645 |
| B-N | 1.4387 |
| C5-H | 1.0847 |
| C3-H | 1.0866 |
| C2-H | 1.0815 |
| C4-H | 1.0828 |
| B-H | 1.1916 |
| N-H | 1.0095 |

**Cartesian Coordinates**

| Symbol | X | Y | Z |
|---|---|---|---|
| H | -0.3405860 | -2.4304790 | -0.0001980 |
| C | -0.2034400 | -1.3577170 | -0.0001150 |
| C | -1.3255080 | -0.4863840 | 0.0001250 |
| C | 1.0618670 | -0.8489990 | -0.0000450 |
| C | -1.1824040 | 0.8787230 | -0.0000940 |
| H | -2.3126610 | -0.9405080 | 0.0003710 |
| H | 1.9374900 | -1.4860050 | 0.0001010 |
| B | 0.2091300 | 1.4689370 | -0.0000410 |
| N | 1.2719310 | 0.4992300 | 0.0001120 |
| H | 2.2373430 | 0.7944070 | 0.0000940 |
| H | 0.5067860 | 2.6227270 | -0.0001770 |
| H | -2.0806260 | 1.4868190 | 0.0000030 |

**Figure 3.6: Structure 2a (B3LYP/TZVP)**



| | |
|---|---|
| **HOMO** | -6.9303eV |
| **LUMO** | -1.9456eV |
| **GAP** | 4.98eV |

**Bond Distances (Å)**

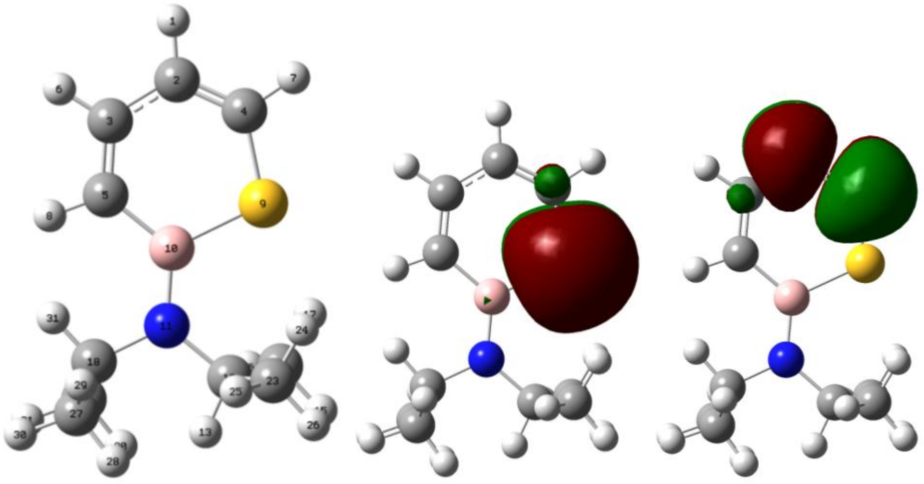
| | |
|---|---|
| C5=C3 | 1.3685 |
| C3-C2 | 1.4235 |
| C2=C4 | 1.3576 |
| C4-S | 1.720 |
| C5-B | 1.5077 |
| S-B | 1.7980 |
| C5-H | 1.0863 |
| C3-H | 1.0864 |
| C2-H | 1.0844 |

| | |
|---|---|
| C4-H | 1.0828 |
| B-H | 1.1879 |

**Cartesian Coordinates**

| Symbol | X | Y | Z |
|---|---|---|---|
| H | 2.0756210 | 1.6461990 | 0.0000000 |
| C | 1.2783940 | 0.9111900 | 0.0000000 |
| C | 1.6392510 | -0.4657890 | 0.0000000 |
| C | 0.0000000 | 1.3680100 | 0.0000000 |
| C | 0.7473510 | -1.5037800 | 0.0000000 |
| H | 2.7044760 | -0.6793410 | 0.0000000 |
| H | -0.2080640 | 2.4306620 | 0.0000000 |
| H | 1.1651450 | -2.5065180 | 0.0000000 |
| S | -1.4013940 | 0.3707660 | 0.0000000 |
| B | -0.7470860 | -1.3039700 | 0.0000000 |
| H | -1.5694140 | -2.1611960 | 0.0000000 |

**Figure 3.7: Structure 2c (B3LYP/TZVP)**



| | |
|---|---|
| **HOMO** | -5.6560eV |
| **LUMO** | -1.3581eV |
| **GAP** | 4.30eV |

**Bond Distances (Å)**

| | |
|---|---|
| C5=C3 | 1.3579 |
| C3-C2 | 1.4320 |
| C2=C4 | 1.3477 |

| | |
|---|---|
| C4-S | 1.7279 |
| S-B | 1.8593 |
| B-C5 | 1.5409 |
| B-N | 1.4227 |
| C5-H | 1.0857 |
| C3-H | 1.0865 |
| C2-H | 1.0841 |
| C4-H | 1.0830 |

**Cartesian Coordinates**

| **Symbol** | **X** | **Y** | **Z** |
|---|---|---|---|
| H | -4.6209220 | -0.9467170 | 0.0000720 |
| C | -3.5655830 | -0.6987890 | 0.0000370 |
| C | -2.6159470 | -1.7706380 | -0.0000570 |
| C | -3.2171340 | 0.6030720 | 0.0000520 |
| C | -1.2658320 | -1.6250380 | -0.0000840 |
| H | -3.0326670 | -2.7740170 | -0.0001280 |
| H | -3.9686650 | 1.3828050 | 0.0000530 |
| H | -0.7155570 | -2.5609330 | -0.0002020 |
| S | -1.6047940 | 1.2244830 | -0.0000040 |
| B | -0.5130810 | -0.2805270 | -0.0000080 |
| N | 0.9016820 | -0.1306680 | 0.0000390 |
| C | 1.6407730 | 1.1568130 | 0.0000060 |
| H | 2.6971480 | 0.8878510 | 0.0000800 |
| C | 1.4200960 | 1.9811440 | -1.2744180 |
| H | 2.0905390 | 2.8445170 | -1.2763320 |
| H | 1.6331100 | 1.3834400 | -2.1620420 |
| H | 0.3998880 | 2.3546080 | -1.3578720 |
| C | 1.7774990 | -1.3252710 | 0.0000320 |
| C | 2.6296880 | -1.4346560 | -1.2708130 |
| H | 3.3646950 | -0.6306900 | -1.3519770 |
| H | 3.1802300 | -2.3785400 | -1.2693730 |
| H | 1.9985580 | -1.4107820 | -2.1608860 |
| C | 1.4199500 | 1.9812530 | 1.2743290 |
| H | 0.3997290 | 2.3547240 | 1.3576400 |
| H | 1.6328530 | 1.3836220 | 2.1620250 |
| H | 2.0903880 | 2.8446310 | 1.2762360 |
| C | 2.6296930 | -1.4346800 | 1.2709050 |
| H | 3.3645830 | -0.6306230 | 1.3522390 |
| H | 1.9985220 | -1.4110520 | 2.1609500 |
| H | 3.1803770 | -2.3784840 | 1.2693420 |
| H | 1.1183050 | -2.1880380 | 0.0000700 |

*NICS and NMR Chemical Shift Calculations*

**Table 3.2: NICS at 0, 1, and 2 Å and NMR at the B3LYP/TZVP level of calculation**

| **Molecule** | **NICS(0)** | **NICS(1)** | **NICS(2)** | **Atom** | **δ(ppm)** |
|---|---|---|---|---|---|
| c-$C_6H_6$ [a] | -8.76 | -10.39 | -2.57 | C | 135.2 |
| | | | | H | 7.5 |
| c-$BNC_4H_6$ (**1a**)[a] | -5.62 | -7.27 | -3.89 | B | 26.9 |
| | | | | N | 246.9 |
| | | | | C4 | 140.2 |
| | | | | C2 | 118.8 |
| | | | | C3 | 151.5 |
| | | | | C5 | 139.0 |
| | | | | H11 | 5.4 |
| | | | | H10 | 7.8 |
| | | | | H12 | 7.3 |
| | | | | H1 | 6.6 |
| | | | | H6 | 8.0 |
| | | | | H7 | 7.4 |
| c-$BSC_4H_5$ (**2a**) | -4.24 | -6.81 | -3.90 | B | 27.0 |
| | | | | S | -272.1 |
| | | | | C5 | 136.0 |
| | | | | C3 | 147.4 |
| | | | | C2 | 130.5 |
| | | | | C4 | 144.9 |
| | | | | H8 | 7.7 |
| | | | | H6 | 8.0 |
| | | | | H1 | 7.5 |
| | | | | H7 | 8.0 |
| c-$BSC_4H_4$NiPr (**2c**)[b] | -1.62 | -3.56 | -2.19 | N | 139.8 |
| | | | | B | 38.7 |
| | | | | S | -391.7 |
| | | | | C5 | 127.4 |
| | | | | C3 | 146.0 |
| | | | | C2 | 124.5 |
| | | | | C4 | 138.6 |
| | | | | H8 | 6.7 |
| | | | | H6 | 7.4 |
| | | | | H1 | 6.7 |
| | | | | H7 | 7.1 |

### *Resonance Stabilization Energy (RSE) Calculations*

**Table 3.3: G4MP2 reaction enthalpies at 298 K in kcal/mol.**

| **Entry** | **Reaction** | **kcal/mol** |
|---|---|---|
| (1) | $c\text{-}C_4BSH_9 \rightarrow c\text{-}C_4BSH_7$ (C=C(B)) + $H_2$ | 23.9 |
| (2) | $c\text{-}C_4BSH_7$ (C=C(B)) $\rightarrow c\text{-}C_4BSH_5 + H_2$ | 10.9 |
| (3) | $c\text{-}C_4BSH_9 \rightarrow c\text{-}C_4BSH_7$ (C=C(S)) + $H_2$ | 26.4 |
| (4) | $c\text{-}C_4BSH_7$ (C=C(S)) $\rightarrow c\text{-}C_4BSH_5 + H_2$ | 8.4 |
| (5) | $c\text{-}C_4BSH_8N(iPr)_2 \rightarrow c\text{-}C_4BSH_6N(iPr)_2$ (C=C(B)) + $H_2$ | 23.3 |
| (6) | $c\text{-}C_4BSH_6N(iPr)_2$ (C=C(B)) $\rightarrow c\text{-}C_4BSH_4N(iPr)_2 + H_2$ | 15.6 |
| (7) | $c\text{-}C_4BSH_8N(iPr)_2 \rightarrow c\text{-}C_4BSH_6N(iPr)_2$ (C=C(S)) + $H_2$ | 23.5 |
| (8) | $c\text{-}C_4BSH_6N(iPr)_2$ (C=C(S)) $\rightarrow c\text{-}C_4BSH_4N(iPr)_2 + H_2$ | 15.5 |
| (9) | $c\text{-}C_6H_6 + c\text{-}C_4BSH_7$ (C=C(B)) $\rightarrow c\text{-}C_4BSH_5 + c\text{-}C_6H_8$ | 18.5 |
| (10) | $c\text{-}C_6H_6 + c\text{-}C_4BSH_7$ (C=C(S)) $\rightarrow c\text{-}C_4BSH_5 + c\text{-}C_6H_8$ | 16.0 |
| (11) | $c\text{-}C_6H_6 + c\text{-}C_4BSH_6N(iPr)_2$ (C=C(B)) $\rightarrow c\text{-}C_4BSH_4N(iPr)_2 + c\text{-}C_6H_8$ | 22.9 |
| (12) | $c\text{-}C_6H_6 + c\text{-}C_4BSH_6N(iPr)_2$ (C=C(S)) $\rightarrow c\text{-}C_4BSH_4N(iPr)_2 + c\text{-}C_6H_8$ | 20.9 |

## 3.5 Conclusions

In summary, the first monocyclic 2*H*-1,2-thiaborine **2c**, has been structurally and spectroscopically characterized. The experimental NMR results indicate that **2c** falls between 6.6 and 7.1ppm in the aromatic region, which is consistent with a diamagnetic ring current. The $^{11}B$ and $^{13}C$ NMR chemical shifts are also consistent with similar electronic structures. The DFT calculations of NMR shifts at the B3LYP/TZVP level were in agreement with the experimental values. However, NICS (1) calculations indicate that the heterocyclic ring has only minimal aromatic character. The π-interaction of the exocyclic amino substituent with boron diminishes the endocyclic π-bonding expected for the parent ring. Provided that the calculations showed minimal aromaticity, synthesis and additional computational characterization of the parent compound remains an attractive goal.

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## Chapter 4

## The Development and Assessment of a Safety and Chemical Hygiene Curriculum in an Undergraduate Organic Chemistry Laboratory Course at the University of Michigan

### 4.1 Introduction

Laboratory safety is important for the welfare of workers, their colleagues, and associates. A university laboratory is no different from any other professional laboratory setting, although students pose an additional challenge in safety training; faculty, staff and students must be properly trained to be conscientious about laboratory safety and hygiene practices to ensure optimal occupational conditions. Educational institutions generally understand that instruction in safe laboratory practices is an integral part of a chemistry curriculum; integration into current courses creates an additional challenge. Proper instruction on the importance of safety and chemical hygiene is absolutely essential for the safety of everyone as they enter the chemistry program. Formal safety instruction has often been largely ignored in chemistry classes, with many believing that laboratory safety is a topic that is not important enough to be included in chemistry curricula.[1-6] Over the past century there have been mixed and infrequent accounts of various safety practices designed to be used in chemical laboratories. Studies of the effectiveness of these procedures were done as early as the turn of the 20th century.[7-9] In fact, even as early as 1910, Keller discussed that, in contrast to the modern industrial plants, chemical laboratories retain much of their medieval aspects.[10] This attitude came to an end in 1990 when the Occupational Safety and Health Administration (OSHA) turned its attention to the safety of chemical laboratories and instituted chemical hygiene regulations based on the work published in 1981 by the National Research Council.[11] Early pioneers such as George G. Lowry at Western Michigan University in Kalamazoo, MI, and L. Jewel Nicholls at the University of Illinois at Chicago Circle, taught chemical hygiene beginning as early as 1978.[12, 13] However, as of 1988, only 6% of the American Chemical Society (ACS) approved chemistry departments offered safety courses, and only 2% of departments required chemistry majors to take them.[14] As stated by Hill and Finster, while many faculty consider chemical and laboratory safety to be an important topic that needs to be covered, they do not necessarily find it to be important or substantive enough to become a stand-alone course within undergraduate curriculum.[15]

Since 1988, there has been a significant increase in the number of universities who are adding laboratory safety to the undergraduate curriculum.[1-6] Along these lines, Robert H. Hill Jr. and David C. Finster published “Laboratory Safety for Chemistry Students,” a manual to assist universities in teaching this topic.[15] The chemistry department at Wittenburg University in Ohio previewed Professor Finster’s book, incorporating the topics into several of their courses. Hendrix University in Arkansas has also adopted a safety training component for their undergraduate classes. Similarly, the University of California at San Diego ensures that students have been trained in proper chemical procedures, although their formal training in this topic comes in their upper level undergraduate course work.[16]

Including safety education in a curriculum or in a specific course does not ensure that students will understand, retain, or even utilize the material. In order to effectively teach laboratory safety and chemical hygiene, the effectiveness of the curriculum must be evaluated. Although faculty members at several institutions have increased the amount of safety training their undergraduates receive, Alaimo, P. J. *et al.* at Seattle University in Washington are the only group to have quantitatively evaluated their program's results.[17] Seattle University incorporated a team-based safety education component into their organic chemistry laboratories. Alaimo found that students in this program performed 30% better than the control students in both their understanding of safety concepts and their self-reported behavior in the laboratory.

With a growing awareness of environmental impact and eco-friendly practices, it seems inevitable that more institutions will add laboratory safety to their formal curriculum. Research on the effectiveness of this new curriculum in laboratory safety, including chemical hygiene instruction, is therefore essential.

## 4.2 Study Context

### *4.2.1 Updates to Undergraduate Chemistry 211 Course Curriculum*

Prior to the fall academic term of 2010, the introductory organic chemistry laboratory, Chemistry 211, at the University of Michigan contained safety training in only the most general sense. Students were instructed to wear proper laboratory attire, but the students' lacked the understanding of why this was important. There was no connection between the initial instruction and their actual laboratory practices. To try to ensure awareness of the laboratory policies among the student body in the undergraduate teaching laboratories, new posters that clearly and colorfully depict what constitutes proper lab attire, personal protection equipment (PPE), and waste disposal were created with assistance of the laboratory instructors (Appendix A-C). These posters were hung outside every teaching laboratory, allowing students to recognize quickly and easily proper laboratory apparel for all chemistry teaching laboratories.

A variety of other teaching tools were also added to the curriculum of the Chemistry 211 course. Weekly readings were assigned based off the book titled "Laboratory Safety for Chemistry Students," by Hill and Finster that pertained to concepts related to the corresponding experiments.[15] The various assigned readings covered a series of relevant topics: the importance of proper lab attire, proper waste disposal, what to do with unknown substances, routes of exposure in a chemistry laboratory, why use chemical hoods, what is OSHA, proper storage of chemicals, and what is the difference between a strong acid and a weak acid. The students were to do the reading prior to entering the laboratory each week; the students were then tested over this material along with the material pertaining to the experiment of the day. There were ten different reading assignments and quizzes. The GSIs were responsible for grading the quizzes.

Although this newly initiated chemical hygiene curriculum at the University of Michigan is not a stand-alone class, it does address chemical safety and allows students to see how the topics are an integral part of a real laboratory setting. Proper evaluation and quantification of teaching effectiveness is required to determine if this curriculum effectively ensures that students at the University of Michigan are gaining and utilizing this important safety knowledge.

### *4.2.2 Why Study the Effectiveness of the New Curriculum?*

This change in how Chemistry 211 is taught at the University of Michigan was brought forth for two reasons. First was a concern for the students' health while conducting research in the chemistry laboratories. Of course, the recent cluster of significant and even fatal academic laboratory accidents that occurred in other institutions in the United States has only reinforced the importance of safety knowledge.[16, 18, 19] Secondly, it was becoming increasingly clear that for the students to be conscientious researchers in the future, they should acquire this knowledge early in their experiences. There is a great need to transform these students into professional chemists who will be responsible and aware of the dangers inherent in the field. With an early intervention, these students could carry this knowledge into their other courses and their professional careers. The Chemistry 211 course at the University of Michigan is just one of the many courses across the nation moving toward teaching chemical hygiene to undergraduate classes.

Approximately 2,000 students are enrolled in the introductory organic laboratory each year at the University of Michigan. For the first time ever, in the fall academic term of 2010, safety training and chemical hygiene was directly taught in Chemistry 211 (1,269 students were enrolled, with 35 graduate student instructors (GSIs)). Surveys were developed to evaluate students' knowledge of chemical hygiene. These surveys contained multiple choice, short answer, and true/false questions of varying levels of difficulty in order to try to get an accurate assessment of knowledge level on the various safety topics.[20] Although it is not possible to measure what a student understands through these data alone, it is possible to identify what a student can recognize or explain. Pre- and post-lab surveys were designed to assess the change in students' learning of safety techniques and practices. Observing the students during the term, together with an assessment of the survey results provided a good description of students' ability to utilize the knowledge gained.

The initial proposed goals in this study were: 1) to evaluate the students' knowledge gained from the chemical hygiene curriculum (would they gain and retain knowledge of chemical hygiene?) 2) to determine students' opinions on the usefulness and effectiveness of the resources used in teaching the curriculum (did they feel more confident after having learned the curriculum?) and 3) to measure the extent to which the student survey and practical results were GSI dependent (does the GSI impact the effectiveness of the curricular changes?).

A theoretical model of the proposed study is based on a cause and effect model. Was there an effect on students' learning from the newly initiated curriculum? Did the students who participated in the intervention learn the material? Were there student or GSI effects? Can we assert that students' learning resulted from the curriculum alone and not from other outside variables? Effect was established through three different sets of data by looking at accident report data, making in-class observations, and surveying students' knowledge with a chemical hygiene based survey administered several times over a one year period. The curriculum contained ten readings based on three general topics: waste disposal, appropriate laboratory attire, and overall chemical hygiene. As an introductory chemistry laboratory course these are foundational notions that have to be taught early in the students' career. The model included variables at the student level (demographics, grades) and at the instructor level (the GSIs' knowledge of safety and hygiene). The intervention variable was whether the students received the modified curriculum or not.

## 4.3 Methods

### *4.3.1 Participants and Sampling*

The sample consisted of (3,513) students total. Of these, 2,918 students received the intervention and 595 did not. The intervention students were distributed in three waves of data, 1,269 associated with 35 GSIs in the fall 2010, 1,528 students associated with 44 GSIs in winter 2011, and 121 students associated with 8 GSIs in spring 2011. Twelve Teaching Assistants (TAs) taught the 595 control students. Students were recruited through public announcements during laboratory lectures and laboratory classes. The purpose of the survey was stated at the moment in which students' participation was requested. The recruitment targeted 110 sections during winter term alone. Of the 44 GSIs that took part of the study, 15 teaching Chemistry 216 had not previously taught or come in contact with the intervention curriculum.

The recruited sample of students in the intervention group consisted of 1,392 Chemistry 211 students (806 students during the fall 2010 term and 586 during the winter 2011 term). This group of students was also monitored throughout their second semester organic chemistry laboratory course, Chemistry 216, in spring 2011. The recruited sample of students in the control group consisted of 289 students from another large public University. An additional group of 41 students that participated only in the spring Chemistry 216 course were also included in this study. Of all the participants, 52% of the students were female and 48% were male. Nearly 57% of the participants were of Caucasian non-Hispanic ancestry, 2% were African American, 16% Asian, 2% Hispanic, 3% were of two or more ethnicities, and nearly 20% did not report an ethnicity.

The demographics of the participants (1,722), including their gender, major area of study, and ethnicity, are given in Table 4.1. Roughly 25% of the students reported having had previous research experience. The majority of the Chemistry 211/216 students were freshmen or sophomores (~70% of the total). Students in the control group, on the other hand, were mostly sophomores and juniors (~80% of the total). The difference stems from the University of Michigan's policy of offering Organic Chemistry to freshmen. About half of students reported not engaging in extracurricular activities (~50%); the remainder reported participating in intramural sports or going to the University's gym (12-18%), belonging to scholastic clubs (10-20%), belonging to a fraternity or sorority (6-20%), competing on a school sanctioned athletic team (6-14%), or being a member of the marching band (1-3%).

**Table 4.1: Percent of Various Demographic Characteristics of Participants**

| | **Pilot**<br>**N= 806** | **Winter 211**<br>**N= 586** | **Control**<br>**N= 289** | **Spring 216**<br>**N= 41** |
|---|---|---|---|---|
| Female | 51 | 52 | 58 | 44 |
| Male | 49 | 48 | 42 | 56 |
| Science | 61 | 59-83[a] | 80-85[a] | 46 |
| Engineering | 15 | 3-15[a] | 2.5[a] | 17 |
| Business | 1 | 2-3[a] | 0-1[a] | 0 |
| Social Sciences | 9 | 6-10[a] | 2-3[a] | 10 |
| Arts | 3 | 3-4[a] | 2-4[a] | 5 |
| Major- Not Reported | 11 | 3-14[a] | 7-11[a] | 22 |
| African American | 1.5 | 3 | 2.4 | 10 |
| Caucasian | 54 | 48 | 84 | 49 |
| Asian | 17 | 20 | 5 | 20 |
| Hispanic | 2.2 | 2.6 | 2.8 | 2.4 |
| Two or More | 3 | 2.2 | 2.8 | 0 |
| Ethnicity- Not Reported | 22.5 | 24 | 1.4 | 20 |

[a] Percentage range of participants' majors over time.

### *4.3.2 Design*

To analyze the effectiveness of the curriculum, quantitative and qualitative data were collected. Reported in-class accident data were acquired and tabulated. Accident data includes any reported incident in which a student was injured; i.e. cuts, burns, chemical spills. All incidents were supposed to be reported at the time of occurrence.

The students' behaviors were tabulated while the students were conducting their experimentations. Two student assistants were assigned to monitor either a Chemistry 211 or Chemistry 216 laboratory class for a 2hr time period using Appendix E as a template.

The students' knowledge was tested and the effectiveness of the curriculum determined through survey analysis. Questions based on the reading and opinion based questions were asked. Students were administered pre-laboratory surveys to determine baseline knowledge and then re-administered the same survey at the end of the term to determine curriculum effectiveness. This survey was also administered to the other large public University that did not undergo the intervention, serving as the control therefore avoiding the ethical issue of withholding safety material from select students.

### *4.3.3 Variables*

There were three outcome variables: the number of accident reports, the number of accidents inferred from in-class observations, and students' scores on the knowledge survey. There were 14 independent variables: (1) SAT/ACT scores, (2) math placement score, (3) chemistry placement score, (4) the GSI that student had, (5) number of college credits earned, (6) number of college credits transferred, (7) gender, (8) ethnicity, (9) previous undergraduate chemistry grades, (10) grades earned in the laboratory class during the term surveyed, (11) whether they had previous laboratory experience, (12) major, (13), class year, and (14) extracurricular activities. SAT/ACT, prior lab experience, and number of credit hours earned were used as covariate variables as they could affect the learning ability and potential to learn new curriculum. Participants gave written consent (Appendix D) for retrieval of their academic records, including SAT/ACT scores, placement exam scores for math and chemistry, the number of credits earned. Controlling for the various GSIs allowed for accounting for differences due to having an instructor who is more versed in the teaching material than another. Students with prior lab experience may be expected to have higher understanding; therefore students with similar backgrounds were compared in this study. Students enrolled in either Chemistry 211 or Chemistry 216 chemistry laboratories were compared both to their peers within the same laboratory section and to other students of the same chemistry course. Gender, ethnicity, major, class year, and extracurricular activities were additional variables that were monitored to see if any interesting trends emerged.

### *4.3.4 Procedures*

#### *4.3.4.1 Accident Report Data*

These data were collected from the Chemistry department; records kept include all laboratory accidents and spills for the entire building. Data from the undergraduate organic teaching laboratories was the only data of concern in this study.

#### *4.3.4.2 Observations*

Throughout the winter 2011 term both Chemistry 211 and 216 were observed. In-class observations were employed to qualitatively assess incorporation of the chemical hygiene practices taught in the introductory course into their more advanced laboratory courses. Two laboratory assistants collected the in-class observations. During the first week of classes the two observers were in the same room, monitoring the same students. After two hours of observation, each observer's notes were compared to determine the consistency of reporting. The agreement reached 100%. Each observer was then assigned to their own laboratory classes to monitor. Throughout the term a random subset of laboratory sections were observed and their in-lab safety practices were tabulated. Two Chemistry 211 and four Chemistry 216 laboratory classrooms were observed weekly. Each class was observed for two to eight consecutive weeks to evaluate longitudinal trends.

#### *4.3.4.3 Surveys*

In the last week of fall 2010, a pilot paper survey (Appendix F) was given to the Chem 211 students. Questions were drawn from the information in the curriculum they were taught throughout the term. Two forms of the same survey were used, each contained the same questions but in a different order. “Open-ended” questions were used with the goal to improve the survey administered the following term. Each survey was distributed in the last week of lab during check-out; students participated voluntarily. The data was entered manually into an excel worksheet. The pilot data was used to formulate a revised survey with ten multiple-choice questions that was used the following terms.

Pre-lab surveys (Appendix G) created from the 2010 pilot data were administered to the Chemistry 211 class and to the control students during laboratory check-in, in week 1 of the winter Term of 2011. At the end of the term, a post-lab survey was administered during laboratory check-out. Students were surveyed again in the second term of organic chemistry II laboratory (Chemistry 216), thus yielding three measures of knowledge and allowing for comparison of how much knowledge was retained.

A factor analysis was used to evaluate the psychometric properties of the ten multiple choice survey questions. The final decision about the number of factors that could be created was based on the criterion of obtaining an eigen value greater than one. The two questions that did not “load highly” into one of the factors were removed. Cronbach’s alpha reliabilities were computed for each factor. Scores were obtained for each factor by averaging the items in each of the factors.

Factor 1, to be referred to as Chemical Hygiene (CH), included five chemical hygiene questions. These questions were representative of chemical hygiene and laboratory attire procedures. The questions covered a common theme of how to protect oneself in the laboratory (i.e. how injuries occur, and what to do when an unknown substance is found in the work area). Factor 2, to be referred to as Waste (W), included three questions on proper waste disposal (including how chemicals are disposed and proper disposal locations).

### *4.3.5 Analysis*

Frequency and percents were calculated for the accident report data and for the behaviors tallied during the in-class observations. Paired t-tests were used to analyze the difference between mean of the first in-class observation with the second for each of the two observations per laboratory class in Chem 211.

Given the nested nature of the data (students within sections of a given GSI and the potential influence that GSIs may exert in the learning outcome), the data on students' knowledge of the curriculum was analyzed with hierarchical linear modeling (HLM) with random intercepts. Covariates of interest included gender, ethnicity, ACT scores, SAT scores, earned credit hours, transferred credit hours, previous research experience, major, class year, and extracurricular activities. An initial HLM for the second application of the survey, (Time 2, T2), for the score on knowledge of Chemical Hygiene (dependent variable) included the interaction between group and the baseline score, that of the first application of the survey (Time 1, T1), to see whether there was a constant gap between the groups or not at Time 2. A significant interaction would suggest that the difference between groups at Time 2 depended on the baseline score. The interaction was not significant, and the dependence of GSI variable was dropped from the model.

A similar analysis was conducted for the Time 2 Waste factor score and with the combined outcome resulting of adding the two scores (SUM).

A k-means clustering method was conducted to find groups of similar characteristics within the intervention and control samples. A hierarchical method was performed to determine the appropriate number of clusters based on the scree plot. Two clusters were created by assessing for gender, ethnicity, ACT scores, SAT scores, credit hours earned at their corresponding university, credit hours transferred and if they had taken a previous laboratory class at their university.

Cluster 1 consists of a more even distribution of gender. This group is composed primarily of students that are either Caucasian or Asian, these students showed a higher average ACT and SAT score, and 75% had not taken previous laboratory courses. Cluster 2 is composed of mostly females, a more diverse ethnic makeup, lower ACT and SAT scores, and 65% had previously taken a college level laboratory course. Demographics of the two clusters are in Table 4.4 t-tests were used to determine whether there were differences between these two groups in the Chemical Hygiene, Waste, and SUM scores at Time 2.

### *4.3.6 Limitations*

One important task ahead is the improvement of the survey used to assess students’ knowledge. While the analysis of the accident reports and the in-class observations suggest important changes in behaviors, presumably consequence of the curriculum, the instrument created did not quantify the change in this knowledge of the chemical hygiene curriculum. The students that experienced the new curriculum scored worse than the students in the control group, who did not receive the curriculum. The lack of statistical significance between the test students and the control students suggests that either the instrument was not successful at capturing students' knowledge of the curriculum or that there might be other variables at play, for example, student maturity: the students in the control group were older than the students in the intervention group.

Another limitation relates to the short time frame used to collect data. If a maturity effect is to be investigated, a long-term study would be necessary. Increasing the length of time would both allow for better formulation of the instrument and a better set up of experimental control (i.e, by controlling the age at which students experience the curriculum). The control group was smaller relative to the intervention group. The short time also constrained the possibilities of accessing reported accident data for the other university and in-class observations. If the accidents had also been reduced in the control group or if over time the number of observed violations decrease, then a maturity hypothesis would have more currency. If on the other hand, the frequency of accidents or the frequency of violations in the control group does not decrease, then we could attribute the success of the reduction in the intervention to the curriculum and not just to the maturity of the students.

These limitations provide reason for further work in optimizing the survey and increasing the length of the study. Most important, the study emphasizes the need for proper training among the GSIs. As will be seen in the results section, GSI training appears to make a difference. The GSIs who experienced the same chemical hygiene training as the Chemistry 211 students were less likely to have accidents in their lab. The GSIs who did not received the training accounted for the majority of the Chemistry 216 laboratory accidents. This variable was not intentionally included in the original design, and thus a future replication of this study needs to include GSI training as one of the control variables. A problem with this design is the ethical implications of such design: if GSI knowledge makes a difference, it is unethical to expose students to a GSI who does not follow correct procedures in chemical hygiene. Thus such design might be problematic from the students' safety perspective. In this study, the circumstances were such that this variable could be tested unintentionally, revealing that GSIs receiving training can positively influence students' behavior in the lab and the reduction of accidents.

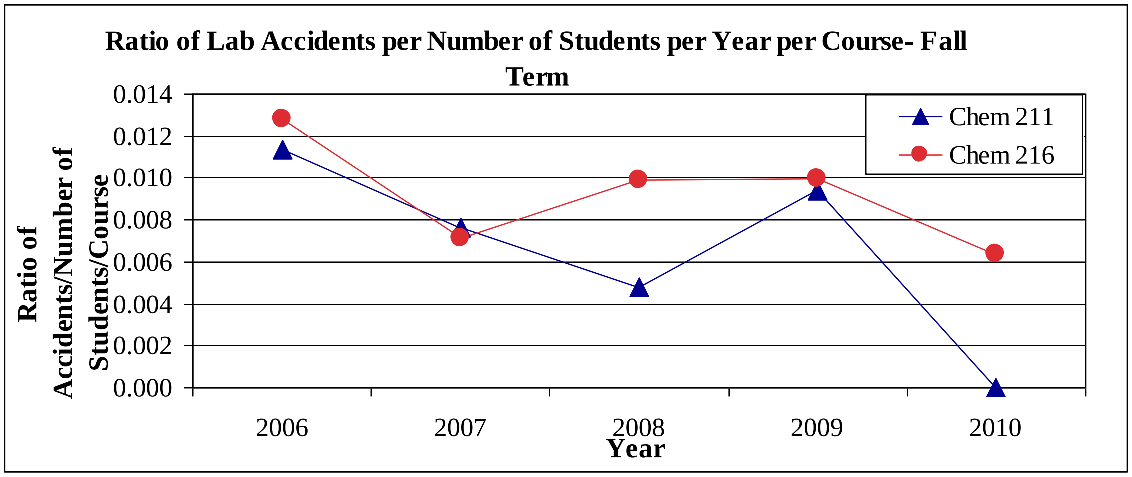
A final limitation has to do with the role of the researcher in writing the curriculum that was being assessed. Personal stake in the research findings could be misconstrued as personal bias, but as the data shows there is a need to better correlate the students and the survey results, to better improve the curriculum. This would need to be investigated with further manipulation of the instrument.

## 4.4 Results and Discussion

### *4.4.1 Reported Accidents in the Teaching Laboratories*

It was shocking to see how many students have been injured annually as indicated by the number of reported laboratory accidents that occurred in the undergraduate organic teaching laboratories at the University of Michigan over the past five years. These accidents strongly suggest that formal training in chemical hygiene and laboratory safety must be a part of the undergraduate curriculum, and provide a rationale for this study. As depicted in Figure 4.1, there is a large number of reported accidents in both Chemistry 211 and Chemistry 216. Decreasing accidents that produce bodily harm is vital for students' and faculty' safety and is overall beneficial to the university in the long term. As seen in the figure, after the implementation of the revised safety curriculum in the Chemistry 211 laboratory class fall 2010, the number of reported accidents, specifically chemical burns or abrasions, dropped from 12 in 2009 to zero in fall of 2010.

**Figure 4.1: Ratio of number of accidents to the number of students per class during the fall term (pilot students) over five years. Decrease in Chem 211 accidents during the fall pilot term.**

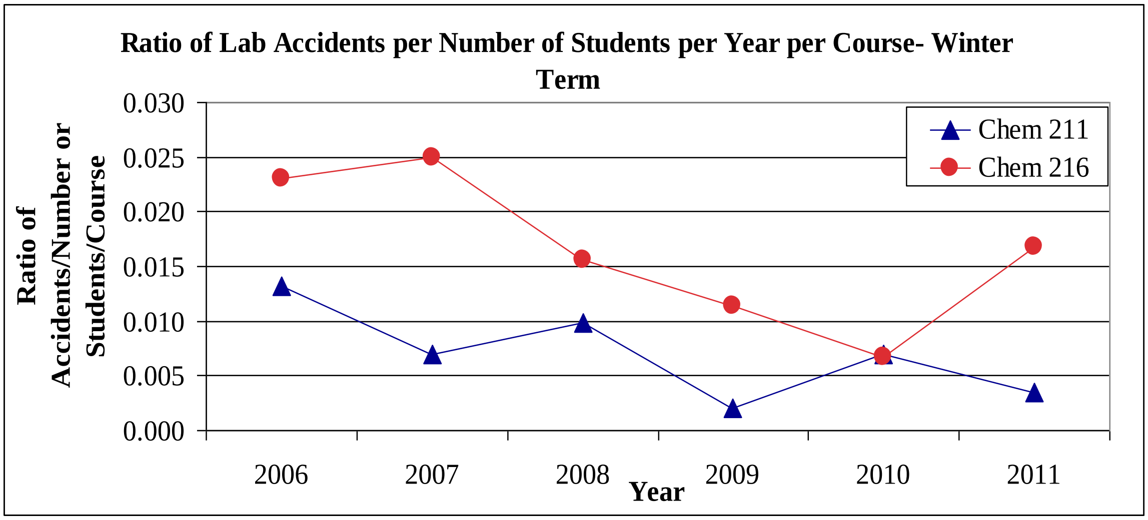


| | 2006 | | 2007 | | 2008 | | 2009 | | 2010 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | Accident | N | Accident | N | Accident | N | Accident | N | Accident |
| **211** | 1324 | 15 | 1308 | 10 | 1257 | 6 | 1274 | 12 | **1269** | **0** |
| **216** | 312 | 4 | 280 | 2 | 303 | 3 | 302 | 3 | 314 | 2 |

The statistical analysis with bivariate correlation coefficients indicated no significant difference between the reported accidents in Chem 211 compared to Chem 216 during the fall or spring/summer terms. The only term that showed a statistical significance was the winter term: there was a dramatic increase in the accident rates in Chemistry 216 due to chemical burns (Figure 4.2).

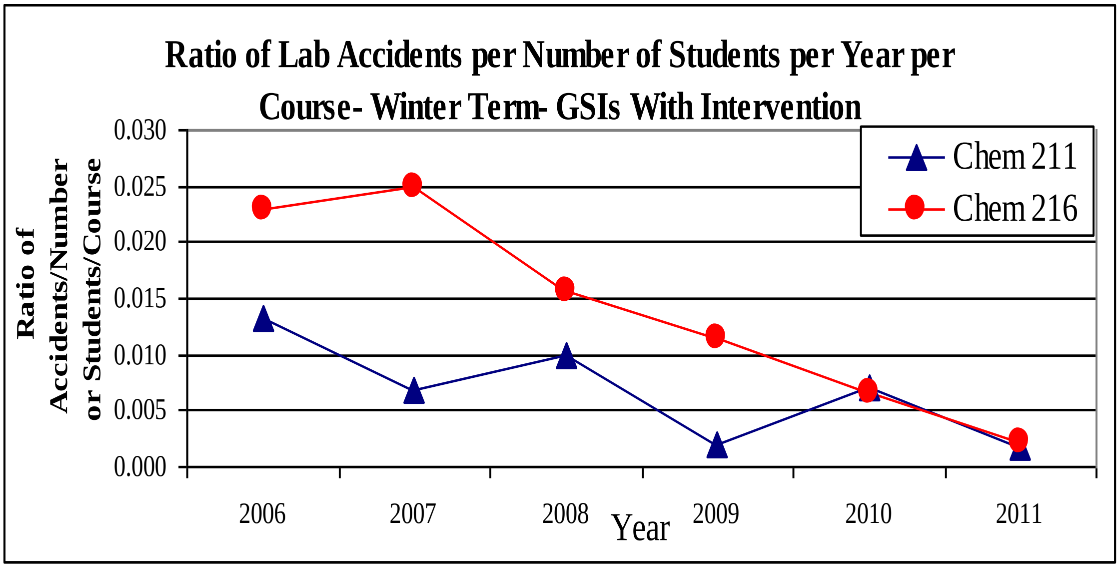
Upon further analysis, most of the reported accidents stemmed from 15 GSIs who had not been trained in the curriculum. After controlling for these GSIs, a decrease in reported accidents was seen in both Chemistry 211 and 216 (Figure 4.3). No significance between reported accidents for each laboratory course was seen.

**Figure 4.2: Ratio of number of accidents to the number of students per class during the winter term over six years. Large increase of chemical burns winter term.**



| | 2006 | | 2007 | | 2008 | | 2009 | | 2010 | | 2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. |
| **211** | 528 | 7 | 432 | 3 | 407 | 4 | 490 | 1 | 572 | 4 | **574** | **2** |
| **216** | 870 | 20 | 960 | 24 | 963 | 15 | 960 | 11 | 899 | 6 | **954** | **16** |

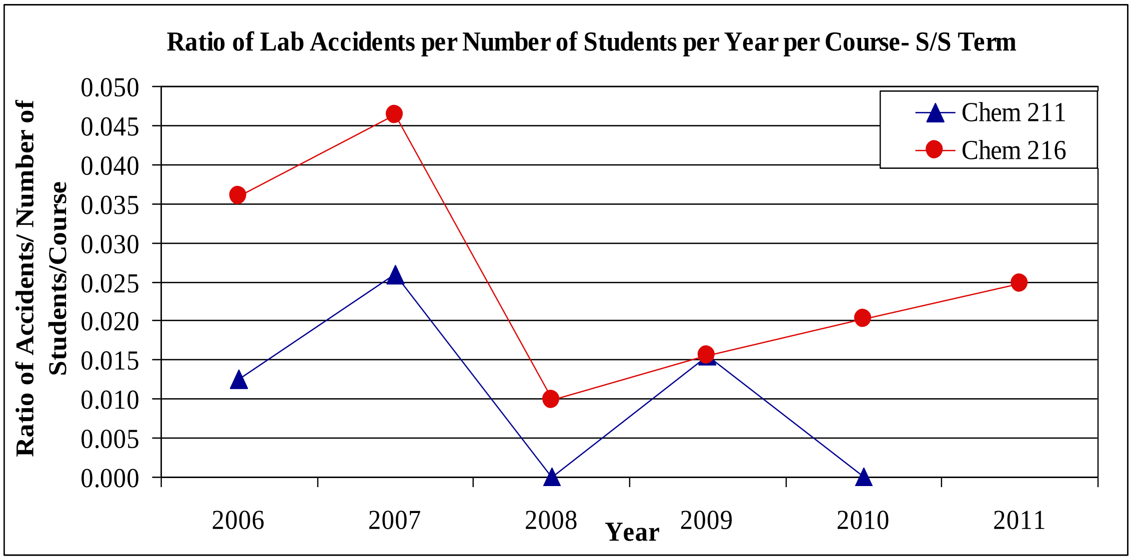
**Figure 4.3: Ratio of number of accidents to the number of students per class during the winter term over six years. After controlling for the GSIs without intervention, decrease in reported accidents is seen.**



| | 2006 | | 2007 | | 2008 | | 2009 | | 2010 | | 2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. |
| **211** | 528 | 7 | 432 | 3 | 407 | 4 | 490 | 1 | 572 | 4 | **574** | **0** |
| **216** | 870 | 20 | 960 | 24 | 963 | 15 | 960 | 11 | 899 | 6 | **954** | **2** |

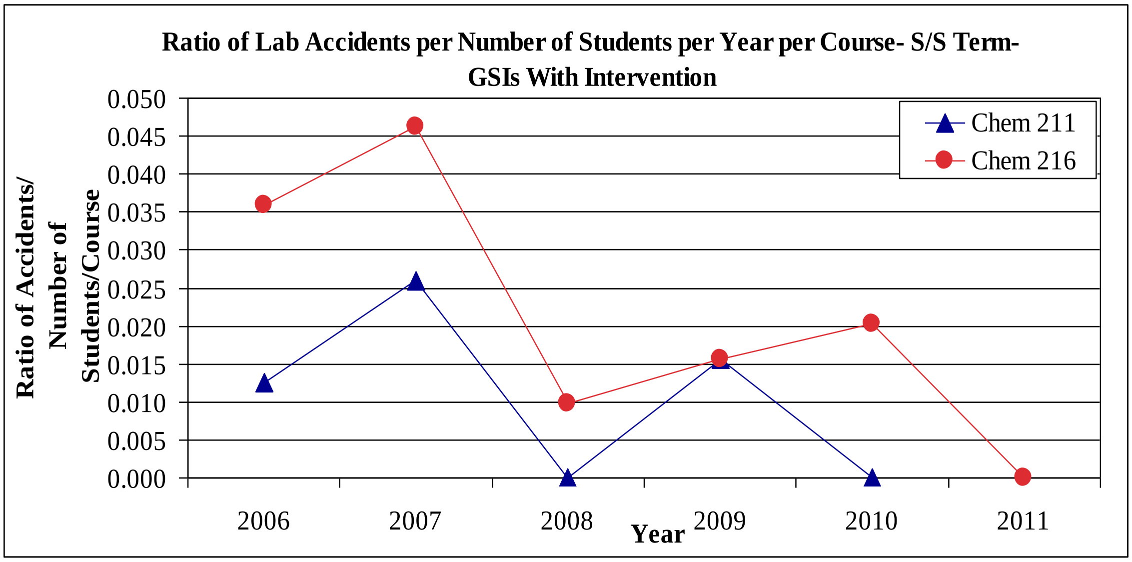
The spring/summer terms (Figure 4.4 and Figure 4.5) show no statistically significant difference between the Chemistry 211 and 216 reported accident rates. As seen in the winter data, the Chem 216 reported accidents did increase compared to past years (Figure 4.4), but when controlling for GSIs that did not receive the training in the safety curriculum, the number of accidents decreased (Figure 4.5).

**Figure 4.4: Ratio of number accidents to the number of students per class during the spring/summer term over six years. Large increase of chemical burns during spring/summer term.**



| | **2006** | | **2007** | | **2008** | | **2009** | | **2010** | | **2011** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. |
| **211** | 80 | 1 | 77 | 2 | 77 | 0 | 64 | 1 | 42 | 0 | | |
| **216** | 139 | 5 | 108 | 5 | 102 | 1 | 128 | 2 | 148 | 3 | **121** | **3** |

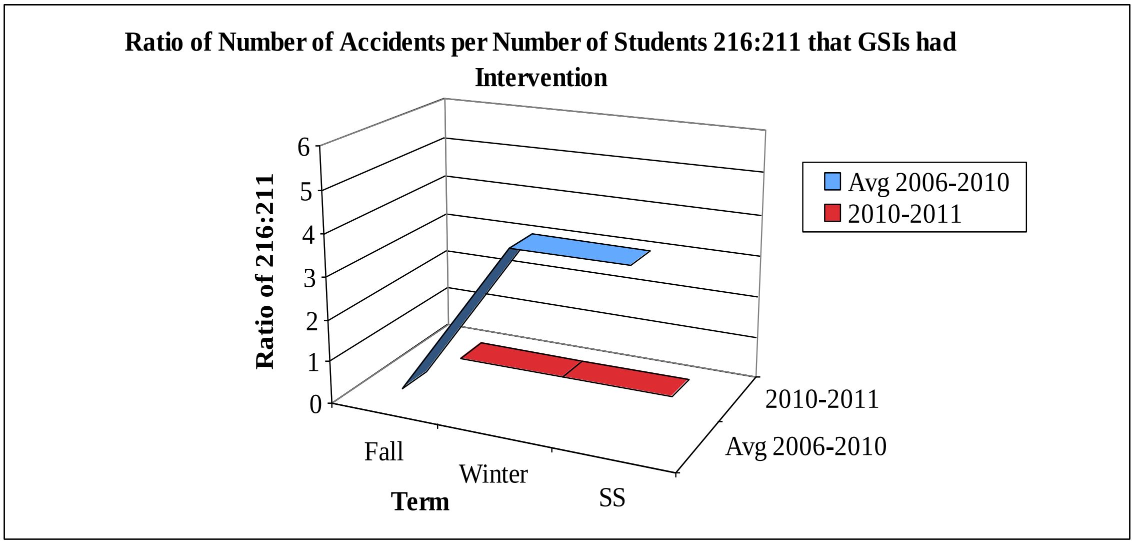
**Figure 4.5: Ratio of number of accidents to the number of students per class during the spring/summer term over six years. After controlling for the GSIs without intervention, decrease in reported accidents is seen.**



| | 2006 | | 2007 | | 2008 | | 2009 | | 2010 | | 2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. | N | Acc. |
| **211** | 80 | 1 | 77 | 2 | 77 | 0 | 64 | 1 | 42 | 0 | | |
| **216** | 139 | 5 | 108 | 5 | 102 | 1 | 128 | 2 | 148 | 3 | **121** | **0** |

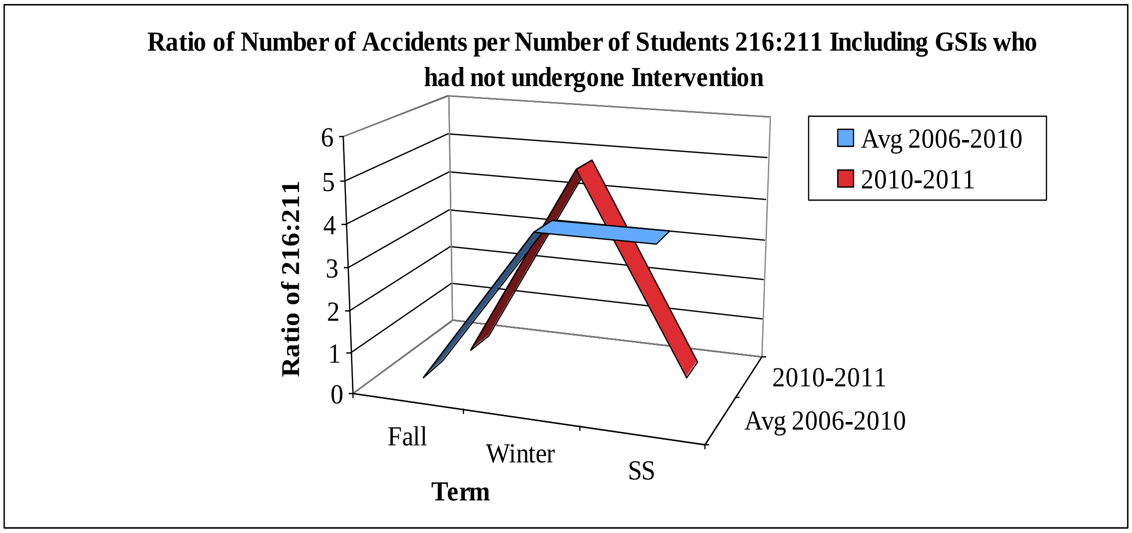
The average number of reported accidents in Chem 211 and 216 over the past five years (2006-10) was compared to the number of reported accidents since the implementation of the present chemical hygiene lessons into the curriculum. There was a decreasing trend in the reported accident rates when considering the GSIs who were trained (Figure 4.6). When including the GSIs who had not previously taught Chemistry 211, and therefore did not receive the new instruction, there was little difference in reported accidents compared to the five year average (Figure 4.7).

**Figure 4.6: Ratio of the number of accidents to the number of students per class during the 2010-11 school year who had completed the new safety initiative compared to the average of the years 2006-2010. With GSIs who have undergone the instruction, the number of accidents is close to zero.**



| | 2006-10 Average | | 2010-11 | |
|---|---|---|---|---|
| | Number of Students | Number of Accidents | Number of Students | Number of Accidents |
| **Fall** | 1590 | 14 | 1583 | **0** |
| **Winter** | 1416 | 19 | 1528 | **2** |
| **S/S** | 193 | 4 | 163 | **0** |

**Figure 4.7: Ratio of the number of accidents to the number of students per class during the 2010-11 school year compared to the average of the years 2006-2010. When all GSIs are included there is no visible decrease in the number of reported accidents.**



| | 2006-10 Average | | 2010-11 | |
|---|---|---|---|---|
| | Number of Students | Number of Accidents | Number of Students | Number of Accidents |
| **Fall** | 1590 | 14 | **1583** | **0** |
| **Winter** | 1416 | 19 | 1528 | 18 |
| **S/S** | 193 | 4 | 163 | 4 |

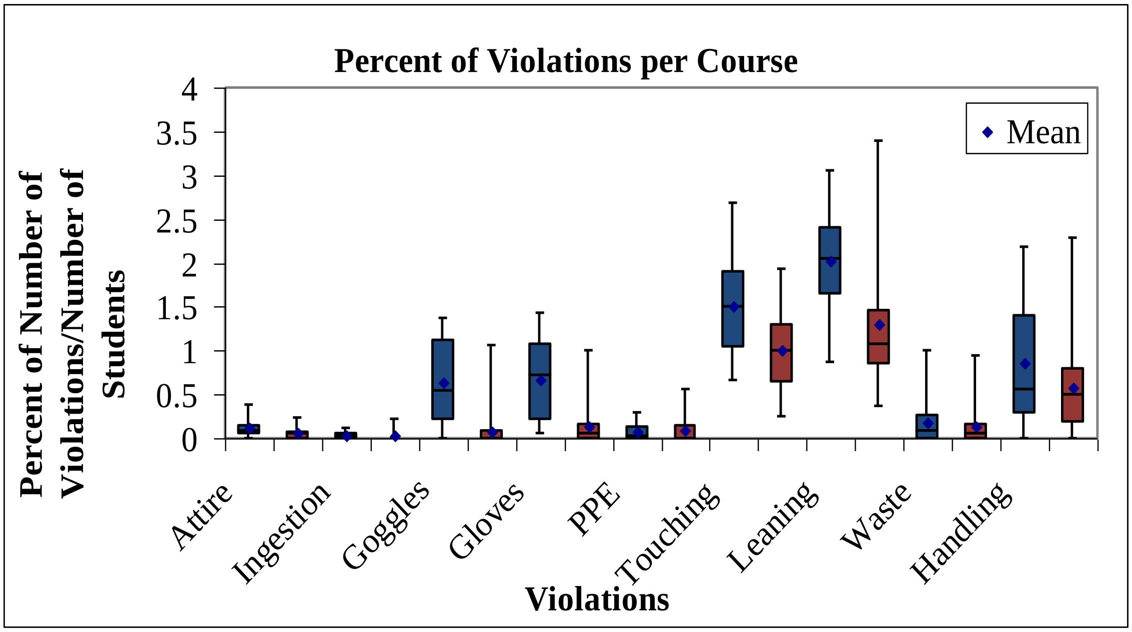
#### *4.4.1.1 Reported Accident Results Summary*

Although efforts were made to train undergraduate students to be more aware and responsible chemists, after consideration of the data above, it seems that the most effective way to minimize risk is to properly train the GSIs. As Figure 4.6 and Figure 4.7 suggest when the GSI is properly trained and familiar with proper chemical hygiene and laboratory safety protocols, the number of accidents decreased at least 20%. For continued improvement of safety overall and to continue this trend of accident reduction all GSIs must receive adequate instruction as well. Future implementation of biannual safety training for all GSIs would be a worthwhile investment to better ensure the safety of the undergraduates in the laboratory setting.

### *4.4.2 In-Class Observations*

The number of violations per the number of students is shown in the box plot in Figure 4.8. The mean and median in Chem 211 was consistently higher for each type of violation, suggesting that these students were more careless or less knowledgeable in their chemical hygiene practices, contrasting with the accident results shown previously. This could indicate that the students were still learning the proper safety and hygiene procedures in the introductory laboratory throughout the term. However, this would also suggest that the knowledge gained in Chemistry 211 was successfully retained in later chemistry laboratories, addressing another goal of this safety training.

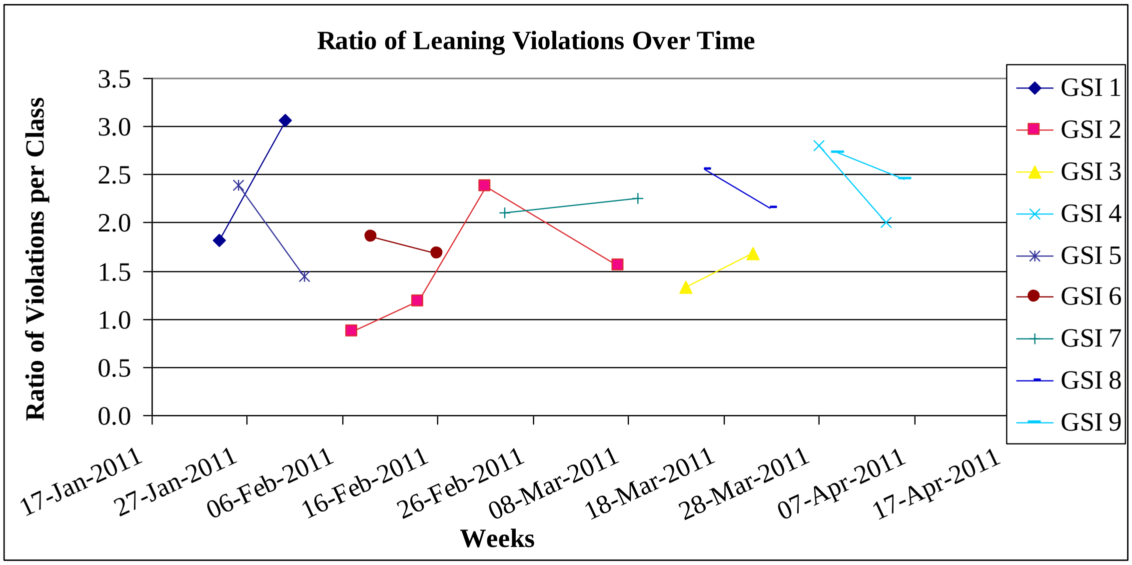
**Figure 4.8: Percent of violations per number of students per course during the 2011 winter term. Blue = Chem 211, Red = Chem 216. Chem 211 consistently had more chemical hygiene violations throughout the term.**



| | Total Students | Number Observed |
|---|---|---|
| **211** | 574 | 155 |
| **216** | 954 | 205 |

A closer examination of a specific violation, leaning, is depicted in Figure 4.9 (additional violation plots are located in Appendix H). At least two data points of leaning violations per each of the nine different laboratory classes during the winter 2011 term is plotted. Most of the labs suggest a positive result: a decrease in violations. However, with only two to four time points, an actual trend cannot be formulated. It is interesting to note that the variation in Lab Classes 2 and 7 occurred around Spring Break, suggesting the students might "forget" subject material over breaks.

**Figure 4.9: Ratio of leaning violations in nine different Chem 211 laboratory classes during the course of winter 2011. Due to a lack of power, no direct conclusions can be made.**



When plotting individual Chemistry 211 class observations over time, a slight decrease in violation occurrences is noticeable. Figure 4.10 and Figure 4.11 illustrate two different laboratory classes with two different GSIs and two different sets of students, thus direct comparisons cannot be made. The paired t-tests of the difference between the two time points revealed that the change over time was not significant (Table 4.2). The lack of significance could be due to the small number of classes giving insufficient statistical power.

**Table 4.2: Means of Chem 211 lab class observations of violations at T1 and T2. N=9**

| | Time 1 | | Time 2 | |
|---|---|---|---|---|
| | Mean | SEM[a] | Mean | SEM[a] |
| Attire | 2.33 | 0.782 | 1.44 | 0.377 |
| Ingestion | 0.78 | 0.278 | 0.44 | 0.176 |
| Goggles | 9.56 | 2.599 | 10.44 | 2.809 |
| Gloves | 9.67 | 2.656 | 11.22 | 2.737 |
| Personal Protection Equipment | 0.78 | 0.434 | 1.89 | 0.696 |
| Touching | 23.56 | 3.167 | 25.33 | 2.698 |
| Leaning | 35.56 | 4.011 | 33.78 | 3.546 |
| Waste | 1.78 | 0.619 | 3.00 | 1.179 |
| Handling | 13.56 | 3.400 | 10.11 | 3.276 |

[a]. SEM is the $Std.ErrorMean = \sqrt{\frac{StdDev^2}{N}}$. None of the differences was statistically significant.

**Figure 4.10: Ratio of each type of violation to the number of students enrolled during the middle of the winter 2011 term, lab 8, general decrease in violations.**

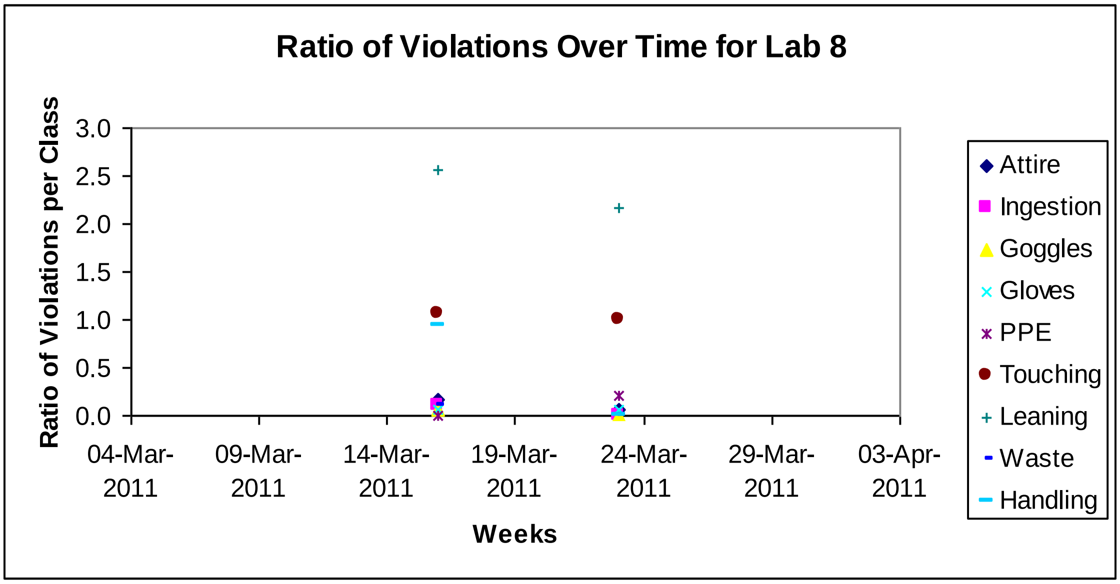
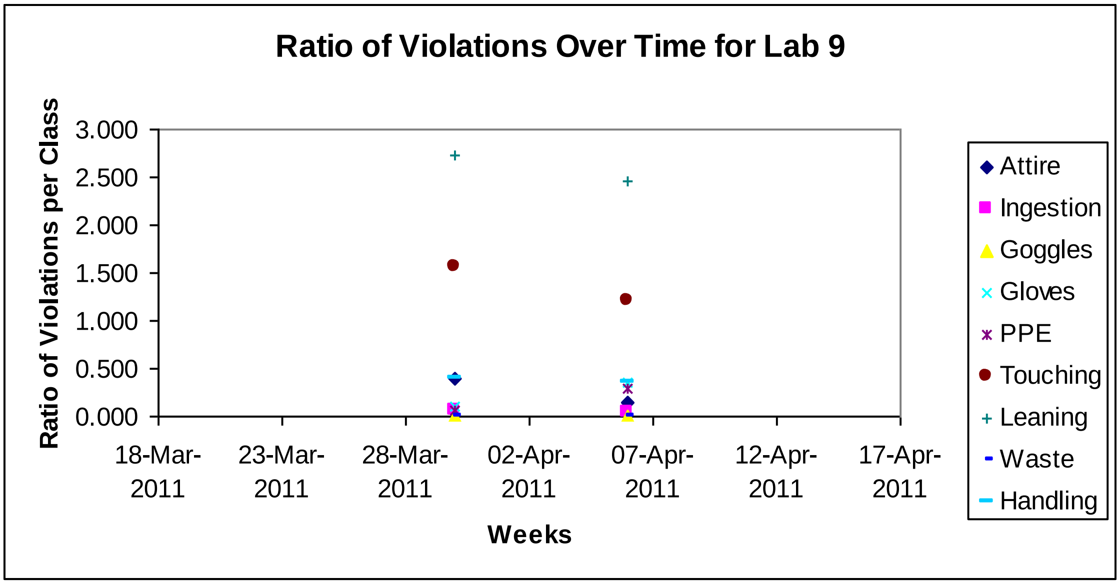


**Figure 4.11: Ratio of each type of violation to the number of students enrolled towards the end of the winter 2011 term, lab 9, general decrease in violations.**



#### *4.4.2.1 In-Class Observation Summary*

In-class observations showed that Chemistry 211 students engaged in less safe behaviors than Chem 216 students as they committed more safety infractions. As expected, the Chemistry 216 students appear to retain some of the chemical safety training gained in the previous course and showed a lower number of violations as illustrated in Figure 4.8.

### *4.4.3 Chemical Hygiene Survey*

The results in Appendix I show the fixed effect parameter estimates in the HLM model without the interaction of GSI dependence. These results suggest that class year has an effect on the score at Time 2 that is approaching significance ($p < 0.06$ for sophomores, juniors, and seniors, with freshmen as the reference category, ‘other’). The estimates indicate that sophomores, juniors, and seniors all tended to score about 2.5 units higher on the Time 2 Chemical Hygiene score than freshmen, holding all other covariates fixed. In addition, the estimated variance component for GSIs (i.e., the estimated variance of the random GSI intercepts) was only 0.043 ($p = 0.912$), suggesting that the variance due to the different GSIs for the Time 2 Chemical Hygiene score was negligible.

The interaction between Time 1 Waste score and group was non-significant, suggesting a constant gap between the groups at Time 2 when taking their baseline scores into account. This interaction was dropped from the model. In the resulting model, a marginally significant difference was found between Group 2 (winter 211) and Group 3 (control) in terms of Time 2 Waste scores, with Group 2 having a marginally lower mean (about one unit lower; $p = 0.087$) than Group 3, holding all other covariates fixed. There was evidence of negligible variance due to GSIs, further suggesting that GSIs did not have an impact on these scores at Time 2. Appendix J shows the HLM results for the Waste factor.

Finally, an HLM was fitted to the overall score, resulting from adding the score in Chemical Hygiene and Waste at Time 2 (Table 4.3). The interaction between the Time 1 added score (SUM) and group was non-significant, suggesting a constant gap between the groups at Time 2 when taking their baseline scores into account. This interaction was dropped from the model. The difference between groups at Time 2 for this variable was only approaching marginal significance, with Group 2 having a mean that was 1.25 units lower than Group 3 holding all other covariates fixed ($p = 0.140$). There was once again evidence of Juniors ($p = 0.049$) and Seniors ($p = 0.053$) having higher means than freshmen on the Time 2 SUM score (by about 4 units), holding the other covariates fixed. There was also negligible variance due to GSIs. This further corroborated that there is no statistical significant difference between the Chem 211 and control students based on any of the collected demographic data.

Although there was no GSI dependence on student survey results, student laboratory practices were dependent on the GSI. This initial discovery led to some additional questions. The study was widened in order to determine if a student's background influenced his or her ability to gain and retain this new knowledge. Additional efforts were made to quantify the amount of chemical hygiene knowledge actually gained by specific groups of the students.

Trends in the scores for the two factors (CH and W) and the summation (SUM) in the k-means cluster data for the control students and the Chemistry 211 students are illustrated in Figure 4.12. There is not a significant difference between the Time 2 scores of the Chem 211 students that went through safety instruction and the control students who did not. However, when comparing Likert results (Table 4.5) to survey results, an interesting trend emerged. Chemistry 211 students noted that they felt more confident in the lab with their safety, yet they scored significantly lower than the control students who reported feeling less safe (Figure 4.13). This is a trend that has been consistently seen in opinion based research.[21, 22]

**Table 4.3: Hierarchical linear model of demographic influence on participant scores.**

| Parameter | Estimate | Std. Error | $t^a$ | Sig. |
|---|---|---|---|---|
| Intercept | 1.700792 | 4.913426 | .346 | .733 |
| [GroupCode=2.00] | -1.253331 | .817179 | -1.534 | .140 |
| T1SUM | -.301277 | .181107 | -1.664 | .111 |
| [Gender=1.00] | .300535 | .540416 | .556 | .584 |
| [Ethnicity=1.00] | 2.537294 | 2.512193 | 1.010 | .324 |
| [Ethnicity=3.00] | 2.023861 | 2.478980 | .816 | .423 |
| ACTCompScore | -.141395 | .146813 | -.963 | .346 |
| SATCompScore | .002434 | .003428 | .710 | .485 |
| [PreviousResearch=1] | -.138011 | .582652 | -.237 | .815 |
| [Major =1] | .530489 | 1.619705 | .328 | .747 |
| [Major =3] | -.585774 | 1.720760 | -.340 | .737 |
| [Major =4] | .936781 | 1.898158 | .494 | .627 |
| [ClassYear =1] | 3.046188 | 2.049344 | 1.486 | .152 |
| [ClassYear =2] | 3.917997 | 2.056150 | 1.906 | .070 |
| **[ClassYear =3]** | **4.063009** | **1.944748** | **2.089** | **.049** |
| [ClassYear =4] | 4.393392 | 2.139883 | 2.053 | .053 |
| [Extracurricular =1] | -1.435241 | 1.590918 | -.902 | .377 |
| [Extracurricular =2] | -.691474 | .746334 | -.926 | .365 |
| [Extracurricular =3] | -.492056 | .867399 | -.567 | .577 |
| [Extracurricular =4] | -.231239 | .967419 | -.239 | .813 |
| CreditHours | .018624 | .012073 | 1.543 | .138 |
| TransferHours | .048523 | .045359 | 1.070 | .297 |

[a]. *df* = 21.

GroupCode 2 = Winter 211, GroupCode 3 = Control; Gender 1 = Male, Gender 2 = Female; Ethnicity 1 = Caucasian, Ethnicity 3 = Asian, Ethnicity 5 = 2 or More; Previous Research 1 = yes, Previous Reserach 2 = no; Major 1 = Science, Major 3 = Engineering, Major 4 = Social Sciences, Major 5 = Business; Class Year 1 = 2011, Class Year 2 = 2012, Class Year 3 = 2013, Class Year 4 = 2014, Class Year 5 = other; Extracurricular 1 = Marching Band, Extracurricular 2 = Athletics, Extracurricular 3 = Greek Life, Extracurricular 4 = Scholastic Clubs, Extracurricular 5 = Intramural Sports.

**Table 4.4: Demographics of the two clusters of participants.**

| | **Cluster 1 N (%)** | **Cluster 2 N (%)** |
|---|---|---|
| Gender | | |
| Male | 93 (53%) | 46 (37%) |
| Female | 81 (47%) | 78 (63%) |
| Ethnicity | | |
| White | 104 (60%) | 79 (64%) |
| Black | 1 (1%) | 4 (3%) |
| Asian | 54 (31%) | 24 (19%) |
| Hispanic | 3 (2%) | 4 (3%) |
| 2 or More | 10 (6%) | 9 (7%) |
| Not Reported | 2 (1%) | 4 (3%) |
| ACT Comp Score | | |
| 15-19 | 0 (0%) | 1 (1%) |
| 20-25 | 2 (1%) | 21 (17%) |
| 26-30 | 40 (23%) | 87 (70%) |
| 31-36 | 132 (76%) | 15 (12%) |
| SAT Comp Score | | |
| 0-800 | 0 (0%) | 1 (1%) |
| 800-1000 | 0 (0%) | 4 (3%) |
| 1000-1200 | 0 (0%) | 53 (43%) |
| 1200-1400 | 88 (51%) | 66 (53%) |
| 1400-1600 | 86 (49%) | 0 (0%) |
| Previous Lab Course | | |
| No | 130 (75%) | 43 (35%) |
| Yes | 44 (25%) | 81 (65%) |
| Credit Hours | | |
| 0-20 | 1 (1%) | 0 (0%) |
| 20-40 | 7 (4%) | 9 (7%) |
| 40-60 | 58 (44%) | 30 (24%) |
| 60-80 | 62 (36%) | 51 (41%) |
| 80-100 | 30 (17%) | 15 (12%) |
| 100-120 | 6 (3%) | 13 (11%) |
| 120-140 | 8 (5%) | 4 (3%) |
| 140-160 | 2 (1%) | 2 (2%) |
| Transfer Hours | | |
| 0-10 | 144 (83%) | 106 (86%) |
| 10-20 | 17 (10%) | 9 (7%) |

| | **Cluster 1 N (%)** | **Cluster 2 N (%)** |
|---|---|---|
| 20-30 | 8 (5%) | 6 (5%) |
| 30-40 | 3 (2%) | 1 (1%) |
| 40-50 | 1 (1%) | 0 (0%) |
| 60-70 | 1 (1%) | 2 (2%) |

**Figure 4.12: Comparison of clustered participant data: overall survey scores. No significant difference is seen between clusters.**

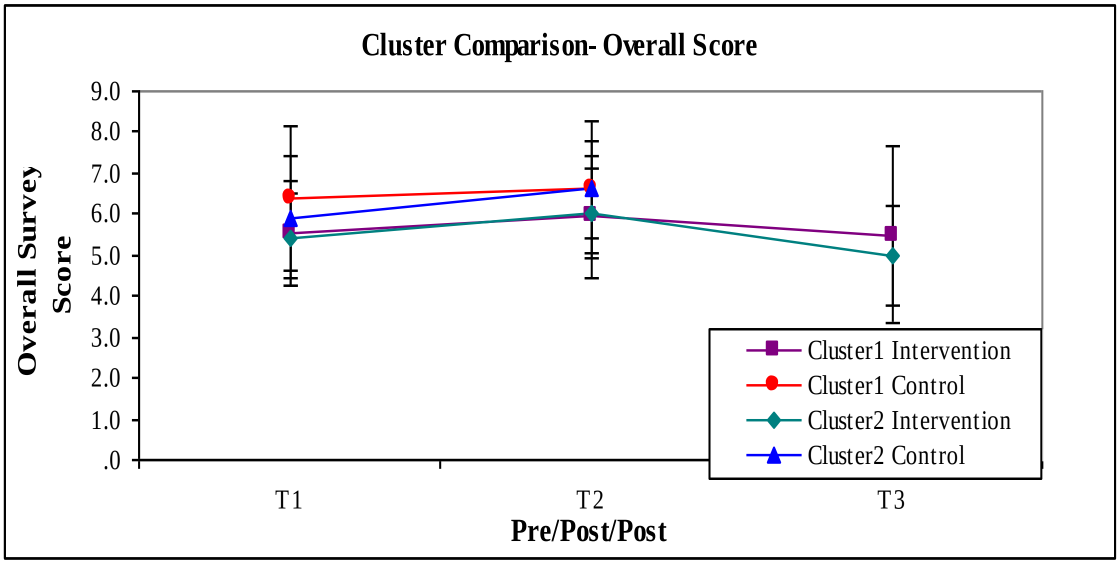


**Figure 4.13: Comparison of cluster 2 student data: overall survey scores compared to Likert results. Students who felt more confident scored more poorly.**

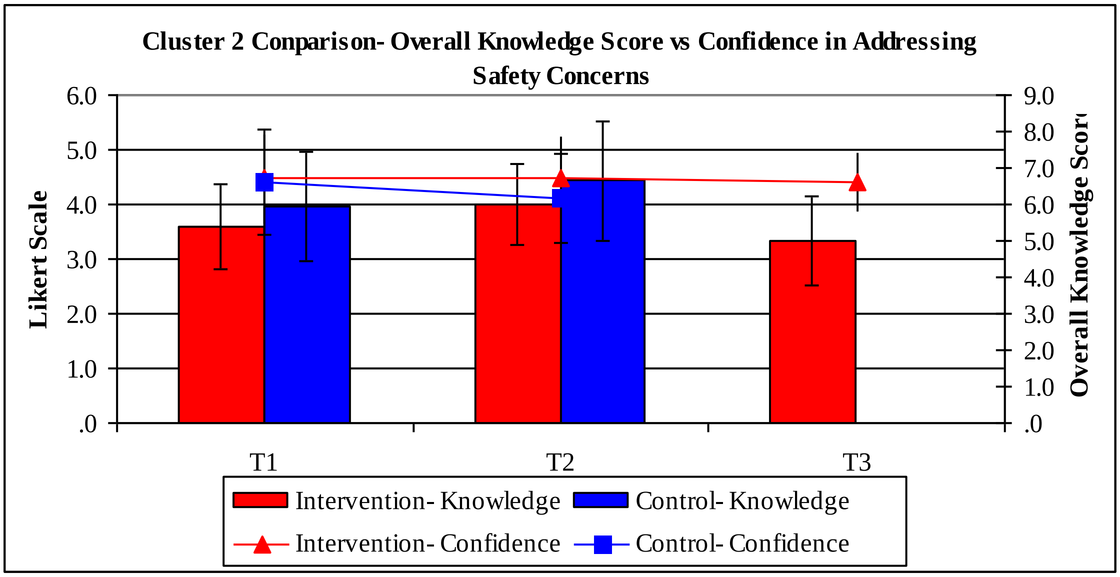


**Table 4.5: Mean and standard deviation for the items: How confident are you that you can: Address Safety Concerns.**

| T1 | | | | T2 | | | | T3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Cluster 1 | | Cluster 2 | | Cluster 1 | | Cluster 2 | | Cluster 1 | | Cluster 2 | |
| Wint N=47 | Cont N=15 | Wint N=31 | Cont N=27 | Wint N=44 | Cont N=9 | Wint N=28 | Cont N=19 | Wint N=6 | Pilot N=108 | Wint N=5 | Pilot N=57 |
| 4.32 (.81) | 4.07 (.704) | 4.46 (.838) | 4.42 (.961) | 4.14 (.930) | 3.60 (.843) | 4.48 (.769) | 4.11 (.801) | 4.17 (.753) | 4.20 (.818) | 4.40 (.548) | 4.02 (1.044) |

#### *4.4.3.1 Chemical Hygiene Survey Summary*

Overall, the instrument developed was inadequate in assessing the effectiveness of the current chemical hygiene curriculum. As seen with the reported laboratory accidents and the in-class observations, there are improvements in student safety, but there is also a need for proper training of GSIs. However, these points did not arise upon analysis of data obtained from the present survey. Both the control students and the students who obtained safety and hygiene instruction scored similarly on these surveys. Different models were used to determine significance in the survey results. In the end, the survey did not meet the appropriate needs of this study and further development will be required.

## 4.5 Conclusion

The most important result from the implementation of the safety curricula was the overall decrease in accidents that occurred in the undergraduate teaching laboratories. This study indicates that the decrease in accidents is greatly due to GSI training. In-class observations revealed that Chemistry 211 students have enormous potential for learning proper procedures when handling chemicals; this potential can grow as they progress through the various chemistry laboratory courses. The results from this study indicate that teaching the students and the GSIs chemical hygiene can decrease the overall number of laboratory accidents and increase awareness of chemical safety. The results of this study further emphasize the importance for teaching proper chemical hygiene and safety in undergraduate laboratory classes.

As future development of the chemical hygiene curriculum evolves, online Occupational Safety and Environmental Health (OSEH) training will be incorporated as well as mid-year GSI training sessions. Chemistry is always evolving, and the safety protocols need to as well.

## 4.6 References

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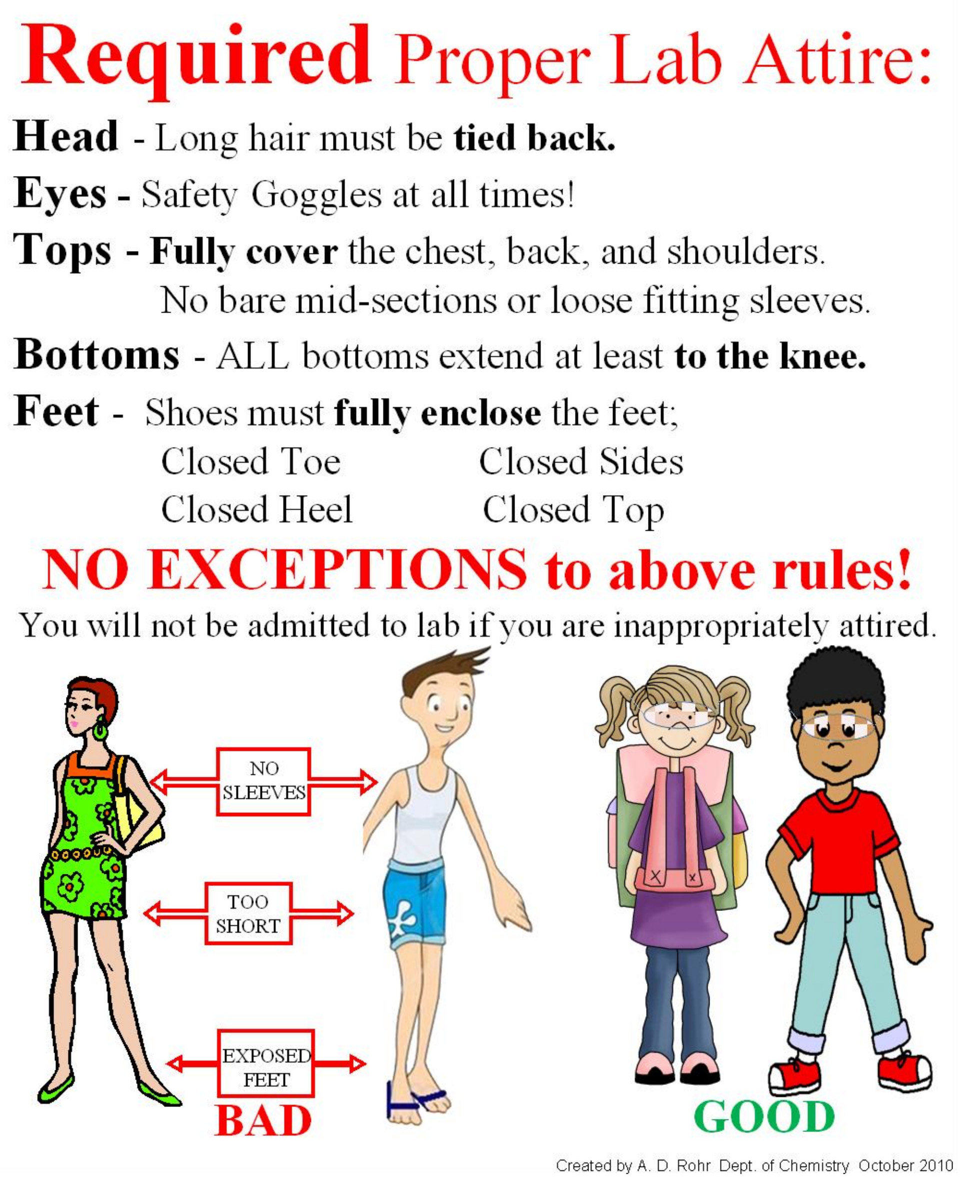
# Appendices

## Appendix A



**Required** Proper Lab Attire:

**Head** - Long hair must be **tied back.**

**Eyes -** Safety Goggles at all times!

**Tops - Fully cover** the chest, back, and shoulders.
No bare mid-sections or loose fitting sleeves.

**Bottoms** - ALL bottoms extend at least **to the knee.**

**Feet** - Shoes must **fully enclose** the feet;
Closed Toe Closed Sides
Closed Heel Closed Top

**NO EXCEPTIONS to above rules!**

You will not be admitted to lab if you are inappropriately attired.

Created by A. D. Rohr Dept. of Chemistry October 2010

## Appendix B

# Required Personal Protection Equipment (PPE):

When in the lab PPE must be worn at ALL TIMES!

**Goggles** – **To protect your eyes.**

**Aprons or Labcoats** – **To protect your body.**

**Gloves** – **To protect your hands.**

**NO EXCEPTIONS!**

Remove ALL PPE when leaving the lab!

Created by A. D. Rohr Dept. of Chemistry October 2010

**Appendix C**

# Proper Waste Disposal

## White Buckets – Solid waste

Gloves, pipettes, vials, excess reagents, etc.

## 1 Gallon Bottles – Liquid waste

Halogenated: Any halogen present.

e.g., Methylene Chloride, Chloroform

Non-Halo: Other organic solvents.

e.g., Ethyl Acetate, Hexanes

Corrosive: Acidic/basic solutions.

e.g., 1M HCl, 1M NaOH

Metals: Salt solutions.

e.g., Copper (II) nitrate, iron (II and III) nitrate

Toxic: None of the above

e.g., anilines, phenols

**LABEL bottles appropriately!**

---

**Don't know where it goes?**

**Don't guess!**

**ASK YOUR GSI!**

* Above rules are subject to change. Updated 8/19/10

Created by A. D. Rohr Dept. of Chemistry October 2010

# Appendix D

## Safety Initiative – Students' Comprehension of Curricula

Informed Consent Form

I, ______________________________ understand that Ahleah Rohr Daniel, in cooperation with the Department of Chemistry, is conducting a study to determine students' comprehension about how much they learned, utilized and how useful they find, the safety curricula and chemical hygiene POLICIES taught in Chemistry 211.

I understand that there are no anticipated risks or benefits to participants in this study. Overall, this study seeks to provide information that may ultimately improve chemistry instruction at the university level.

I understand that I am allowed to ask questions about this study both before agreeing to participate and during the course of the study and that I may refuse to participate in this study, discontinue at any time, or not answer questions without any consequences. Participation or non-participation in this study will, in no way, affect my academic standing or record.

I understand that the survey responses will be compiled and analyzed by a collaborator who is NOT DIRECTLY associated with ANY Chemistry LABORATORY course.

I understand that my personal background information from the University of Michigan databases (i.e., scores from: Chemistry Placement Exam, Mathematics Placement Exam, SAT Exam, ACT Exam, AP Exam; credits earned at the University of Michigan, credits transferred to the University of Michigan; gender; ethnicity; previous UM Chemistry grades, and grade in Chemistry 211/216 from the semester in which these responses are collected) may be accessed and used during this study. By signing, I am giving my consent to this.

This consent is being given voluntarily. I UNDERSTAND THAT I may refuse to participate in the entire study or in any part of the study. I UNDERSTAND THAT I am free to withdraw at any time without any negative effect on my relations with the University of Michigan or with any other participating institutions or agencies.

I will receive a copy of this consent form via the Chemistry 211, 216 CTools websites.

Any inquiries about this study should be directed to Ahleah Rohr Daniel, Department of Chemistry, 930 N University, Ann Arbor, MI 48109-1055, 734-763-2394 or Dr. Mark M. Banaszak Holl or Dr. John P. Wolfe, Department of Chemistry, 930 N University, Ann Arbor, MI 48109-1055. Should you have questions regarding your rights as a participant in research, please contact the Behavioral Sciences Institutional Review Board office, 1040 Fleming Building, 503 Thompson Street, Ann Arbor, MI 48109, 734-615-8427. email: irbhsbs@umich.edu

I hereby state I am of 18 years or older, and can legally agree to be a participant in this study.

| | |
|---|---|
| Participant Signature & Date | Ahleah Rohr Daniel, Investigator |

UM ID Number

# Appendix E

**GSI:** **Number of Students Following/Not following**

| **GOOD** | **BAD** |
|---|---|
| **Q1:** Students wearing proper lab attire? | |
| **Q2:** Students eating/drinking/chewing in the lab? | |
| **Q3:** Students wearing goggles? | |
| **Q4:** Students wearing gloves? | |
| **Q5:** Students removing PPE when appropriate? | |
| **Q6:** Students touching themselves and other inappropriate items while wearing gloves? | |
| **Q7:** Leaning on Benchtops? | |
| **Q8:** Students placing waste in proper containers? | |
| **Q9:** Inappropriate chemical handling? | |

# Appendix F

Dear Students,

I am Ahleah Rohr Daniel and I have been investigating new safety and chemical hygiene instruction methods in your laboratory course, Chemistry 211, this term. To assess these new policies and methods, I have devised a final survey and I hope you are willing to share your thoughts by filling it out.

I assure you that your answers are confidential, the survey should take no more than 15-20 minutes, your identification will not be revealed to anyone other than myself, and no one connected to 211 will see these surveys at all. Your participation is totally voluntary, and you can skip any parts that you do not wish to answer. By completing this survey (in part or in its entirety) you are agreeing that we may use the data to better instruct students in laboratory safety and to make the laboratory a safer environment for everyone.

If you have any questions about the survey, or if you would like to withdraw from participating after you have finished the survey, please contact Ahleah Rohr Daniel at rohrac@umich.edu.

**I hereby state I am of 18 years or older, and can legally agree to be a participant in this study.**

**Last Name:**

**First Name:**

**UM ID:**

Which class is this? (Circle one)

A.) Chem 211

B.) Chem 216

Write down your section number________________

What time of day is this lab? (Circle one)

A.) 8-11am

B.) 11-2pm

C.) 2-5pm

## PART I: SAFETY QUESTIONS

**Q1:** List four ways chemicals can enter the body while in a laboratory, that is, identify routes of exposure:
1.
2.
3.
4.

**Q2:** List three types of personal protective equipment (PPE) in the lab:
1.
2.
3.

**Q3:** Which of the following statements **best** describes the importance of appropriate laboratory attire? (Choose one)

A.) Maximum coverage allows for maximum response time when chemicals have been spilt.
B.) Maximum coverage decreases the probability of burning when exposed to flammable materials.
C.) Maximum coverage decreases the possibilities for physical contact with chemicals.
D.) Minimal skin exposure decreases the possibilities for you to be injected by chemicals.

**Q4:** Explain your answer choice in Q3.

**Q5:** Describe general methods for proper waste disposal.

**Q6:** Which of the following definitions **best** describes exposure as it applies to lab?

A.) Looking at TLC under the UV
B.) Coming into contact with a chemical
C.) Touching glassware while it is hot
D.) Not wearing personal protection equipment

**Q7:** In which case does a hood provide adequate protection?

A.) Implosion
B.) Explosion
C.) Neither

**Q8:** Proper chemical storage is important for several reasons in laboratories. Which of the following statements is an example of good long term chemical storage?

A.) Chemicals are stored in the hood so they are ventilated.
B.) Chemicals are stored on the top shelf, out of the reach of children.
C.) Chemicals are stored in cabinets away from ignition sources.
D.) Chemicals are stored on the countertops so they are in close reach

**Q9:** Explain your answer choice in Q8.

**Q10:** Food or beverages are not allowed in the laboratories. Is it okay to chew gum in a lab? Why?

**Q11:** You have conducted solubility test, results are shown in the table below. Which is the best waste container to place solubility test F?

| | Hexanes | Ethyl Acetate | 5% NaOH | 5% HCl |
|---|---|---|---|---|
| Benzophenone | A | B | C | D |
| Bromobenzene | E | F | G | H |
| Benzene | I | J | K | L |

A.) Acidic.
B.) Halogenated.
C.) Non-Halogenated.
D.) Basic.

**Q12:** Explain your answer in Q11.

**Q13:** Which of the following statements best describes personal protection equipment used properly?
A.) Sam is completing the lab write up without goggles, Joe trips and acid is splashed at Sam.
B.) Alexis is washing glassware with acetone, her nail polish is now on her beakers.
C.) Brent spilled NaOH, he then leaned against the bench wearing his apron where he had spilled the base.
D.) Heather removed her apron then she leaned where Brent had spilled the base.

**Q14:** You really want to impress someone in your lab. You carefully pick out your lab attire: dress to impress. Which outfit(s) poses safety hazard(s)?
A.) Ballet flats, jean-mini, hair pulled back.
B.) Dress slacks, nice loafers, dress shirt and tie.
C.) Jeans, T-Shirt, tennis shoes.
D.) Contact lenses, sandals, tank-top.

**Q15:** Explain your answer choice in Q14.

**Q16:** There is an unknown compound in a vial on the lab bench. Which of the following actions is the **most** appropriate to be taken?

A.) Leave it. The rightful owner will claim it.
B.) Tell your GSI, he/she will know what to do.
C.) Ask your benchmate, in case it is his/hers.
D.) Dump it in the waste, wash the glassware.

**Read the following excerpt to answer questions 17-22:**

**[1]** It is Friday afternoon, Sally arrives to lab dressed to go for the evening; heels, mini-jean skirt, tank-top with her hair down. **[2]** She enters the lab, puts on her apron, gloves and goggles. **[3]** After the class finished taking the quiz, experiments commenced. **[4]** Sally took off her gloves to write in her lab notebook, and then continued to weigh out starting materials. **[5]** All starting materials were stored in the hood at the front of the room, she ran past other lab mates while carrying vials full of samples. **[6]** At her bench Sally mixed the reagents and spilled them on her bench and the floor. **[7]** To clean up the bench she brushed the compounds on her foot as it fell to the floor. **[8]** Next to Sally was Tom, he saw Sally brushing compound to the floor and he walked over to stop her. **[9]** Tom, dressed in jeans, a t-shirt, and gym shoes grabbed a broom with his gloved hand to help. **[10]** After sweeping up the compound, Tom rubbed his eyes. **[11]** Sally, thanked Tom then proceeded to remind Tom goggles are best worn covering his eyes, not his forehead. **[12]** Together they sought out to find a waste container.

**Q17:** What are the advantages of Tom's attire compared to Sally's?

**Q18:** What types of risk does Sally expose herself to with her lab attire?

**Q19:** Which statement from the passage above best explains personal protection equipment used appropriately?

A.) After sweeping up, Tom rubbed his eyes with his hand.
B.) Sally took off her gloves to write in her lab notebook.
C.) Sally puts on her apron, gloves and goggles, entering lab.
D.) Tom must be reminded goggles are best worn covering his eyes.

**Q20:** When cleaning up, in the above passage, the students disposed of their compound. What is the most appropriate location for placement of their waste?

A.) The chemical waste produced is placed in the garbage cans.
B.) The chemical waste produced in placed in the halogenated container.
C.) The chemical waste produced is placed in the white buckets.
D.) The chemical waste produced is placed in the acidic container.

**Q21:** Tom and Sally have each participated in unsafe behavior. List the numbers of the sentences, from the passage above that indicate unsafe behavior for each person.

| **TOM** | **SALLY** |
|---|---|

**Q22:** How could the GSI have helped in this situation?

## PART II: OPINION QUESTIONS

**Q23:** How **likely** are you to…

| | Not at all likely | | | | Extremely likely |
|---|---|---|---|---|---|
| Take another chemistry lab | 1 | 2 | 3 | 4 | 5 |
| Major in chemistry | 1 | 2 | 3 | 4 | 5 |
| Remember to dress appropriately | 1 | 2 | 3 | 4 | 5 |
| Come to lab prepared | 1 | 2 | 3 | 4 | 5 |
| Read the weekly assignments | 1 | 2 | 3 | 4 | 5 |
| Attend lab lecture | 1 | 2 | 3 | 4 | 5 |
| Remember to wear PPE | 1 | 2 | 3 | 4 | 5 |
| Remove PPE when appropriate | 1 | 2 | 3 | 4 | 5 |
| Continue to practice safety | 1 | 2 | 3 | 4 | 5 |

**Q24:** How **confident** are you that you can…

| | Not at all confident | | | | Extremely confident |
|---|---|---|---|---|---|
| Safely work independently | 1 | 2 | 3 | 4 | 5 |
| Place waste in appropriate containers | 1 | 2 | 3 | 4 | 5 |
| Remember to dress appropriately | 1 | 2 | 3 | 4 | 5 |
| Take care of others in need | 1 | 2 | 3 | 4 | 5 |
| Address safety concerns | 1 | 2 | 3 | 4 | 5 |

**Q25:** Of the safety teachings, how much did you **learn** from the following?

| | Not at all | | | | A lot |
|---|---|---|---|---|---|
| The weekly readings | 1 | 2 | 3 | 4 | 5 |
| The weekly quizzes | 1 | 2 | 3 | 4 | 5 |
| The lab lectures | 1 | 2 | 3 | 4 | 5 |
| The posters outside the laboratory | 1 | 2 | 3 | 4 | 5 |
| The posters inside the laboratory | 1 | 2 | 3 | 4 | 5 |
| GSI instructions | 1 | 2 | 3 | 4 | 5 |

**Q26:** Do you **agree** with the following statements?

| | Strongly disagree | | | | Strongly agree |
|---|---|---|---|---|---|
| I will pass on the knowledge gained | 1 | 2 | 3 | 4 | 5 |
| I have learned to work independently | 1 | 2 | 3 | 4 | 5 |
| I understand the importance of chemical hygiene | 1 | 2 | 3 | 4 | 5 |
| I am responsible for my own health in the lab | 1 | 2 | 3 | 4 | 5 |
| I am conscientious about laboratory safety | 1 | 2 | 3 | 4 | 5 |
| I feel I am SAFE enough to work independently | 1 | 2 | 3 | 4 | 5 |
| I can safely take care of others in a laboratory | 1 | 2 | 3 | 4 | 5 |
| The GSI provided adequate instruction of laboratory safety | 1 | 2 | 3 | 4 | 5 |
| I know what to do in case of an accident | 1 | 2 | 3 | 4 | 5 |

## PERSONAL BACKGROUND

**Q1:** Which chemistry lab(s) at the University of Michigan have you taken?
A.) Chem 125
B.) Chem 211
C.) Chem 211H
D.) Chem 216
E.) Chem 216H
F.) Other

**Q2:** Have you worked in a research lab? If so, where?

**Q3:** What is your major?

**Q4:** What is your class year?
A.) First-year
B.) Sophomore
C.) Junior
D.) Senior
E.) Other (please specify)__________________

**Q5:** What is your gender?
A.) Female
B.) Male

**Q6:** Do you participate in extracurricular activities? If yes, which ones?
A.) Marching Band
B.) Athletics
C.) Greek Life
D.) Scholastic Clubs
E.) Other (please specify)__________________

**Thank you for completing the survey! Your input is important to us, and will help us to help chemistry instructors improve teaching and learning in their courses.**

**If you have any questions, please contact me:**

**Ahleah Rohr Daniel, primary investigator**
**rohrac@umich.edu or 734-763-2394**

## Appendix G

Dear Students,

My name is Ahleah Rohr Daniel and I am investigating new safety and chemical hygiene instruction methods in the laboratory course, Chemistry 211 at the University of Michigan. To assess these new policies and methods, I have devised a survey and I hope you are willing to share your thoughts by filling it out.

I assure you that your answers are confidential, and the survey should take no more than 5 minutes. Your identification will not be revealed to anyone other than myself, and no one connected to 255 will see these surveys. Your participation is totally voluntary, and you can skip any parts that you do not wish to answer. By completing this survey (in part or in its entirety) you are agreeing that we may use the data to better instruct students in laboratory safety and to make the laboratory a safer environment for everyone.

If you have any questions about the survey, or if you would like to withdraw from participating after you have finished the survey, please contact Ahleah Rohr Daniel at rohrac@umich.edu.

**I hereby state I am of 18 years or older, and can legally agree to be a participant in this study.**

**On your Scantron fill out the following information in the blanks provided.**

**Last Name, First Name, MI**
**Section Number**
**Form #3**
**ID Number**

## PART I: SAFETY QUESTIONS

**Q1:** In the laboratory, there are four ways chemicals can enter the body, or four routes of exposure. Which are they?

A.) Injection, inhalation, abrasion, contact.
B.) Injection, absorption, ingestion, contact.
C.) Injection, inhalation, ingestion, insertion.
D.) Injection, inhalation, ingestion, contact.

**Q2:** Which of the following statements **best** describes the importance of appropriate laboratory attire? Coverage is directly related to: (Choose one)

A.) Decreased probability of exposure.
B.) Increased probability of burns.
C.) Increased probability of abrasions.
D.) Decreased probability of ingestion.

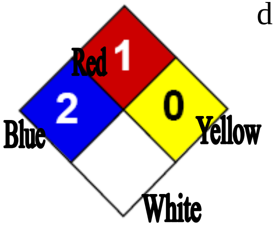
**Q3:** Proper waste disposal requires solid waste to be placed in buckets and liquid waste to be separated by composition. Which of the following does **not** belong in the waste buckets?

A.) Gloves worn in the lab.
B.) Paper towels used to clean a spill.
C.) Unknown white powder.
D.) Notebook paper.

**Q4:** In which case does a hood provide adequate protection?

A.) Implosion
B.) Explosion
C.) Neither
D.) Both

**Q5:** Shown is the NFPA (National Fire Protection Association) diamond for methylene chloride. Each diamond represents a specific type of hazard. What hazard is the yellow diamond depicting?



A.) Flammability
B.) Instability
C.) Health
D.) Special Hazard

**Q6:** You conducted solubility tests and the labeled vials are shown in the table below. Which is the best waste container to place solubility test **C**?

| | **Hexanes** | **Ethyl Acetate** | **Acetone** | **5% HCl** |
|---|---|---|---|---|
| **Benzophenone** | A | B | C | D |
| **Bromobenzene** | E | F | G | H |
| **Benzene** | I | J | K | L |

A.) Flammable.
B.) Acidic.
C.) Non-Flammable.
D.) Basic.

**Q7:** There is an unknown compound in a vial on the lab bench. Which of the following actions is the **most** appropriate?

A.) Leave it. The rightful owner will claim it.
B.) Ask your benchmate, in case it is his/hers.
C.) Tell your TA, he/she will know what to do.
D.) Dump it in the waste, wash the glassware.

**Q8:** Which statement **best** explains the most appropriate use of personal protection equipment (PPE)?
A.) After sweeping up, Tom rubbed his eyes with his hand.
B.) Sally took off her gloves to write in her lab notebook.
C.) Tom must be reminded goggles are best worn covering his eyes.
D.) Sally puts on her apron, gloves and goggles before entering lab.

**Q9:** A student arrives to lab dressed to go out: flip-flops, jeans, tank-top with her hair down. Which of the following is appropriate lab attire for them to change into?

A.) Ballet flats, shorts, T-Shirt, ponytail.
B.) Sneakers, jeans, T-Shirt, ponytail.
C.) Sneakers, jeans, tank-top, ponytail.
D.) Crocs, jeans, T-Shirt, ponytail.

**Q10:** Where do powdered chemicals get disposed of?
A.) The chemical waste is placed in the garbage cans.
B.) The chemical waste is placed in the flammable container.
C.) The chemical waste is placed in the waste buckets.
D.) The chemical waste is placed in the acidic container.

## PART II: OPINION QUESTIONS

How **confident** are you that you can…

| | Not at all confident | | | | Extremely confident |
|---|---|---|---|---|---|
| **Q11.** Safely work independently | 1 | 2 | 3 | 4 | 5 |
| **Q12.** Place waste in appropriate containers | 1 | 2 | 3 | 4 | 5 |
| **Q13.** Remember to dress appropriately | 1 | 2 | 3 | 4 | 5 |
| **Q14.** Take care of others in need | 1 | 2 | 3 | 4 | 5 |
| **Q15.** Address safety concerns | 1 | 2 | 3 | 4 | 5 |

## PERSONAL BACKGROUND

**Q16:** Have you worked in a research lab?
A.) Yes
B.) No

**Q17:** Your major, if you have chosen one, belongs to which of the following areas? If you have not chosen a major, which area do you think you will choose?
A.) Science
B.) Arts
C.) Engineering
D.) Social Sciences
E.) Business

**Q18:** What is your class?
A.) 2011
B.) 2012
C.) 2013
D.) 2014
E.) Other

**Q19:** What is your gender?
A.) Woman
B.) Man
C.) Transgender

**Q20:** Do you participate in extracurricular activities? If yes, which ones?
A.) Marching Band
B.) Athletics
C.) Greek Life
D.) Scholastic Clubs
E.) IM Sports

**Thank you for completing the survey! Your input is important to us, and will help us to help chemistry instructors improve teaching and learning in their courses.**

**If you have any questions, please contact me:**
**Ahleah Rohr Daniel, primary investigator**
**rohrac@umich.edu or 734-763-2394**

# Appendix H

**Figure 0.1: Ratio of Attire Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

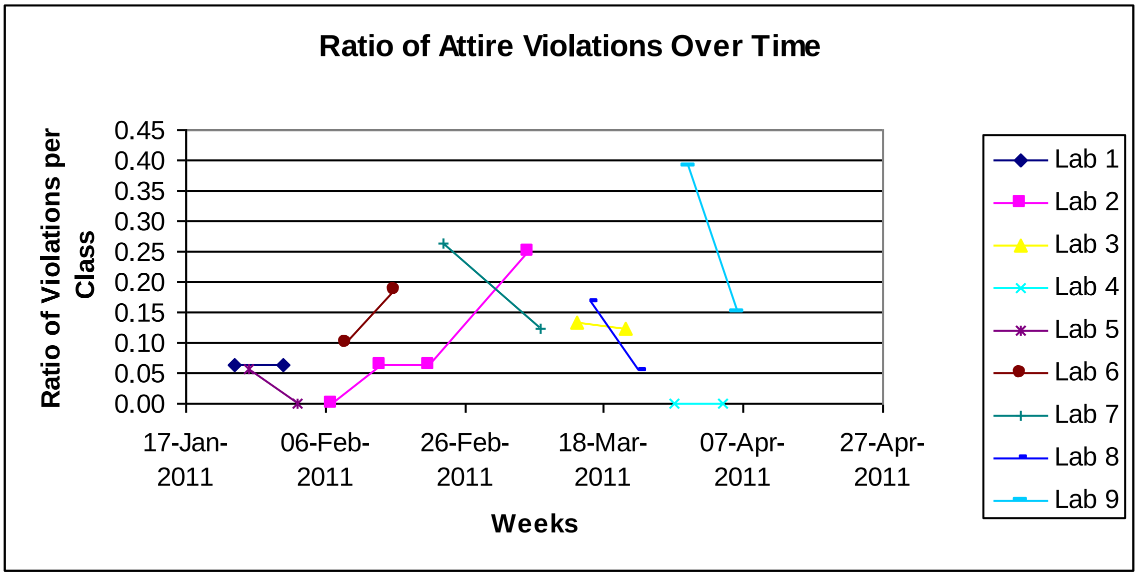


**Figure 0.2: Ratio of Ingestion Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

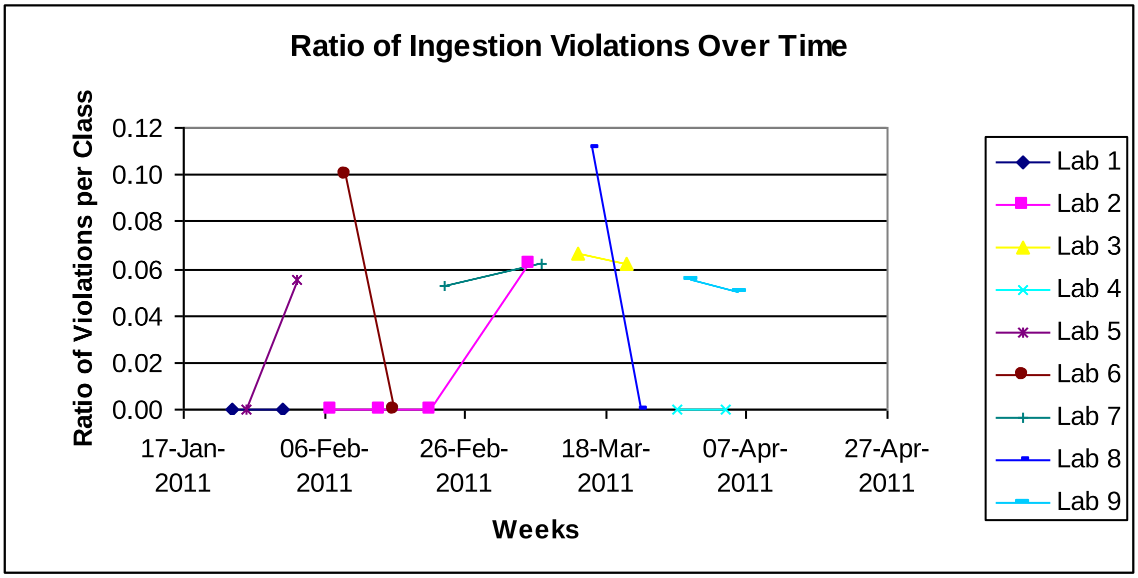


**Figure 0.3: Ratio of Goggle Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

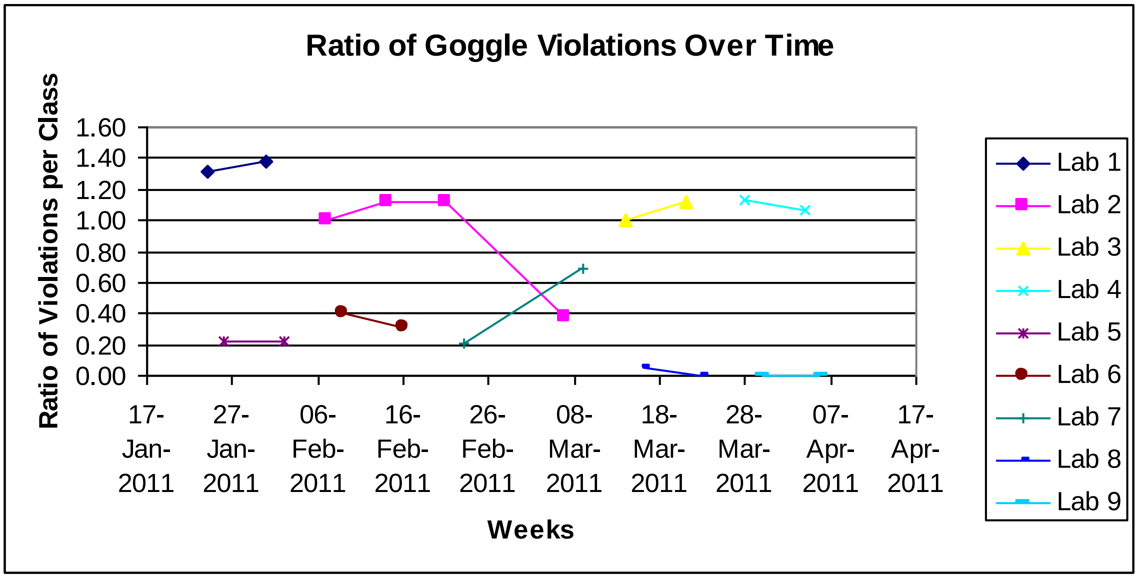


**Figure 0.4: Ratio of Glove Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

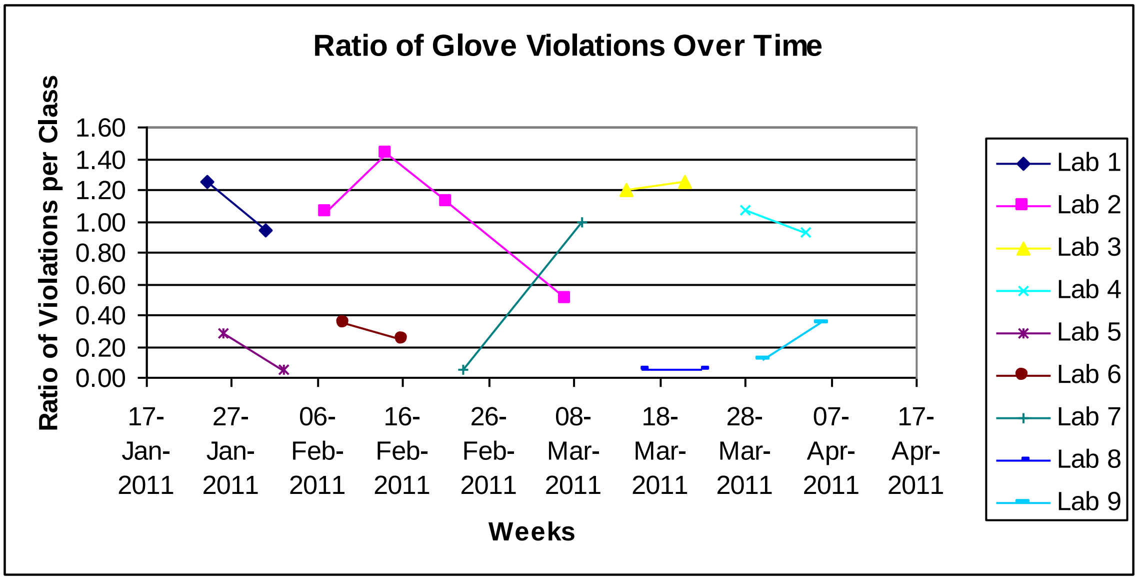


**Figure 0.5: Ratio of PPE Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

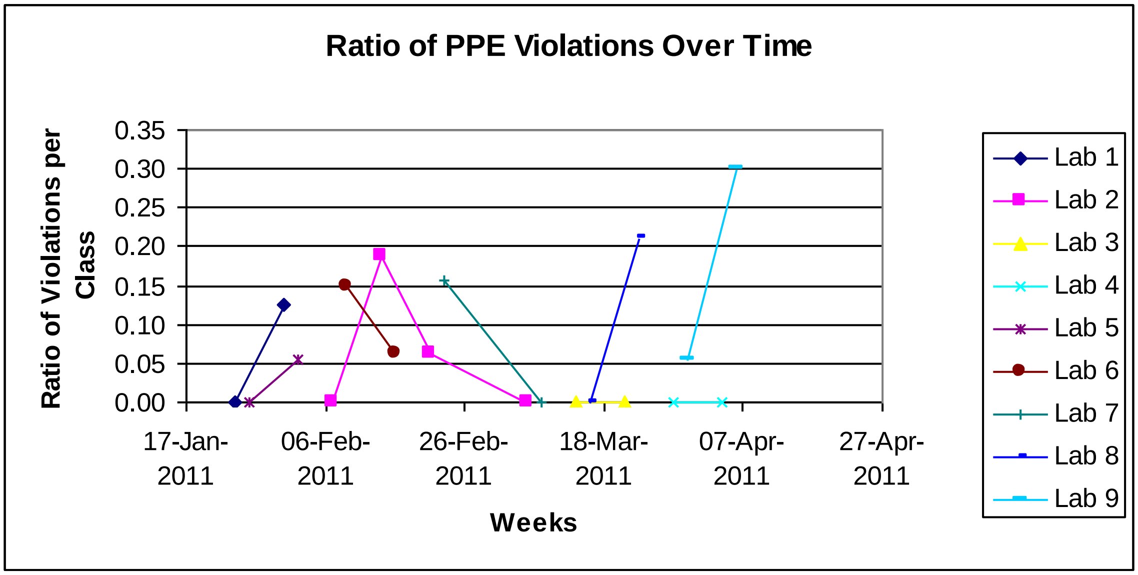


**Figure 0.6: Ratio of Touching Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

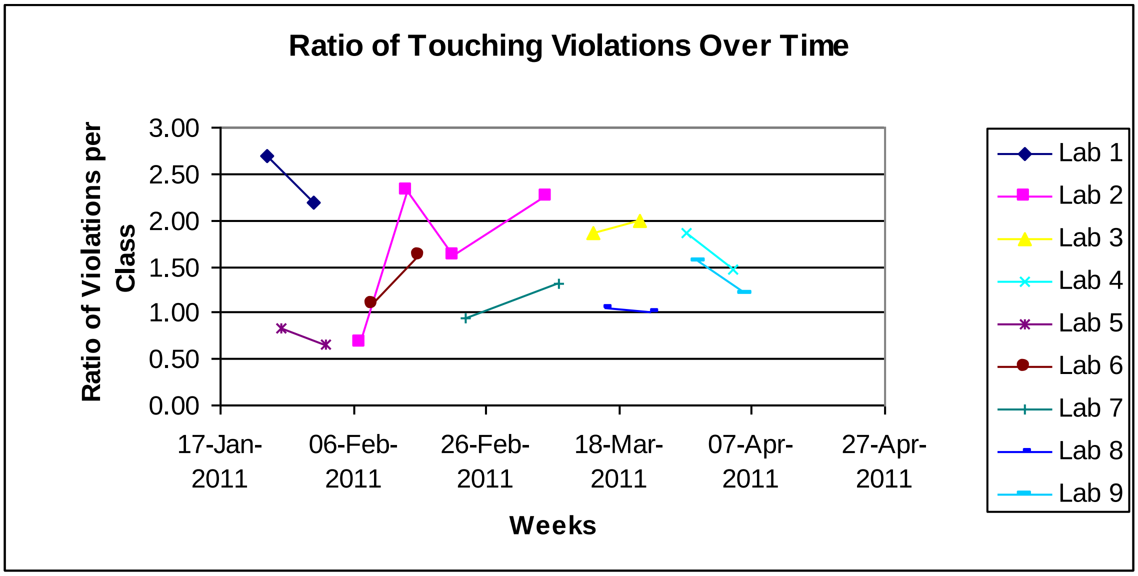


**Figure 0.7: Ratio of Waste Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**

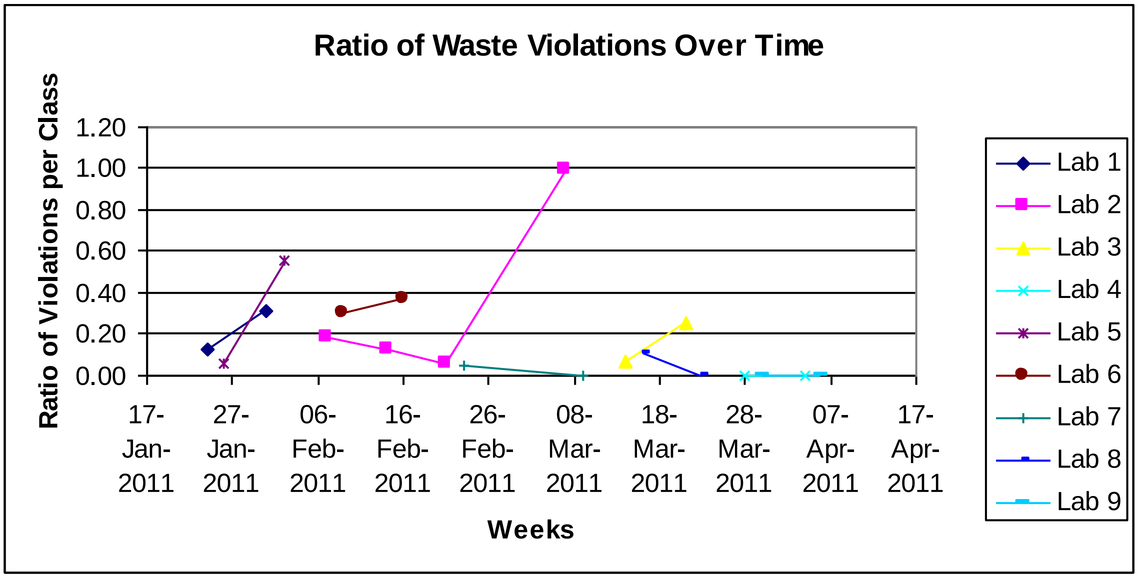
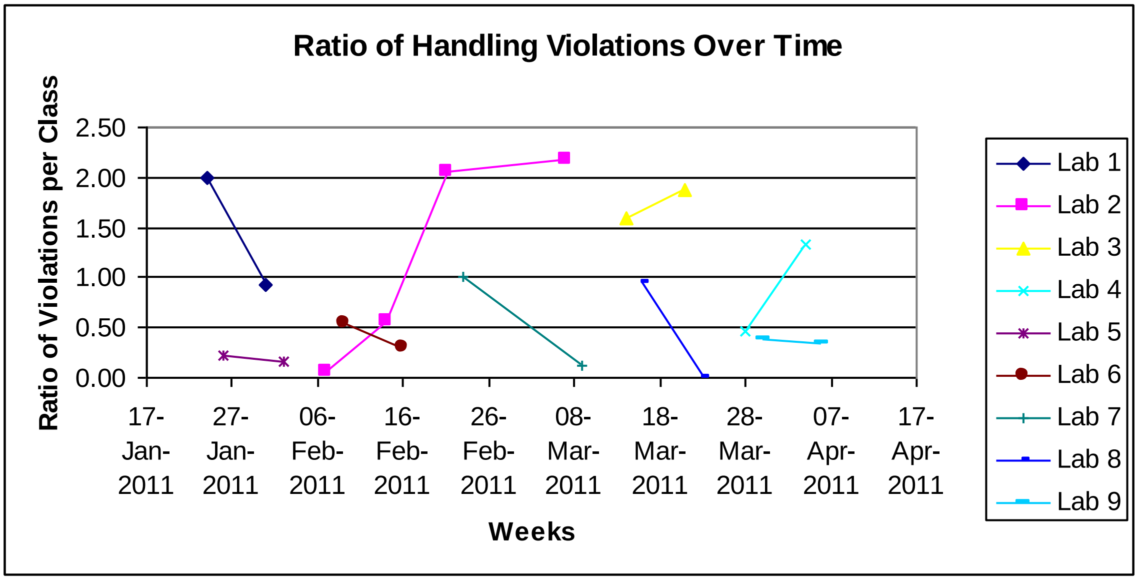


**Figure 0.8: Ratio of Handling Violations in Nine Different Chem 211 Laboratory Classes During the Course of Winter 2011. Due to a lack of power, no direct conclusions can be made.**



# Appendix I

## Table 0.1: Hierarchal Linear Model of Demographic Influence on Participant Chemical Hygiene Scores

| Parameter | Estimate | Std. Error | df | t | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|---|
| | | | | | | Lower Bound | Upper Bound |
| Intercept | 2.000392 | 2.275248 | 29 | .879 | .387 | -2.653013 | 6.653797 |
| [GroupCode=2.00] | 1.026617 | 1.519835 | 29 | .675 | .505 | -2.081794 | 4.135028 |
| [GroupCode=3.00] | 0[a] | 0 | . | . | . | . | . |
| T1CH | .180859 | .279448 | 29 | .647 | .523 | -.390676 | .752393 |
| [GroupCode=2.00] * T1CH | -.308115 | .325081 | 29 | -.948 | .351 | -.972980 | .356750 |
| [GroupCode=3.00] * T1CH | 0[a] | 0 | . | . | . | . | . |
| Gender | -.138147 | .271883 | 29 | -.508 | .615 | -.694209 | .417915 |
| Ethnicity | .018356 | .150532 | 29 | .122 | .904 | -.289517 | .326229 |
| ACTCompScore | -.055935 | .072676 | 29.000 | -.770 | .448 | -.204573 | .092704 |
| SATCompScore | .002204 | .001724 | 29.000 | 1.278 | .211 | -.001323 | .005730 |
| Previous Research | .245381 | .292481 | 29 | .839 | .408 | -.352809 | .843571 |
| Major | -.246905 | .163224 | 29 | -1.513 | .141 | -.580737 | .086926 |
| Class Year | .029257 | .182870 | 29 | .160 | .874 | -.344754 | .403268 |
| Extracurricular | .044876 | .118399 | 29 | .379 | .707 | -.197276 | .287029 |
| CreditHours | .005137 | .006232 | 29 | .824 | .417 | -.007610 | .017883 |
| TransferHours | .009577 | .021491 | 29 | .446 | .659 | -.034377 | .053531 |

a. This parameter is set to zero because it is redundant.

b. Dependent Variable: T2CH.

# Appendix J

## Table 0.1: Hierarchal Linear Model of Demographic Influence on Participant Waste Scores

| Parameter | Estimate | Std. Error | df | t | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|---|
| | | | | | | Lower Bound | Upper Bound |
| Intercept | 3.154018 | 1.691037 | 29.000 | 1.865 | .072 | -.304541 | 6.612576 |
| [GroupCode=2.00] | .125408 | .578159 | 29.000 | .217 | .830 | -1.057060 | 1.307877 |
| [GroupCode=3.00] | 0[a] | 0 | . | . | . | . | . |
| T1Waste | .266621 | .224484 | 29.000 | 1.188 | .245 | -.192500 | .725743 |
| [GroupCode=2.00] * T1Waste | -.503465 | .320605 | 29.000 | -1.570 | .127 | -1.159176 | .152246 |
| [GroupCode=3.00] * T1Waste | 0[a] | 0 | . | . | . | . | . |
| Gender | -.058316 | .280731 | 29.000 | -.208 | .837 | -.632476 | .515843 |
| Ethnicity | -.216299 | .164420 | 29.000 | -1.316 | .199 | -.552575 | .119977 |
| ACTCompScore | -.065784 | .071951 | 29.000 | -.914 | .368 | -.212941 | .081372 |
| SATCompScore | .000514 | .001705 | 29.000 | .302 | .765 | -.002974 | .004002 |
| Previous Research | -.173465 | .291249 | 29.000 | -.596 | .556 | -.769137 | .422207 |
| Major | .004367 | .165521 | 29.000 | .026 | .979 | -.334161 | .342896 |
| Class Year | .131754 | .175544 | 29.000 | .751 | .459 | -.227274 | .490782 |
| Extracurricular | -.029886 | .119614 | 29.000 | -.250 | .804 | -.274524 | .214752 |
| CreditHours | .004303 | .006168 | 29.000 | .698 | .491 | -.008312 | .016918 |
| TransferHours | -.002394 | .021900 | 29.000 | -.109 | .914 | -.047184 | .042396 |

a. This parameter is set to zero because it is redundant.

b. Dependent Variable: T2Waste.